Bangor University

DOCTOR OF PHILOSOPHY

Availability, continuity, and selection of maritime DGNSS radiobeacons

Grant, Alan James

Award date:
2002

Awarding institution:
University of Wales, Bangor

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 27. Apr. 2024

Availability, continuity, and selection of maritime DGNSS radiobeacons

Thesis submitted in candidature for the degree of

Doctor of Philosophy

November 2002

Alan James Grant

I'W DDEFNYDDIO YN Y LLYFRGELL YN UNIG

TO BE CONSULTED IN THE LIBRARY ONLY

• PRIFYSGOL CYMRU •
UNIVERSITY OF WALES
BANGOR
1884

School of Informatics

University of Wales

Bangor

United Kingdom

P.C.B LLYFRGELL U.W.B LIBRARY

Acknowledgements

First and foremost, I would like to thank Professor David Last for his guidance in this research and for the confidence and belief he has shown in me.

A special thanks goes to everyone who has assisted over the past three years, especially to Dr Paul Williams and Alwyn Williams for their encouragement, assistance, advice and sense of humour. I'd also like to thank Dr Lucy Kuncheva and Mr Chris Whitaker for their guidance.

I would like to take this opportunity to formally thank my family; my parents, for their blind faith and support throughout my education. For my brothers Colin and Keith for the support and encouragement they gave and continue to give through the years of me being 'poor Alan'. And the overall sense of pride I feel from them and towards them – Thank you!

This research has been funded by the General Lighthouse Authorities of the British Isles and the Engineering and Physical Science Research Council (EPSRC).

A huge thank you goes to my friends who have helped with support and encouragement, namely: Chris, Matthew, John, Paul R, Paul S, Iestyn, Colin, Cathie, Pablo, Stef, Siôn, Sa'ad, Vicky, Bex, Jamie, Neil, Phil, Sanjay and all my friends whom I haven't named.

Finally I would like to dedicate this work to my family, I simply couldn't have done this without your love, belief and support! **Thank you!**

Summary

Differential Global Satellite Navigation Systems (DGNSS) are based on the principle that the main sources of error in satellite navigation are consistent over substantial geographical areas. The magnitudes of these errors can be measured by installing reference receivers at fixed, known locations. The corrections they generate are then broadcast via a radio system. DGNSS users in the vicinity receive these corrections and employ them to adjust their own position measurements accordingly.

Marine radiobeacons are widely used to transmit these correction messages to maritime users. These radiobeacons enjoy an existing, protected, frequency band and large numbers of them are available world-wide. Recent research has studied the many factors that affect the coverage of radiobeacons. These include propagation losses, skywave-borne interference from the many beacons that share the radio band, and atmospheric noise. The results have been embodied in a widely-used computer model for predicting the coverages of beacons when planning DGNSS systems.

Of comparable importance, however, is ensuring that the beacons' signals are available with an adequate probability across that coverage region. This research analyses this question of DGNSS radiobeacon availability. It identifies and quantifies the many factors which determine the probability of obtaining a service of adequate quality. Stochastic elements, such as atmospheric noise and skywave propagation, are evaluated. So are deterministic factors such as groundwave propagation of the beacon's signal, and interference. Novel techniques are then proposed for combining these multiple factors so as to allow a single probability of availability to be calculated at any location. This work is then extended to include continuity: the probability of the service remaining available over a specified period.

These new techniques have been built into a computer model that evaluates the availability, continuity, and coverage for both individual stations and networks of DGNSS radiobeacons. The resulting software enables administrations to plan their systems, ensuring that all three criteria are met.

The development of this new software model paved the way for analysing an additional important factor: the effectiveness of the algorithms employed by beacon receivers for establishing at each location which beacon to select as the source of correction data. Software was written to do this, analysing and comparing the performance of the commonly-used receiver algorithms that employ the *nearest beacon* and *strongest beacon* selection methods. Both were shown to fall short of the ideal. Two new, superior, strategies were then proposed and evaluated, one appropriate for use when selective availability (SA) was in operation and a second for use with SA set to zero.

An important practical outcome of this research is the software model, with its two main functions. One enables mariners to select the beacon which offers them the best service. The other allows service providers to identify and plan where their beacons meet the international availability and continuity requirements, giving a safe and reliable service.

Abbreviations

BCPM	Bangor Coverage Prediction Model
BER	Bit Error Rate
C/A	Coarse/Acquisition
CCG	Canadian Coast Guard
CDMA	Code Division Multiple Access
CS	Commercial Service
CTI	Continuity Time Interval
DF	Direction Finding
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
DoD	(US) Department of Defence
DOP	Dilution of Precision
DoT	(US) Department of Transportation
EMA	European Maritime Area
EMRF	European Maritime Radionavigation Forum
FDMA	Frequency Division Multiple Access
FoM	Figure of Merit
FRP	(US) Federal Radionavigation Plan
FTA	Fault Tree Analysis
GDOP	Geometrical Dilution of Precision
GLAs	General Lighthouse Authorities (of the British Isles)
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HP	High Precision
IALA	International Association of Maritime Aids-to-Navigation and Lighthouse Authorities.
IEC	International Electrotechnical Commission
IFCA	Interference Free Coverage Area
IGEB	Interagency GPS Executive Board
IMO	International Maritime Organisation
ITU	International Telecommunication Union
LBS	Location Based Services
LF	Low Frequency
MB	Marine Beacon
MEO	Medium Earth Orbit
MENAS	Middle East Navigation Aids Service
MF	Medium Frequency
MSK	Minimum Shift Keying
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NDB	Non-directional radiobeacon (aeronautical)
OS	Open Service
PDOP	Position Dilution of Precision
PPS	Precise Positioning Service
P(x)	Probability of X
Pr(x)	Probability of X
PRC	Pseudorange Correction
PRN	Pseudo-random noise
PRS	Public Regulated Service

RF	Radio Frequency
RMS	Root Mean Square
RTCM	Radio Technical Committee for Maritime Services
RTK	Real Time Kinematic
SA	Selective Availability
SAR	Search and Rescue
SGR	Skywave-to-Groundwave Ratio
SIR	Signal-to-Interference Ratio
SIS	Signal-in-Space
SNR	Signal-to-Noise Ratio
SoL	Safety of Life
SP	Standard Precision
SPS	Standard Precision Service
TASC	The Analytical Sciences Corporation
TDOP	Time Dilution of Precision
TEC	Total Electron Content
TTA	Time-to-Alarm
USCG	United States Coast Guard
VDOP	Vertical Dilution of Precision
WER	Word Error Rate
WGS 84	World Geodetic System 1984

List of symbols

α	Geographic latitude
A_{DGPS}	Availability of DGPS service
A_{GPS}	Availability of GPS service
A_{LDAS}	Availability of the local differential augmentation service
β	Geographic longitude
b_{Hz}	Bandwidth in Hz
B_i	Clock bias of the *i-th* satellite
B_{user}	User's GPS clock bias
c	Speed of light
$\cap$	Logical AND function
d	Distance in km
Δ_{path}	Differences in path length between skywave and groundwave
$\Delta\rho$	Pseudorange error
Δt	Discrete time interval
Δ_{time}	Differences in propagation time between skywave and groundwave
e_i	1-σ pseudorange error
E_n	RMS noise field strength
Φ	Geomagnetic latitude
F_{am}	Median noise level from world map
Φ_d	Standard normal cumulative distribution function
F_i	Probability of failure of path $_i$
f_{kHz}	Frequency in kHz
floor	Either signal-to-noise ratio floor or signal-to-interference ratio floor
f_{MHz}	Frequency in MHz
Gnd_{dB}	Groundwave field strength in dB
G_s	Sea gain
G_v	Antenna gain factor
h	Ionospheric height
k	Basic loss factor
$L_{9\text{-}3}$	Message length in bits (of Type 9-3 message)
ld	Base 10 logarithm of distance in km
μ_n	Mean of the noise distribution
μ_s	Mean of the signal distribution
n	Number of messages
new	New distribution
p	Slant propagation distance in km

$P(t+\Delta t)$	Probability at the discrete time $t+\Delta t$
p_d	Probability of correct reception
q_d	Probability of missing one set of messages
Q_i	Availability of the i-th beacon and its signal-in-space
q_s	Probability of service failure
R	Baud rate
R_i	Range from *i-th* satellite
R_{user}	Range to the user
ρ_i	Pseudorange from the *i-th* satellite
R_i	Probability of recovery for path $_i$
σ	Standard deviation
σ_n	Standard deviation of noise signal
σ_s	Standard deviation of wanted signal
T_{ai}	Time of arrival (*i-th* satellite)
T_{max}	Length of time interval
T_{ti}	Time of transmission (*i-th* satellite)
U_i	Probability of i-th event occurring.

Table of contents

CHAPTER 4
REQUIREMENTS FOR PREDICTING AVAILABILITY

CHAPTER 5
BEACON SELECTION

CHAPTER 6
AVAILABILITY

CHAPTER 7
MODELLING AVAILABILITY

CHAPTER 8
CONTINUITY

CHAPTER 9
CONCLUSIONS

APPENDICES

Chapter 1

Introduction

In 1995 the United States government declared its NAVSTAR-Global Positioning System (GPS) operational [1]. GPS is a satellite-based navigation system that provides an all-weather navigation service world-wide. It currently allows civilian users to locate themselves within 13m* 95% of the time [2]. GPS is often grouped with GLONASS, the Russian equivalent which is already operational [3], and Galileo, the European satellite navigation system planned to be operational by 2008 [4], as a Global Navigation Satellite System (GNSS).

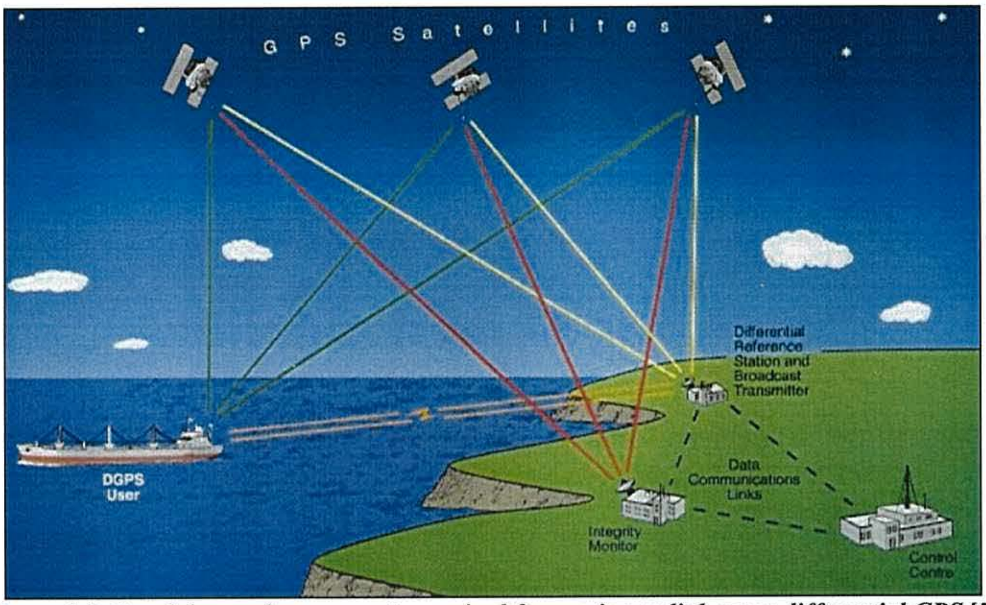

Figure 1.1: Breakdown of components required for marine radiobeacon differential GPS [5].

Differential Global Navigation Satellite Systems (DGNSS) allow the uncertainties in a user's position to be reduced to below 10m, 95% of the time, and to less than 5m near the reference station [6,7]. Figure 1.1 shows the components required to create a DGNSS: a reference station with a high-grade GPS receiver, a communications link to the user, and a differential receiver for the user. The basic principle of differential operation is that errors in the user's measured GPS position are essentially the same as those experienced at the reference station.

* Stated for signal-in-space only.

The reference station is at a known, surveyed, location so the magnitudes of any errors can be calculated. The reference station broadcasts corrections for these errors, commonly via a radio link. Users receive these broadcasts and apply the corrections within their own receivers, so enhancing accuracy of their position fixes. A further important bonus of differential operation is that the reference station promptly signals the failure of any satellite's signal to meet a pre-set quality standard. The user's receiver then excludes this satellite from the navigation solution. In this way, differential operation enhances the integrity of the user's position fixes, as well as their accuracy.

For maritime users, marine radiobeacons have proved attractive as a means of broadcasting differential messages since they were available, could easily be modified, and had an existing, protected, frequency band and infrastructure; developing a new radio system would have required much more time and expenditure. Corrections are transmitted using additional messages that employ minimum shift keying (MSK) modulation [8]. This modulation technique results in a narrow signal bandwidth, with a compact spectrum, low error rates, and requiring only simple demodulation and synchronisation circuits [9,10]. Radiobeacons supply differential corrections throughout extensive coastal regions of Europe, the US, and parts of the Middle East; currently (2002) 28 countries offer marine radiobeacon DGNSS services [11]. The use of marine radiobeacons in this way has become the standard means of precise and reliable navigation in coastal waters and in harbours worldwide [12,13].

In order to ensure high service quality, the factors affecting the signals of radiobeacons have been carefully analysed [14]. The principal elements are the attenuation of the signal (especially over land paths), interference between the signal's own groundwave and skywave components, the level of natural atmospheric noise, and the levels of interference from other transmitters on the same and adjacent frequencies. Previous studies have analysed these factors and developed a software model that enables administrations to plan their radiobeacon networks to ensure that the required standards are met by the most effective and efficient networks of stations [14].

However, these studies did not take into account the availability or continuity of the radiobeacon signal. Signal availability is defined as '*The availability of a radio signal in a specified coverage area*' [15]. This definition is generally interpreted as being applicable across the entire coverage area of each beacon. Continuity is defined as '*The ability of a system to function within specified performance limits without interruption during a specified period*' [15]. This *specified period* is commonly set at 3 hours [16].

Availability and continuity are as important factors as is the coverage of a radiobeacon's signal. Service providers are required to ensure that the availability and continuity of their service meet internationally-agreed standards, established to ensure that the service is consistently available for the mariner's use.

Until recently, the several authoritative documents that specify these factors gave conflicting standards for signal availability and continuity; this confusion is analysed in detail further in Chapters 7 and 8. Table 1.1 shows the final service standards that are employed in this research.

Area	Availability	Continuity
Coastal/Harbour with low risk	*> 99.5% (2 years)*	*≥ 99.85% (3 hrs)*
Coastal/Harbour with high risk	*> 99.8% (2 years)*	*≥ 99.97% (3 hrs)*

Table 1.1: Service requirements as set by the latest IMO resolution for availability and continuity. The calculation period is shown in brackets [17].

To date, service providers and standards authorities have limited their attempts to meet availability and continuity standards to the availability of the reference station signal alone [16,18]. The mariner, however, is interested in the availability of the service provided by his receiver. This depends on not only the availability of the signal but also on propagation conditions (the coverage-determining factors listed above) allowing the received signal to meet a minimum acceptable reception standard.

Further, since several of the international standards concerning availability are unfortunately unclear and ambiguous, an important aim of this research has been to understand and interpret the present methods of considering availability employed by service providers [16,19,20]. That done, the factors that determine signal quality are analysed in order to create a method for estimating availability at any location.

This method is then embodied in a computer model designed to map the availability and continuity of single beacons or networks of beacons, taking into account the many factors that affect the service. The resulting computer model will allow administrations to plan not only the coverages of their systems as before, but now also their availability and continuity.

1.2 Overview of thesis

Chapter 2 introduces radiobeacon Differential Global Navigation Satellite Systems (DGNSS). The chapter starts by introducing the three GNSS services: GPS, GLONASS and Galileo. The operation of GPS is explained in depth since it is the system used by the radiobeacons in this research. Sources of error in the GPS service are identified. The concept of marine radiobeacon differential operation is introduced and examined, to show how it minimises the effect of GPS errors and enhances integrity. Although differential GPS (DGPS) is the most commonly-used system at present, the term DGNSS will be used throughout this document so as to include differential augmentations of the other GNSS services.

Radiobeacon performance is the topic of Chapter 3. This chapter examines the nature of the propagation of the signal from the transmitter, taking into account the effects of the ground conductivity and the influence of interference. For a beacon's signal to be deemed usable it must fulfil coverage requirements stipulated by the International Telecommunication Union (ITU) which are introduced at this stage. The operation of the Bangor Coverage Prediction Model is investigated; the model predicts the coverage of the beacon's signal by using the methods explained in this chapter.

Chapter 4 looks at the requirements for predicting availability. In this chapter the requirements of the software tool developed for calculating availability and continuity are examined. It is clear that the Bangor Coverage Prediction Model is unable to meet these needs; in this chapter a new model, with a new architecture, is introduced that has been conceived, implemented and tested by the candidate.

Chapter 5 briefly takes us away from availability and continuity and to the topic of beacon selection. The development of the new architecture allowed the candidate to undertake novel work on this timely and important topic. Beacon selection methods employed in current-generation differential receivers are modelled and significant differences of approach highlighted. A novel method is then proposed that selects the best beacon for use when Selective Availability (SA) is active. Another novel method was then proposed once SA was set to zero. This selects the beacon whose use minimises spatial dilution whilst ensuring that the time-to-alarm criterion is met. The results of using these various strategies are modelled for the United Kingdom and Ireland, and also across the entire European Maritime Area (EMA). The results are presented in both pictorial form and as text-based lists that can be employed within a receiver. In addition, this chapter also introduces the technique of calculating the total number of beacons that can provide each location with a usable service, the basis of later work.

In Chapter 6 the focus returns to availability. Existing modelling techniques are reviewed and found to be too complex for the needs of this research or unclear in their derivation. Fault Tree Analysis (FTA) is selected as the most appropriate method of modelling the service. An FTA is constructed for the radiobeacon service and then reviewed and refined. The model is developed alongside a commercial fault tree analysis software package in order to verify its correct operation. An important consideration at this stage is the degree to which various failure modes may be correlated and also the degree of correlation between multiple beacons. A series of measurements were devised which demonstrated that failures due to atmospheric noise, skywave interference and self-fading are virtually uncorrelated and so are failures between neighbouring beacons.

International and national availability standards are reviewed in Chapter 7. Unfortunately, the many authoritative sources provide conflicting standards and it is unclear just what service availability standards and definitions should be employed! The chapter tackles this problem, critically reviewing each source and finally establishing the standards to be employed in the subsequent analyses. That done, a methodology for calculating availability is developed. Starting with a coarse approach, which is then progressively refined to yield a method that accurately models reality, taking into account the various factors at each location. Service availability is then plotted for the first time. Then, separate day and night results are brought together to compute the availability required by the standard employed: the service availability over two years.

Continuity is the topic of Chapter 8. As with availability, the standards set by various sources are reviewed and found to be conflicting. After again identifying the most appropriate standard to be used, the factors that affect continuity are shown to be the same ones that determine availability. Calculating the continuity of the beacon's transmissions is found to be straightforward. However, this is not the case for the various stochastic factors. A number of assumptions are introduced to allow this analysis to be completed. Once availability and continuity can be plotted, it becomes possible for the first time to establish the areas where the radiobeacon service meets all the standards - coverage, availability and continuity - simultaneously.

Chapter 9 draws together the conclusions from this research and proposes future work.

1.3 Contributions to knowledge

In the course of the research set out in this thesis, the candidate has made the following contributions to knowledge:

- Created an extended annual average atmospheric noise database for areas beyond the EMA.

- Critically analysed existing beacon selection methods and shown them to be vary considerably, with some being unsuitable for the purpose.
- Proposed and analysed a new *"quality"* beacon selection method.
- Proposed and analysed a new *"post-SA"* beacon selection method, producing results both pictorially and in the form of a data file.
- Identified the best beacon to use at each location across the EMA.
- Identified the alternate beacon to use at each location across the EMA.
- Developed a novel method for identifying the number of beacons that provide a usable service to each location.
- Critically reviewed the conflicting availability standards set by authoritative bodies and selected a suitable requirement, which since has been adopted by IMO.
- Critically analysed existing methods of predicting availability and identified significant deficiencies.
- Shown that only stochastic events affect the availability and continuity of the radiobeacon service.
- Developed and implemented a Fault Tree Analysis for marine radiobeacon differential GNSS.
- Proposed and validated a novel method of predicting availability for a single beacon.
- Proposed and validated a novel method of predicting availability for a network of beacons.
- Investigated experimentally the degree of correlation of potential failure mechanisms for networks of beacons, taking into account atmospheric noise, self-fading and skywave-borne interference.
- Developed a means of calculating the standard deviation of stochastic skywave fading for any given skywave-to-groundwave ratio.
- Developed and evaluated a first-stage method, using edge-of-coverage techniques, for calculating availability and shown how it might be drastically improved.
- Developed and evaluated a novel technique for predicting the availability using data at each location, and shown how it too could be improved.

- Developed and evaluated a final novel technique for predicting availability using the statistical distributions of all stochastic elements to provide a realistic model.
- Assembled noise databases covering the European Maritime Area for day and night hours.
- Implemented a method of predicting availability over two years to meet international standards.
- Produced British Isles and EMA availability plots for the first time.
- Reviewed the conflicting continuity standards as set by authoritative bodies and selected a suitable requirement, which since has been adopted by IMO.
- Investigated methods of predicting continuity for a reference station.
- Proposed a novel method of predicting continuity for the signal-in-space.
- Produced plots showing continuity results for the first time.
- Implemented a software model to predict locations where the service provided by a single beacon or a network of beacons, simultaneously meets all the standards, ie those for coverage, availability and continuity.
- Analysed existing work on optimisation of the frequency band and found it to overlook powerful beacons.
- Evaluated the effect of beacons of greater power on frequency band optimisation.

Chapter 2

Radiobeacon Differential GNSS

2.1 Introduction

This chapter introduces the various Global Navigation Satellite Systems (GNSS) available now or expected to become available in the near future. At present there are two operational GNSS systems, GPS and GLONASS. A third, Galileo, is currently under development and is planned to reach full operational capacity (FOC) in 2008 [4]. Each of these three systems is now examined.

2.2 GPS

GPS is a satellite navigation system operated by the United States Department of Defense (DoD) and controlled by them in collaboration with the United States Department of Transportation (DoT) and others, as part of the Interagency GPS executive board (IGEB) [21]. Their system is designed to provide a means of navigation with high accuracy for both civilian and military users, on a world-wide, all-weather, basis.

GPS satellites are Medium Earth Orbit (MEO) satellites. The GPS constellation consists in principle of 24 satellites (currently there are also several in-orbit spares) operating in circular orbits, at a height of 20,200km, with an orbital period of 11h 58mins. The 24 satellites are equally distributed between 6 orbital planes, each at an inclination of 55° to the equator (Fig. 2.1)

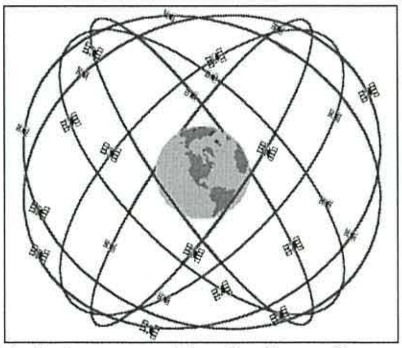

Figure 2.1: Orbital planes used by the Space Segment of GPS [22].

GPS provides two levels of service: the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The PPS in principle, offers the most accurate positions but to authorised users only. These users include United States' and allied governments' agencies and their military forces. Selected civilian GPS users can also be authorised to use the PPS, should they need to do so in the national interest of one of these states [23]. The horizontal positioning accuracy of the PPS is claimed to be at least 22m, $2d_{rms}$ [24], a figure that benefits from the use of two signal frequencies (See Section 2.2.6); here "$2d_{rms}$" means twice the root mean square (rms) error.

The standard positioning service was originally designed to provide non-authorised and civil users with a less accurate position than did PPS. A major component in this accuracy reduction was intended to be use of a single signal frequency since the effects of delays as the signals traversed the Earth's atmosphere were to be uncorrected. A further accuracy reduction was later provided by Selective Availability (SA), a method of introducing random errors in measured positions. The resulting horizontal accuracy was designed to be 100m, $2d_{rms}$ [25].

Since SPS was introduced, changes of policy and improvements in technology have dramatically reduced SPS position errors. In May 2000, Selective Availability was set to zero - effectively switched off [26]. The SPS service is now claimed to provide a global average signal-in-space horizontal position accuracy of better than 13m, 95% of the time [2]. That is, if a circle with a radius of 13 metres were drawn with a static receiver in its centre, 95% of the points measured by this receiver would fall within that circle.

GPS is a code division multiple access system; that is, all satellites transmit their messages on the same two carrier frequencies, each satellite's carriers being phase-modulated with a unique pseudo-random noise (PRN) code to produce spread-spectrum signals. Table 2.1 shows the frequencies and modulation rates of the SPS and the PPS navigation information [27].

	L1	L2
Service	SPS and PPS	PPS
Frequency	1575.42 MHz	1227.6 MHz
Bit rate	1.023 Mbps	10.23 Mbps

Table 2.1: Carrier frequencies and PRN code rates of SPS and PPS signals [27]

The PRN code used for the SPS is known as the Coarse/Acquisition (C/A) code and it repeats every 1ms. PPS uses the C/A code on L1 and the longer 'precise code (P-code)', to further encrypt the service to help prevent jamming and spoofing and is then referred to as the Y-code. The carriers on each channel are also modulated at 50bps with a navigation message that carries data concerning the satellite's clock, ephemeris, and health. This message is repeated every 30s, with the full almanac of locations of the satellite constellation being updated every 12.5minutes (with 24 satellites). Since the research detailed in this thesis deals with the differential correction of the SPS service only, no further details of PPS will be discussed at this stage.

2.2.1 Ranges and Pseudoranges

GPS makes use of the measured distances between several satellites and the user to establish the user's position. The user's apparent range from each satellite is determined in the receiver by measuring the precise time it takes for the signal to propagate from the satellite to the receiver. This propagation time can, in principle, be calculated by subtracting the time-of-transmission from the time-of-arrival.

The receiver uses the individual PRN of each satellite to determine that satellite's range and recover its navigation message from the received signal, which contains the superimposed spread-spectrum transmissions from all satellites in view. Range is established by measuring the time-of-arrival of the signal. The receiver correlates the (C/A) PRN code of the signal received from the satellite with a copy of the same code it generates internally (Fig. 2.2) [28,29]. The receiver progressively shifts its copy in time until it is aligned with the received copy; the time shift then gives a measure of the time-of-arrival with respect to the receiver's clock, which ideally is synchronised with the universal time.

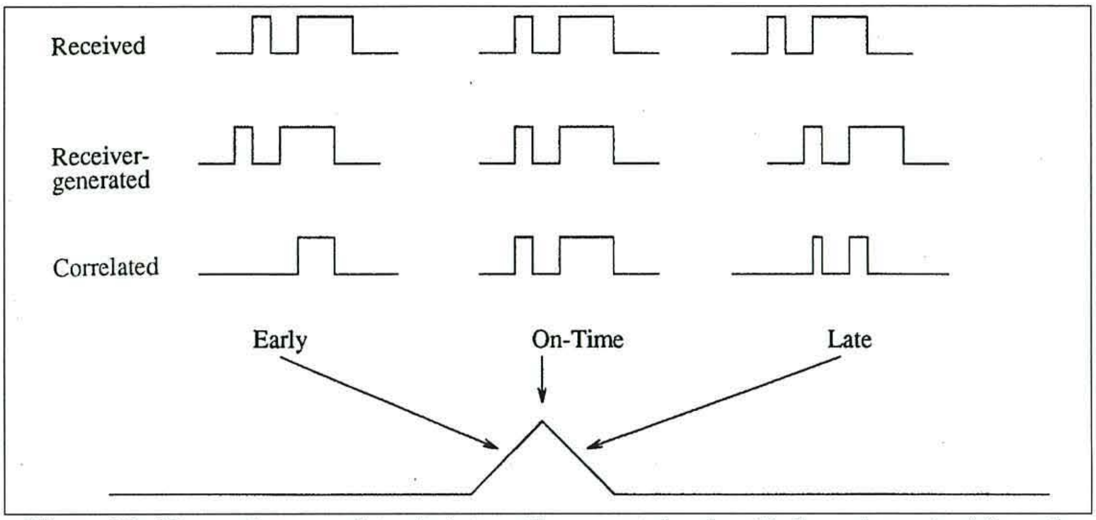

Figure 2.2: The receiver correlates its internally generated code with the code received from the satellite. In this way it determines the time offset between the two [28,29].

The receiver establishes the time-of-transmission of each signal from details given in the navigation message. The message contains three polynomial coefficients (a_0, a_1, a_2), which represent the bias of the satellite clock, and a reference time (t_0) [27]. Together these are used to model the bias of the satellite clock with respect to universal time and so to establish precisely the time-of-transmission.

If, for the moment, one assumes that the signal travels from the satellite to the receiver at the speed of light, the range of the user from the satellite is given by:

$$R_i = c\left(T_{ai} - T_{ti}\right), \tag{2.1}$$

where R_i is the range of the *i-th* satellite, T_{ai} and T_{ti} represent the times-of-arrival and times-of-transmission respectively, and c is the speed of light.

This propagation time could be measured very accurately if the receiver employed a precise and stable atomic clock synchronised with the atomic clock on the satellite. In practice, a cheaper and less accurate clock is used which introduces a time error, or time "bias", B_{user}. The apparent range measured, including this error term, is called the "pseudorange":

$$\rho_i = c\left(T_{ai} - T_{ti} + B_{user}\right). \tag{2.2}$$

2.2.2 Locating the satellites

In order for the receiver to use the range information it measures, the location of each satellite at the moment of transmission of each PRN sequence must also be known. The receiver reads the ephemeris parameters the satellites transmit within their navigation messages [30,31]. It then calculates each satellite's position at each time of transmission. Satellites' and the receivers' position are all expressed in the World Geodetic System 1984 (WGS84) earth-centred, earth-fixed, reference frame.

To calculate the user's position, (at least) four simultaneous pseudorange measurement equations are solved within the receiver. The four unknowns calculated are the users position (that is, R_{user} [x y z]), and the receiver clock bias, B_{user}. If pseudoranges from only three satellites are available, a solution may be obtained by assuming that the receiver altitude is zero.

2.2.3 Error sources in GPS positioning

Differential systems were developed well after the development of GPS itself, initially with the primary aim of reducing positioning errors, notably those due to SA. Even without SA, GPS is subject to the many sources of error set out in Table 2.2.

Error source	Expected range measurement error (m rms)		
	PPS	SPS	DGPS
Ephemeris Errors	2.5 – 7	2.5 – 7	0 – 0.1
Satellite clock errors	1 – 3	1 – 3	0
Ionospheric delay (after modelling)	0.4 – 2	2 – 15	0.1 – 1
Tropospheric delay (after modelling)	0.4 – 2	0.4 – 2	0.1 – 1
Multipath propagation	1 – 2	2 – 4	2 – 5
Resulting range error in receiver	1 – 2	2 – 6	2 – 6
Resulting 95% position error			
Horizontally	4.5 – 12	13 (SIS only)	1-10
Vertically	7.5 – 20	22 (SIS only)	5 – 15

Table 2.2: Errors that affect GPS positioning in PPS, SPS and DGPS modes of operation. For DGPS, a separation of 90 km between reference station and receiver is assumed [6] SIS: signal-in-space[25].

2.2.4 Ephemeris error

The ephemeris data transmitted as part of the navigation message allows receivers to compute the satellites' current positions moment-by-moment. Ground monitoring stations measure the satellites' orbits to determine these parameters. However, there are significant delays before the parameters are transmitted to the satellite and from the satellite to the user. In certain circumstances, this source of error can be ignored. These include surveying applications in which real-time positions are not required. In these cases, orbital parameters measured simultaneously with the pseudoranges are employed in post-mission position calculations [31].

2.2.5 Satellite Clock Bias

The satellite clock bias can be of the order of tens of nanoseconds, despite the use of multiple atomic clocks on board. This bias is measured by the ground stations and transmitted as part of the navigation message, reducing its effect to 5-10ns, equivalent to pseudorange errors of 1.5-3m [25].

2.2.6 Additional Signal Delay

The delay encountered by the satellite signals propagating through the ionosphere and troposphere is estimated in the receiver [32-34]. Its magnitude depends on the Total Electron Content (TEC) along the propagation path through the ionised layer. This delay is typically tens of nanoseconds and may be as great as 200ns. Fortunately, the delay is proportional to the square of the frequency. Thus, if both the L1 and L2 frequencies are used, as in PPS, the delay can be estimated by comparing the time-to-arrivals of the signals on the two frequencies. SPS users, however, only use the L1 frequency. SPS receivers employ a model that takes into account season, solar flux, and time of day, to estimate the delay, reducing it by typically 50% [35,36].

Delays through the troposphere are largely frequency-independent and so affect SPS and PPS in the same manner. Correction models that estimate the delay by reference to the satellite's elevation angle above the horizon, as viewed from the user's location, can remove some 90% of these errors. With this ionospheric correction model applied, satellites well below a 5^{o} elevation generally have pseudorange errors of tens of metres [37] whilst those well above 5^{o} have errors of only a few metres. Most users limit the minimum elevation angle of satellites included in the navigation calculation to 5^{o} or 10^{o} to minimise these tropospheric delay errors.

2.2.7 Multipath propagation

Multipath propagation is caused by the satellites' signals bouncing off buildings or other objects in the vicinity of the receiver. These indirect routes to the receiver can cause errors in the range of 1-100m. This effect can be somewhat reduced by Kalman filtering the pseudorange measurements to extract the wanted signal from the noise. Kalman filters are a form of active filter which work by estimating the received signal in the presence of noise. Then, using correlation techniques, Kalman filters adjust the estimation on each iteration to get a good, quick, convergence and a cleaner signal [38]. Another technique for minimising multipath errors is to use antennas sensitive to the direction of rotation of the signals' circular polarisation only (reflected signals often have the polarisation reversed) and selecting the antenna location carefully.

2.2.8 Satellite Geometry

As the user's position is determined by ranges from satellites, the geometry of the fix plays a major role in the resulting position accuracy. Poor geometry (eg satellites apparently close together in the sky) can dramatically increase the effects of small uncertainties in pseudorange measurements. Fig. 2.3 shows examples of low and high Geometrical Dilution of Precision (GDOP):

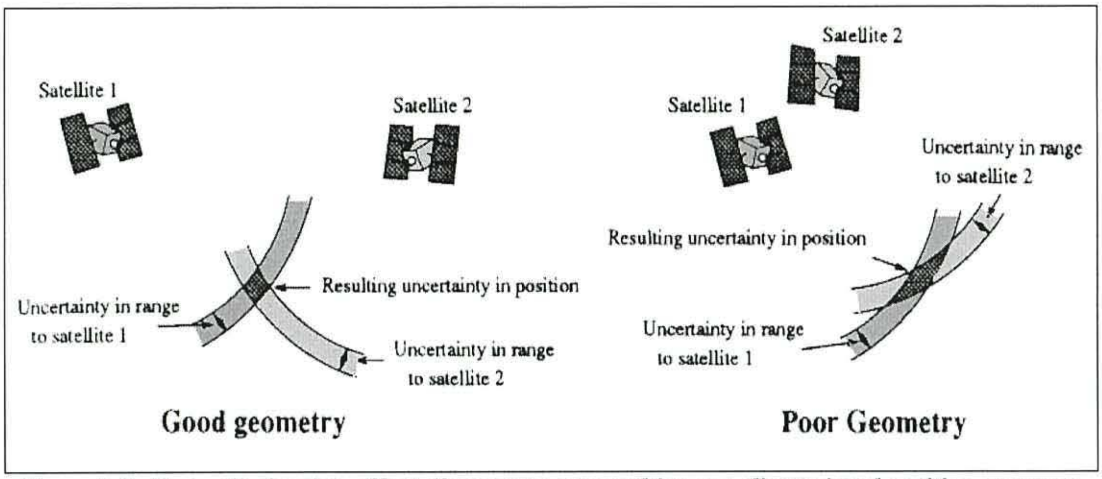

Figure 2.3: Example showing effect of geometry on resulting two-dimensional position accuracy, given the same degree of uncertainty in pseudorange measurements. Clearly, poor geometry (high GDOP) increases the position uncertainty [25].

GDOP consists of two parts: Position Dilution of Precision (PDOP) and Time Dilution of Precision (TDOP). PDOP is further divided into Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP). The greater any of these positional DOP figures is, the greater the resulting position or time errors. Where a receiver has a clear view of the sky and receives more than four satellites, it is free to choose the combination of satellites that offers the lowest DOP. Normally, PDOP values above 6 are avoided [24,30,39]. Many receivers make use of all healthy satellites in view, improving the GDOP and increasing accuracy.

2.2.9 Selective Availability

The main source of error in the SPS service, until it was set to zero, was Selective Availability (SA) [27]. SA consisted of two parts: an intentional clock dither, plus the intention to manipulate the ephemeris data. While SA has been set to zero for the foreseeable future, there is still a possibility of its being reintroduced in times of conflict.

2.3 GLONASS

The GLObal NAvigation Satellite System (GLONASS) is a GNSS operated by the Russian Federation Government. GLONASS was declared operational in September 1993 with a full constellation consisting of 24 satellites in 3 orbital planes, at an inclination of 64.8° to the equator [3,40,41].

GLONASS provides two levels of service: standard precision (SP) and high precision (HP). The SP service is available to all users and uses a single frequency (L1), whereas the HP service uses two (L1 & L2). One of the main differences between GLONASS and its US equivalent GPS is that GLONASS satellites transmit Frequency Division Multiple Access (FDMA) signals, with satellites using different frequencies (although antipodal satellites share the same frequency) [3,42]. GLONASS also uses the PE90 reference frame, rather than WGS84 [6].

Unfortunately a lack of investment in recent years has resulted in a decline in the number of available satellites. At the time of writing (2002), only 7 satellites out of a constellation of 24 are available, resulting in an unreliable service [42]. However, there are apparently plans to launch new satellites and re-fill the constellation by 2007 [43].

2.4 Galileo

Unlike GPS and GLONASS, the proposed future European satellite navigation system, Galileo, will not be controlled by the military of a single nation. Rather, Galileo will be under civilian control, eventually being controlled by a civil body, but is being developed by the European Commission and European Space Agency.

Galileo is expected to have a constellation of 30 satellites, of which 27 will be operational, and three active spares. These will be positioned in a Medium Earth Orbit (MEO) with an inclination of 56^{o} to the equator. These satellites will provide dual frequencies as standard, enabling users to calculate their positions with metre level accuracy.

Galileo will provide five levels of service, each with their own performance standards: Open Service (OS), Safety-of-Life (SoL), Commercial Service (CS), Public Regulated Service (PRS) and Search and Rescue service (SAR). Galileo is expected to provide timely warnings of integrity failure, within a few seconds, and promises high availability [44]. Among its novel features will be a system to relay distress messages to COSPAS-SARSAT service centres while keeping the user informed [44-46].

Galileo will almost certainly be inter-operable with GPS, and possibly with GLONASS. It will operate in essentially the same frequency bands [47]. The inter-operability of these two systems is currently a 'hot' topic; for example, compatible frequency allocations were the subject of many discussions and papers at the recent ION GPS conference [48]. Full operational capability is at present scheduled for 2008. As Galileo is not yet operational and GLONASS is barely operational, GPS has established itself as overwhelmingly the most-used global navigation system. Although the research depicted in this thesis has the potential to be applied to any GNSS system, it is GPS that is currently employed in marine radiobeacon DGNSS and on which this research will focus.

2.5 The need for DGNSS

The initial object of introducing differential GPS was to enhance the positional accuracy available to the civil user. Differential GPS reduced the errors of SPS with SA from the nominal 100m to below 5m, both $2d_{rms}$. Table 2.3 lists the accuracy required for a variety of important applications of GPS [6,49-51]. From this it is clear that many applications can only be satisfied by using differential operation.

The removal of SA has meant that the main driving force behind the use of differential operation is its ability to increase "integrity" [52,53]. Integrity is the reassurance that the navigation information presented is correct and that the user will be made aware of errors promptly. Integrity is formally defined as "*The ability to provide users with warnings within a specified time when the system should not be used for navigation*" [15].

Application	**Accuracy (2drms)**	**Achieved with SPS?**	**Achieved with DGPS**
Intelligent Vehicle Highway Systems			
Navigation	5 – 20m	No	Yes
Mayday/Incident Alert	5 – 30m	No	Yes
Fleet Management	25 – 2500m	Yes	Yes
Automated Stop Announcement	5 – 30m	No	Yes
Vehicle Command and Command	30 – 50m	Yes	Yes
Collision Avoidance	1m	No	No
Accident Data Collection	30m	Yes	Yes
Infrastructure Management	10m	No	Yes
Railroad Traffic Management			
Train Position Tracking	10 – 30m	No	Yes
Train Control	1m	No	No
Automated Road Vehicle Warning at Crossing	1m	No	No
Marine Transportation			
Harbour / Harbour Approach	8 – 20m	No	Yes
Harbour Research Exploration	1 – 3m	No	No
Coastal	460m	Yes	Yes
Ocean	3700 – 4700m	Yes	Yes
Air Transportation			
En Route Oceanic	23km	Yes	Yes
En Route Domestic	1000m	Yes	Yes
Terminal	500m	Yes	Yes
Approach / Landing: non-precision	100m	Yes	Yes
Approach / Landing: Cat I-iii	H: 17.1 – 4.1m V: 4.1 – 0.6m	No	No
Non-Transportation			
Search and Rescue	10m	No	Yes
Aerial Crop Dusting	10m	No	Yes
Aerial Surveillance	1 – 5m	No	No
Emergency Management	8 – 10m	No	Yes

Table 2.3: In numerous applications, including many safety-critical civilian ones, the positioning accuracy of SPS is insufficient (updated from [6,49-51]).

Non-differential GPS has minimal integrity: it may take several hours before a satellite malfunction is detected by a ground monitoring station and a warning conveyed to the user. This delay is unacceptable in safety-critical and many mission-critical applications. In contrast, DGPS reference stations can confirm continuously that satellites are healthy by constantly monitoring the accuracy of the DGPS corrected pseudoranges and calculating the resulting position error and comparing it against their known location [54]. If an unhealthy satellite is detected, no differential corrections are transmitted for it. In this way, the user's receiver is warned immediately and so excludes the unhealthy satellite from the navigation solution.

2.5.1 Radiobeacon DGPS

The radiobeacon implementation of Differential GPS was introduced briefly in Chapter 1; this section will now examine the system in more depth. The infrastructure required to provide timely corrections to the user (Fig. 2.4) is a reference station consisting of a high grade GPS receiver at a known location and a MF transmitter. The two are normally installed on the same site.

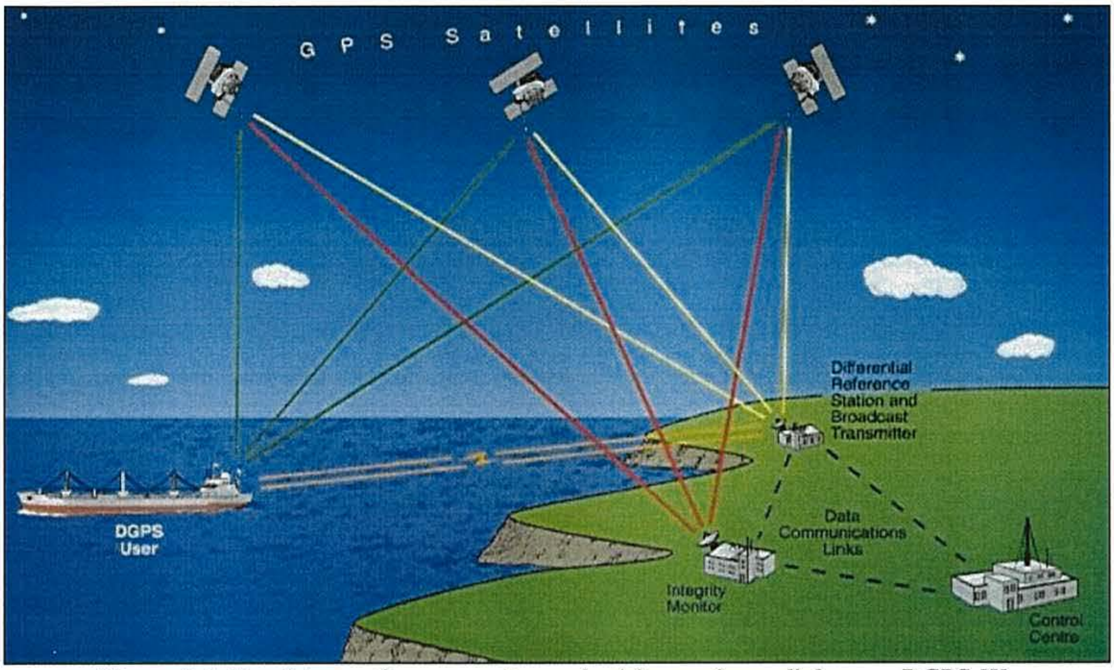

Figure 2.4: Breakdown of components required for marine radiobeacon DGPS [5].

The reference station compares each measured pseudorange with the corresponding value it calculates from knowledge of its location and the satellite's ephemeris. Any difference is regarded as an error and a corresponding "pseudorange correction (PRC)" is calculated. The reference station calculates PRCs for all healthy satellites in view and broadcasts them to users via the radiobeacon transmission. The users receive this transmission and decode the PRCs which they add to the pseudorange they measure from the corresponding satellite. Any satellites not in the "common view" of both user and reference station are excluded from the navigation solution.

The greater the distance between the user and the reference station, the less accurately the corrections made at the reference station correspond to the errors experienced by the user. Approximately 1m of error is introduced for every 150km separation from the broadcast site [6].

Differential techniques cannot, of course, reduce multipath or receiver errors. Indeed, such errors must be minimised at the reference station if they are not to be included in the PRCs and so affect all users' positions. The principal error sources in DGPS are listed in Table 2.3; it can be seen that DGPS can offer a positioning accuracy significantly better than that of either SPS or PPS.

2.5.2 Radiobeacons

Marine radiobeacons, located at lighthouses or on light vessels, have been used by the maritime community for direction finding (DF) for many years. Vessels take bearings on the radiobeacon's signal or steer towards a beacon in a homing mode. Navigators can plot their ships' positions as cross-cuts between pairs of beacons' bearings, or by triangulating three or more bearings. These are traditional ways of working that have now largely dropped out of use, being replaced by satellite navigation. So, employing radiobeacon stations to transmit differential GPS data to mariners has given the beacons a second lease of life.

2.5.3 Radiobeacon signals as DGNSS data links

Radiobeacons calculate corrections which are then transmitted to the user in the form of a data message. The structure and contents of these messages are specified in recommendations of the Radio Technical Commission for Maritime Services, Special Committee 104 (RTCM SC–104) [55]. These recommendations also cover GLONASS, and developments are under way to extend them to Galileo. Recently a new version of the RTCM SC-104 standard was published, one which includes new messages including, new messages for Real Time Kinematic (RTK) users, new messages conveying corrections on the Loran-C/Chayka data channel as well as a message to cope with antenna phase centre variations [56,57].

Pseudorange corrections can be transmitted over an RF link, or any other medium that can maintain regular and reliable communication. When selective availability was in operation a data rate of at least 50bps was required to ensure that corrections were received at a rate sufficient to keep up with the relatively rapid variations in the pseudoranges [58].

With the removal of SA, these variations have become much slower (Fig. 2.5). This means that there is now scope for changes in the frequency with which correction messages are sent out. This is turn has implications for beacon power levels and message types [56].

Figure 2.5: A plot of the resulting error experienced 95% of the time (R95) as a function of time in minutes for the SPS service with SA removed, after [18].

A radiobeacon is modified to broadcast RTCM data messages by adding Minimum Shift Keying (MSK) of its carrier. This form of modulation is ideal as it minimises the effect of the message on DF reception. MSK is a narrow-band technique, which gives a transmitted signal of narrow bandwidth. This in turn allows narrow filters to be employed in the receiver, so maximising the received signal-to-noise ratio (SNR). This technique of utilising existing radiobeacons has been adopted by many national and international organisations including the General Lighthouse Authorities of the British Isles (GLAs), the United States Coast Guard (USCG), and the Canadian Coast Guard (CCG) [7,58,59]. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) [60], and the International Telecommunication Union (ITU) [61], have approved the re-employment of radiobeacons for this use, and drawn up standards for the new service.

Radiobeacons are very suitable for transmitting DGNSS corrections since they occupy surveyed and protected locations, are fully equipped with the necessary infrastructure, and their frequency band had already been allocated for use by the radio determination service, and protected accordingly.

The nominal ranges of many beacons are of the order of 100-200km, distances over which the errors experienced by the user are well correlated with those at the reference station. As a result, upgrading existing radiobeacons to provide DGNSS correction data has proved straightforward. Many countries already had DF radiobeacons systems in place, and the cost of adapting them to the new service was much lower than would have been that of building a set of new stations [10,60]. In recent years, the tendency has been for administrations to abandon their DF services, their radiobeacons being provided for DGNSS service only.

Radiobeacon standards are set primarily by IALA, who co-ordinate frequency planning and specify performance requirements for both GPS and GLONASS. IALA collaborate with the United Nations Organisation's International Maritime Organisation (IMO) and International Telecommunication Union-Radio (ITU-R) concerning frequency assignment and future planning. In addition to these bodies, several others contribute to the governing of the service. The International Electro-Technical Commission set standards for receiver manufacturers. The European Maritime Radionavigation Forum is a body that advises on Europe's navigation requirements.

2.5.4 Radiobeacons in the EMA.

Although the research described in this thesis is applicable world-wide, the study has focussed predominantly on the European Maritime Area (EMA). This is an area within ITU Region 1, lying within the boundaries 30°N-72°N and 30°W-55°E. The frequency band allocated for the radiobeacon service in this Region is 283.5–315kHz. At the Geneva Conference of 1985 [62], this band was split into 64 channels, spaced at 500Hz. Currently, some 162 DGNSS beacons, plus 143 traditional marine beacons and 156 aeronautical beacons within the EMA share this frequency band (Fig. 2.6), details of which are given in Appendix B.

Of course, radiobeacon differential corrections can also be applied to GLONASS and, in the future, Galileo. DGLONASS corrections are planned for some Russian reference stations [11].

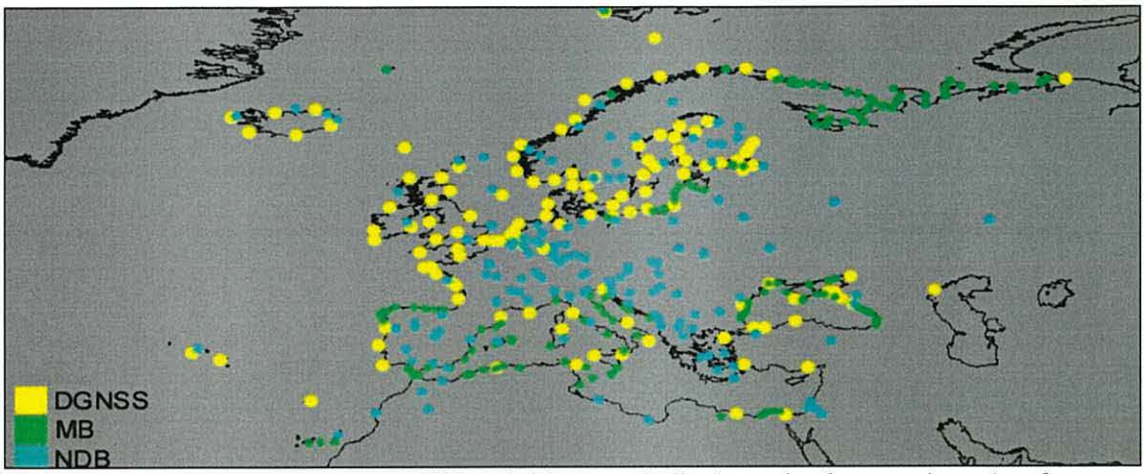

Figure 2.6: A plot of the many, differential beacons (yellow), marine beacons (green) and aeronautical beacons (blue), that are spread about the EMA.

2.6 New developments – E-Dif

Recently in 2002, Communications Systems International (CSI) patented a new 'e-Dif' position solution method [63,64]. This method is a virtual differential augmentation that works by estimating a true start position by averaging the user's position over several minutes. With the removal of SA, all errors experienced by the user are slow to change and over a few minutes the average position will be very near the user's true position (assuming no multipath). While the receiver is calculating the average position, it is also generating corrections to each satellite's pseudorange. These corrections are then used to augment any future positions, providing greater accuracy. However, this technique does not give any additional integrity and is only as good as the first estimate of the true position.

2.7 New developments – RAAS

Concurrent research within the Radionavigation group at the University of Wales, Bangor, to which the candidate has contributed, has investigated the possibility of using corrections received from multiple beacons in a Regional Area Augmentation System (RAAS) manner [65].

The investigation explored whether there were any benefits from using a result constructed by interpolating corrections from three or more beacons should the primary beacon (the beacon of choice) becomes unavailable. For example, at Bangor, Point Lynas is the primary station (Fig. 2.7). The beacons whose PRCs were interpolated were Wormleighton, Tory Island and Mizen Head.

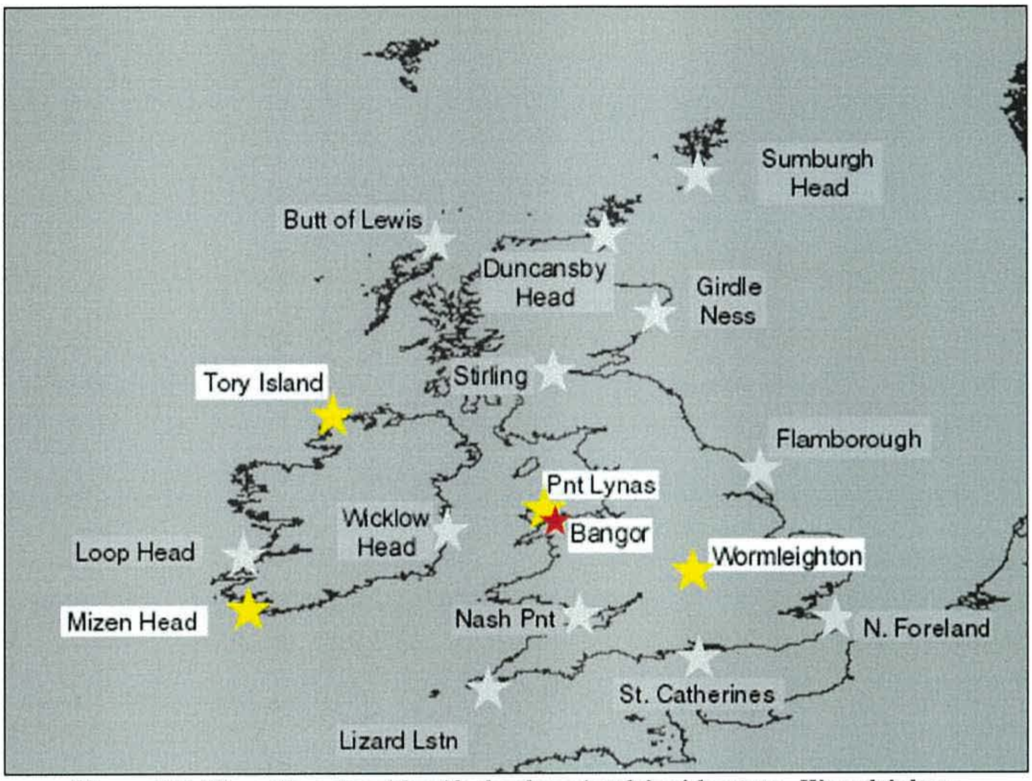

Figure 2.7: The yellow stars identify the three 'outlying' beacons, Wormleighton, Tory Island and Mizen head, along with Point Lynas, the test station.

Measurements were made to ensure that the clock biases were sufficiently similar to ensure that the results did not include an offset and so could be interpolated directly. The interpolation used was weighted by distance, so that the effects of spatial dilution could be taken into account. In the first of two tests, the PRC's from the three outlying stations, and their result interpolated at Point Lynas, were compared with the PRC from Point Lynas. The second test was to compare the corresponding positional errors. The results showed high levels of correlation. This appears to be a promising approach which is recorded in detail in [65].

2.8 Conclusions

Satellite navigation is a rapidly growing area, with GPS and GLONASS currently in operation, and Galileo due to be operational from 2008. Very large and rapidly increasing numbers of civilians currently use GPS, in many different applications in stand-alone or differential mode. Radiobeacon DGNSS has become the standard worldwide for maritime use, not only because of the additional accuracy it provides but also for its additional integrity.

DGNSS radiobeacons have been installed throughout the EMA and in substantial areas of the world. Many of these stations re-employ existing direction-finding radiobeacons; this has been shown to be a very efficient means of transmitting DGNSS correction data. The system is continuing to develop technically.

Chapter 3

Performance of Radiobeacons

3.1 Introduction

The availability to a user of the maritime radiobeacon DGNSS service depends firstly upon the availability of the transmission and secondly on whether that transmission reaches the user with adequate quality. This second factor is complex: assessing it depends upon a detailed knowledge of several elements relating to the propagation of the signal. Happily, these elements have been extensively studied by Poppe and Last in their work to establish a method of predicting the coverages of radiobeacons [14]. In calculating availability (and later continuity), these elements will be re-interpreted in accordance with the requirements of the availability calculations, which will be set out in Chapter 4. This present chapter will analyse the propagation factors in preparation for those calculations.

Poppe and Last studied the performance of marine radiobeacon DGPS and developed a software model which predicts the coverage areas of single beacons or networks of beacons, taking propagation factors and interference into account. Their resulting model has been used successfully to plan radiobeacon DGNSS networks worldwide, including the Middle East Navigation Aids Service (MENAS), Norway and Australia, to name a few. Each factor employed in that analysis will now be examined.

3.2 Coverage prediction

A radiobeacon, whether a traditional marine beacon (MB), an aeronautical non-directional beacon (NDB), or a DGNSS beacon, is deemed to provide coverage when its signal parameters exceeds minima set by the International Telecommunications Union (ITU), (Table 3.1). Calculating these parameters at multiple locations is a complex task, involving many factors.

	Units	Marine (MB)		Aero (NDB)	DGNSS
Minimum Field Strength	μV/m	N of 43°N	50	70	10
		S of 43°N	75		
	dBμV/m	N of 43°N	34	37	20
		S of 43°N	37.5		
Minimum Signal-to-Noise ratio (SNR)	dB	15		15	7

Table 3.1 Minimum field strengths and signal-to-noise ratios for marine, aeronautical, and DGNSS beacons in the European Maritime Area [58,61,66].

The coverage of a radiobeacon depends on the signal strength of its signal and on the signal-to-noise ratio. In this case "noise" may include atmospheric noise, ship's noise, and signals from other "unwanted" beacons. Calculating the strengths of these various components is a complex process, often stochastic, and with results that change with location. Many systems planners avoid all such complexity by simply drawing the coverage of a radiobeacon as a circle with the beacon at its centre, the radius being its nominal range [67]! This approach completely disregards all location-dependent parameters and is, as we shall see, very inaccurate.

Figure 3.1: Coverages of beacons in the EMA with their ranges represented by circles of radius equal to their nominal ranges [67]

3.3 Bangor Coverage Prediction Model

The Bangor Coverage Prediction Model developed by Poppe and Last is considerably more precise than the method shown in Fig. 3.1. It predicts the regions in which the radio signal from a beacon exceeds the minimum field strength and signal-to-noise ratio (SNR) set out in Table 3.1 and the signal-to-interference ratios defined by the IEC [68].

The coverage of an individual radiobeacon depends upon the power of the radiobeacon, the attenuation of its groundwave signal as it travels over seawater or land of various types, fading of that signal due to interference from the accompanying time-dependent skywave component, the time-dependent level of atmospheric noise, and interference from other beacons on the same or adjacent frequencies. This interference depends upon the strengths of the groundwave signals from potentially large numbers of such interfering beacons, their time-dependent skywave signals, and the frequency separation between the wanted and unwanted signals. These factors are now examined.

3.3.1 Propagation modes

A radiobeacon normally transmits omni-directionally in the horizontal plane. Its signal reaches the receiver via by two main paths: groundwave and skywave. The groundwave-propagated component travels over the surface of the Earth. The skywave-propagated one is refracted by the ionosphere.

3.3.1.1 Groundwave propagation

As a groundwave signal propagates, its field strength is progressively attenuated. The rate of this attenuation depends on the frequency of the signal and the type of ground. Fig. 3.2 shows attenuation rates determined by the ITU, for eight types of ground, at a frequency typical of the DGNSS radiobeacon band, 300kHz [69]. The principal factor that varies with the type of ground is its electrical conductivity. The 5000mS/m conductivity curve is that for sea-water; in this single case, the permittivity is also different from the fixed value used on land (see Section 3.3.1.1.1).

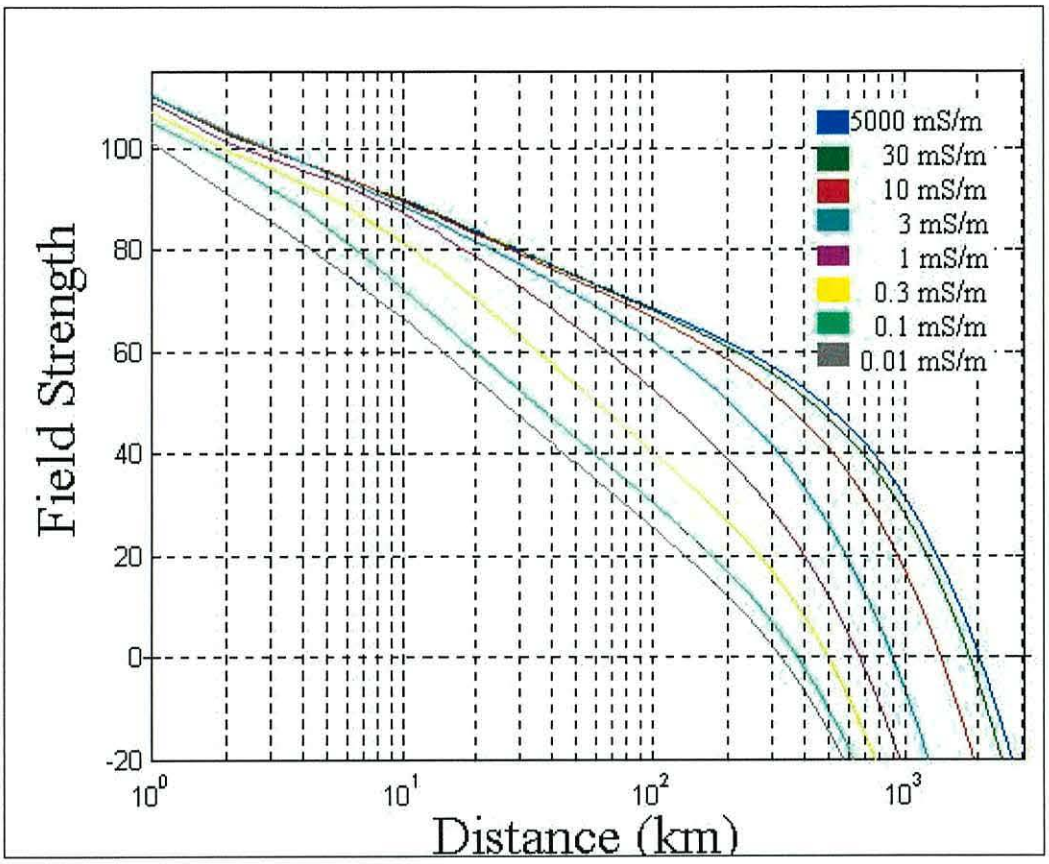

Figure 3.2: Groundwave field strength curves for a 1kW transmitter at 300 kHz. Each curve represents a different electrical conductivity [69]

Poppe has shown that, given the narrow radiobeacon frequency range used in the EMA (283.5-315.0 kHz), these 300kHz curves may be used at frequencies across the band with the resulting errors at the band edges being less than 1dB [14]. Where a propagation path crosses ground of more than a single conductivity type, the ITU recommend the use of Millington's method to calculate the total path attenuation [70]. This technique is explained in detail in Appendix A. Once the path attenuation and the power of the transmitter are known it is straightforward to calculate the field strength of the signal at the receiver. This groundwave field strength is constant; that is, in contrast with other factors which will be examined later, it does not have a random component that varies with time.

Generally the transmitter power is listed in the form of its '*nominal range*', which is the distance at which its signal falls to either 34dBμV/m or 37.5dBμV/m, depending on the transmitters latitude, over a sea path. From the nominal range, the transmitters power with respect to the 1kW transmitter used in the ITU curves can be calculated.

3.3.1.1.1 Ground Conductivity

The electrical conductivity of the ground is the key factor when calculating the groundwave attenuation and thus groundwave field strength. Last, Searle and Farnsworth [71] conducted extensive studies of the electrical conductivity of the EMA (amongst other areas) using data taken from principally the ITU World Atlas of Ground Conductivities [72]. Where this was inadequate they identified alternative sources. The result was the Bangor Ground Conductivity Database. This is a digitised map of conductivity, with a resolution of 0.1° in latitude and longitude, an example section of which is shown in Fig. 3.3. Table 3.2 elaborates further on the 8 standard ITU conductivity types employed; in constructing the database the nearest of the 8 levels at each location was selected.

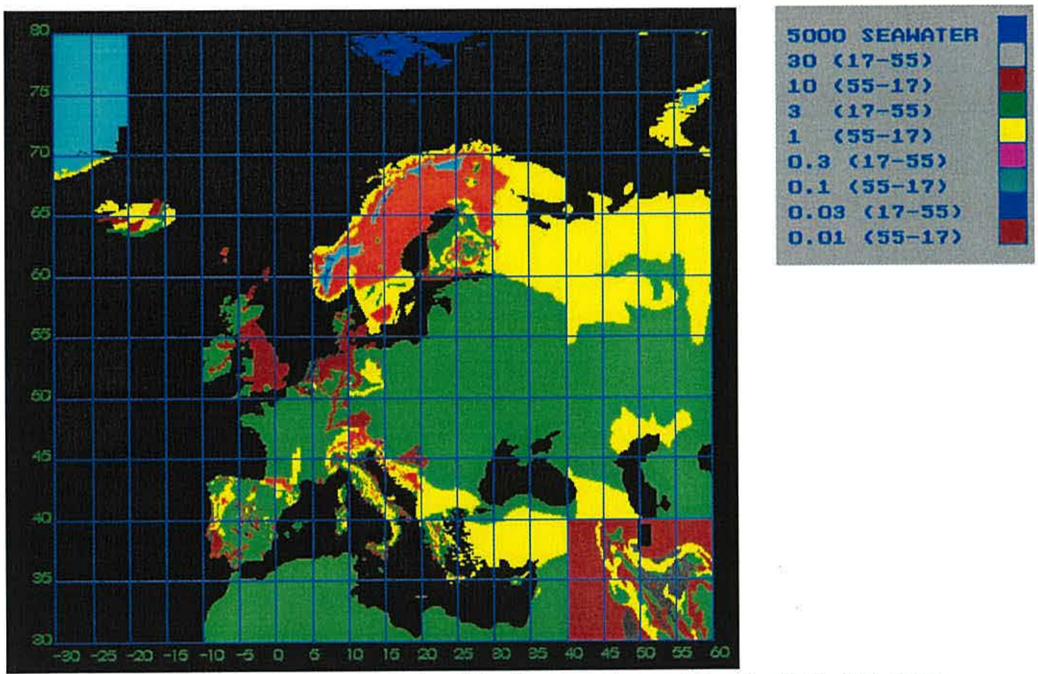

Figure 3.3: An example of the Bangor Ground Conductivity Database. The colours represent the level of conductivity.

Conductivity (mS/m)	Ground Type	Penetration (m)
5000	Sea water	0.45
30	Very good ground	5
10	Wet ground, good dry soil	9.5
3	Fresh water, cultivated ground	20
1	Medium dry, average ground, mountainous areas	30
0.3	Dry ground, permafrost, snow covered mountains	75
0.1	Extremely poor, very dry ground	100
0.01	Glacial ice	>100

Table 3.2: The eight ground conductivity values employed by the ITU, including the type of terrain they represent and the penetration depths at 300kHz [72].

Fig. 3.4 gives an example of the Bangor Ground Conductivity Database in use; it shows the coverage area of the radiobeacon at Girdle Ness, Scotland. Clearly, the signal propagates further over sea paths than over land and further over the well-conducting British Isles than the glacial ice of Norway, with its greater attenuation.

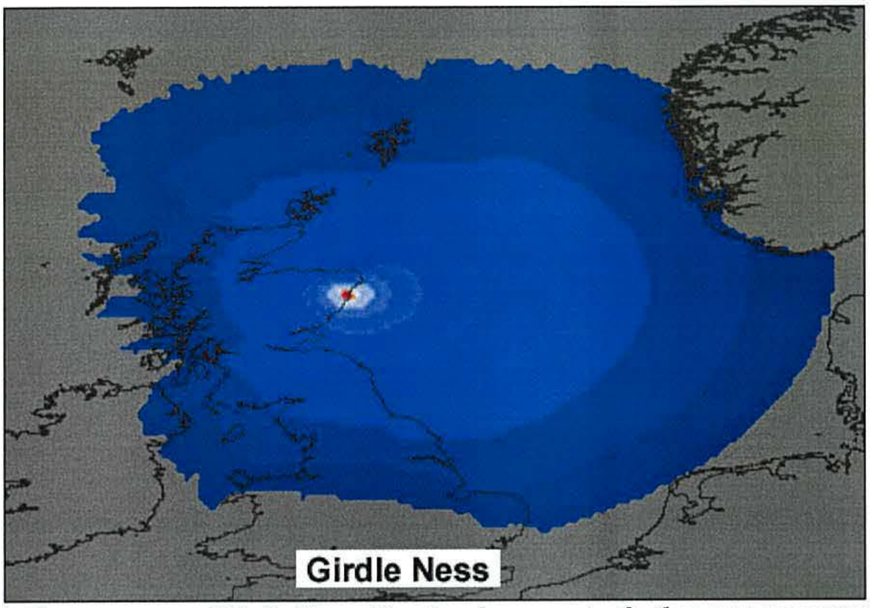

Figure 3.4: Coverage area of Girdle Ness. The signal propagates further over sea-water path than over land, and further over the well-conducting land of the British Isles than the glaciers of Norway. The contours represent the field strength.

3.3.1.2 Skywave Propagation

At night, signal components propagating as skywaves reach the receiver by refracting in ionospheric layers of the Earth's atmosphere [73]. A radiobeacon DGNSS user can make use of a skywave signal as well as a groundwave one. This is in contrast with the situation with many other low-frequency radio-navigation systems, such as Loran-C, where the extra, and essentially unknown, signal path lengths lead to fixes of low accuracy [74].

While the data transmitted in the skywave signal is valid, the skywave component does have a detrimental effect on coverage since it can cancel the groundwave signal and so cause "self-fading". The effect of self-fading on coverage depends critically on the relative strengths of the groundwave and skywave signals. It is crucial that these factors and the resulting fading are estimated accurately.

The Earth's atmosphere is made up of several layers. It is the E-layer which refracts the signal, causing skywave propagation. Since, the height and degree of ionisation of the E-layer depend on solar activity, the strength and delay of the skywave signal change with time of day and season of the year. By day, there is very little skywave propagation, principally because the lower D-layer absorbs the skywave component. The D-layer gradually dissipates after sunset and the skywave signal appears.

The ITU have developed a method of estimating the skywave field strength which embodies the results of very large numbers of measurements made world-wide [73]. This method can be used to calculate values of the median field strengths of radiobeacon signals over propagation paths, as shown in this example (Fig. 3.5).

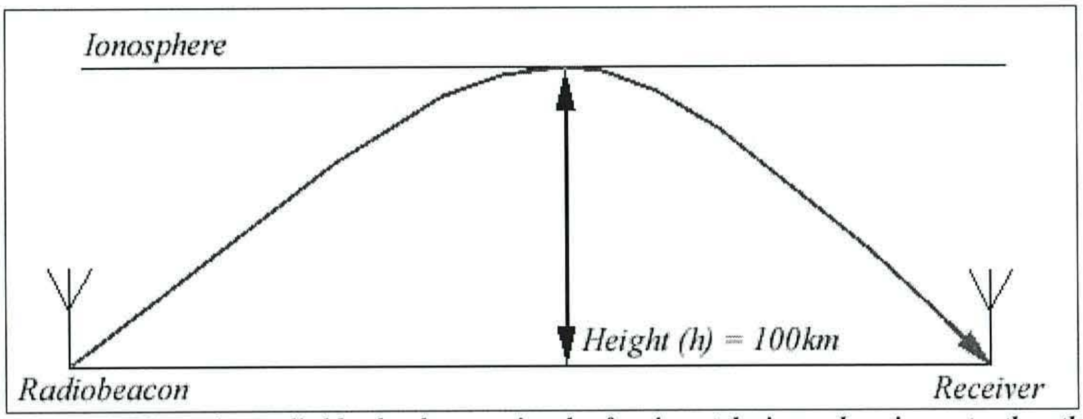

Figure 3.5: The path travelled by the skywave signal refracting at the ionosphere is greater than the groundwave path.

The ITU method gives the median strength, Sky_{dB} (dBμV/m), at a range d (km) as:

$$Sky_{dB} = A - 20\log(p) - 10^{-3} k\, p + G_s + G_v + \Delta p\,, \qquad (3.1)$$

where A = 106.6 – sin (Φ), Φ being the geomagnetic latitude; k is the basic loss factor; p is the slant propagation distance in km; G_s is the sea gain; G_v is the antenna gain factor; and Δp is the beacon's power with respect to 1kW. Each of these factors will now be examined in turn.

For calculating A, the geomagnetic latitude Φ, at the mid-point of the propagation path, is required. Geomagnetic latitude is latitude with respect to the poles of Earth's magnetic field.

The co-ordinates of the north geomagnetic pole are currently 78.5°N, 69°W. Thus, the geomagnetic latitude of a point at geographic latitude α and geographic longitude β is given by:

$$\Phi = arcsin\left(sin\,\alpha.sin\left(78.5^o\right) + cos\,\alpha.cos\left(78.5^o\right).cos\left(\beta - 69^o\right)\right). \quad (3.2)$$

The slant propagation distance, p, is the total path length travelled by the skywave signal component (Fig. 3.5). With a typical E-layer height of 100km this distance would be:

$$P = \sqrt{d^2 + 200^2}\,. \quad (3.3)$$

The basic loss factor attenuation due to the ionosphere, k, is calculated using:

$$k = 3.2 + 0.19\,{f_{kHz}}^{0.4}\,tan^2\left(\Phi + 3\right), \quad (3.4)$$

where f_{kHz} is the frequency in kHz.

Sea gain, G_s, takes into account the small increase in skywave field strength experienced when either the transmitter or the receiver is located close to the sea. Fig. 3.6 shows that there is a sea gain of 1.5dB over a 1000km path, for each end that is close to the sea. Sea gain falls with distance from the sea, becoming negligible by 5km [75].

G_v, the antenna gain factor, depends on the vertical polar diagram of the antenna. Almost all radiobeacon antennas are vertical monopoles, with or without capacity hats, and thus short in terms of wavelength.

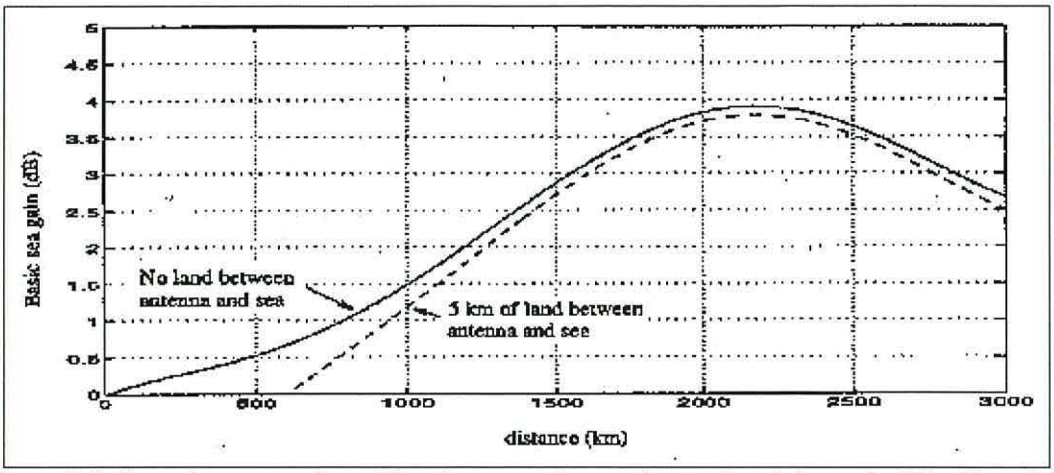

Figure 3.6: Sea gain occurs when either the transmitter or the receiver is located within 5km of the sea. Its magnitude depends on the separation of the transmitter and the user. [75].

Thus the E-field polar diagram has a maximum in the horizontal plane and a null vertically above. Equation 3.5 shows a polynomial fit to this radiation pattern [14]:

$$G_v = -12.4530 + ld\left(91.2214 + ld\left(-26.8642 + 2.6164\, ld\right)\right), \quad (3.5)$$

where $ld = \log_{10}$ (distance in km).

Fig. 3.7 shows that the G_v term causes high attenuation to those skywave components reflected at high angles that would return to earth close to the station. It decreases with increasing range, having negligible effect beyond 3000km [75].

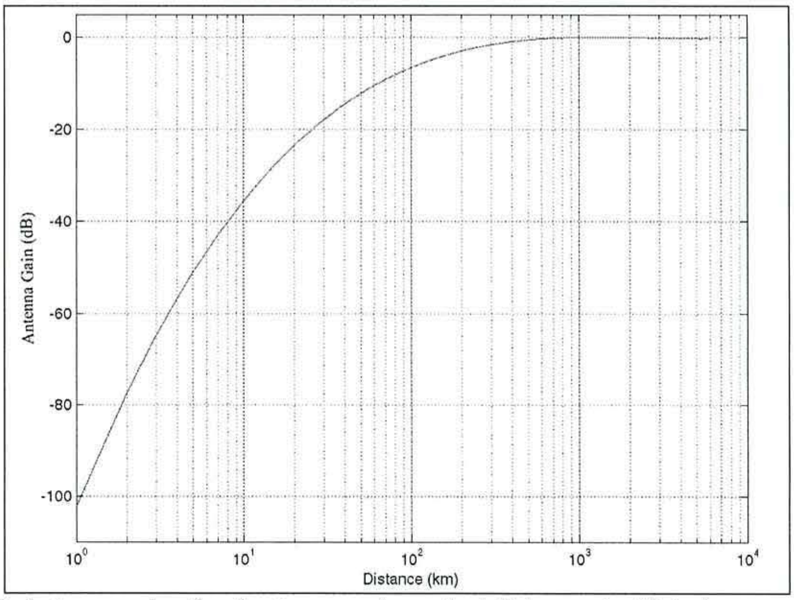

Figure 3.7: Antenna gain of a short monopole against distance at which skywave component returns to earth

Poppe built all of the above factors of equation 3.1 into her coverage model [14] from which the plot of the skywave field strengths from Girdle Ness in Fig. 3.8 was computed. In this plot one can see both the weak skywave signals close to the station and the effect of sea gain.

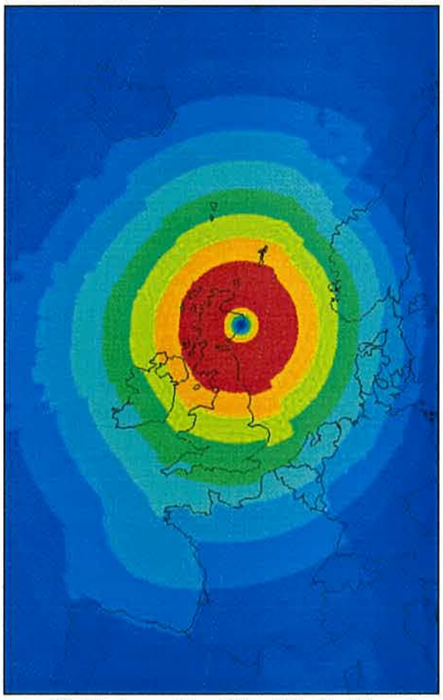

Figure 3.8: Skywave field strength of the Girdle Ness beacon in Scotland. Red is the greatest field strength attenuating through to blue.

3.3.1.3 Own-skywave interference (Self-fading)

At night, both groundwave and skywave signals are received simultaneously, and the receiver experiences their vector sum (Fig. 3.9). The result may, of course, be larger than either component. But it may also be smaller, with the skywave causing self-fading. Self-fading is greatest when the two components are equal in magnitude and opposite in phase. The phase lag of the skywave component with respect to the groundwave is due to its greater path length plus any phase shift experienced in the ionosphere. Since this path length difference corresponds to many cycles of the carrier, and varies relatively rapidly in time, the phase of the skywave with respect to the groundwave is, in practice, randomly distributed.

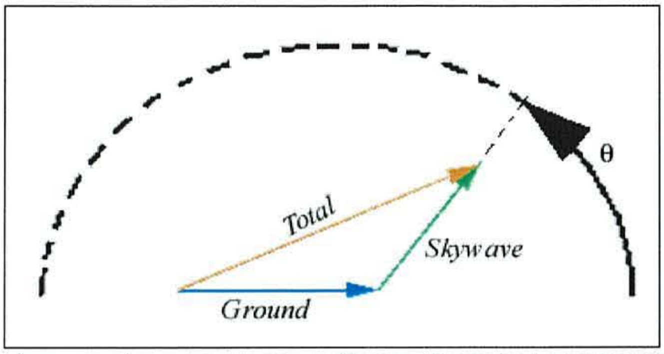

Figure 3.9: Receiver experiences vector sum of groundwave and skywave signals. Skywave component lags the groundwave component by θ. The skywave signal my lag the groundwave component by several cycles.

The degree of self-fading depends on the relative field strengths of the groundwave and skywave components. Skywave signal strengths vary relatively rapidly with time in the short term, since ionospheric refraction is variable and multiple signal paths are involved. Thus, one must take a statistical approach to this factor. Fig. 3.10 shows the median skywave curve (red) and the value not exceeded 95% of the time (magenta), as a function of range. It also shows the strength of the groundwave signal over sea-water (blue) and poor land (green). Taking the poor land case, within about 45km of the station the groundwave component dominates. From there to approximately 600km, the two components have comparable amplitudes; this is the fading zone. Beyond about 600km, the skywave dominates [14].

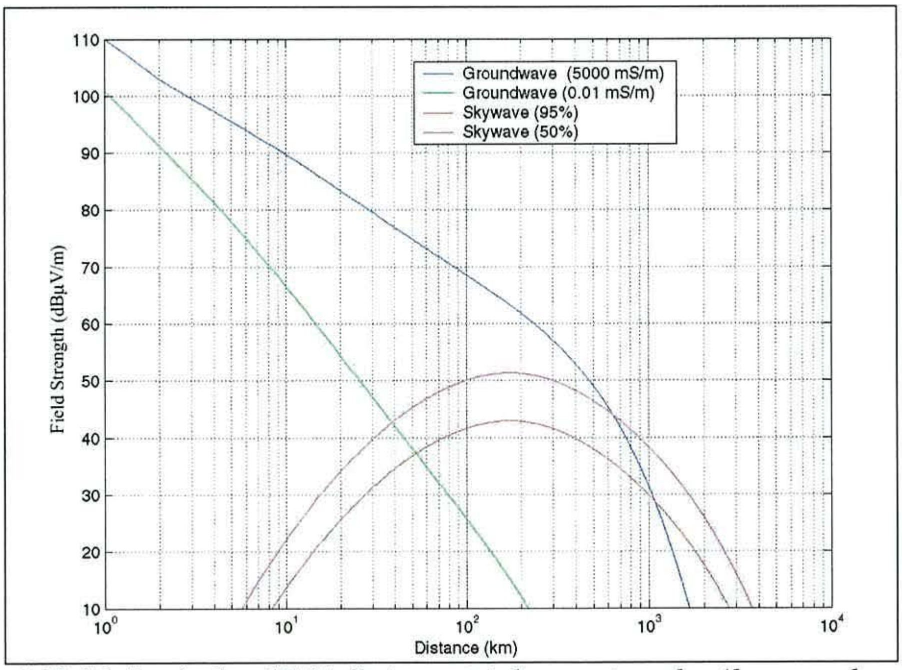

Figure 3.10: Median (red) and 95%-tile (magenta) skywave strengths. Also, groundwave field strengths over sea-water (blue) and poor land path (green). Fading occurs principally between 45 and 600km where strengths of the two components are comparable.

The depth of the fading depends on the phase delay of the skywave component relative to the groundwave. This delay is related to range by:

$$\Delta_{time} = \frac{\Delta_{path}}{c}, \tag{3.6}$$

$$\Delta_{path} = p - d. \tag{3.7}$$

Substituting from equation 3.3, gives

$$\Delta_{path} = \sqrt{d^2 + 2 \times h^2} - d \tag{3.8}$$

where, Δ_{time} and Δ_{path} are the differences in path length and propagation time between the skywave and groundwave components, and c the speed of light, altogether resulting in Fig. 3.11 [14]. In the fading zone, the extra delay is between 0.03 and 0.21ms. This demonstrates the point made above: these delays are equivalent to many cycles of the 300kHz carrier, with its period of approximately 0.003ms. Thus, it is reasonable to deduce that the phase difference between the two components will vary randomly.

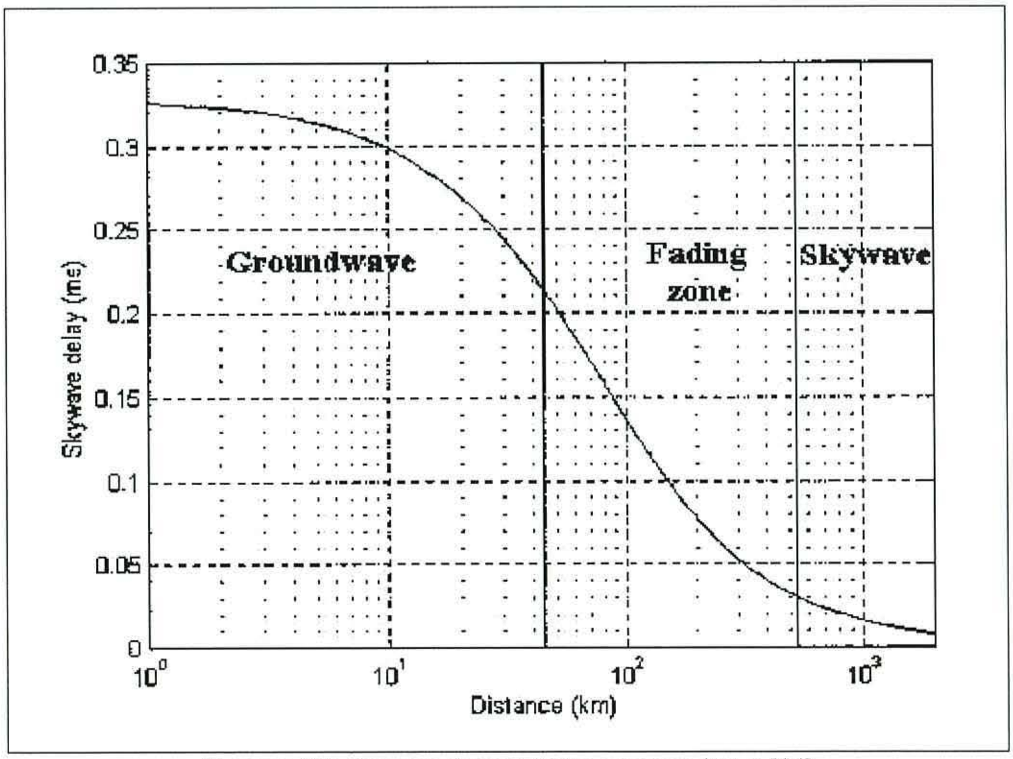

***Figure 3.11: Skywave delay relative to groundwave* [14].**

Radiobeacons employ message bit rates of either 100bps or 200bps. The corresponding bit durations, of 5-10ms, are considerably greater than the signal delays experienced in the fading zone. Thus, the delays of the skywave components with respect to the groundwave will cause negligible corruption of the message and the receiver can use either the groundwave or the skywave component, or the vector sum of the two [76].

3.3.1.4 Modelling Fading

Poppe studied self-fading extensively and developed a method of predicting the depths of the fades from knowledge of the skywave-to-groundwave field strength ratio (Fig. 3.12) [14]. She showed that the total (ie vector sum) field strength that can be guaranteed at least 95% of the time is given by:

$$Total_{dB} = \begin{cases} Gnd_{dB} & SGR < -30 \\ Gnd_{dB} + F_3(SGR) & -30 \le SGR < -5 \\ Gnd_{dB} + F_4(SGR) & -5 \le SGR < 15 \\ SGR + Gnd_{dB} - 8.45 & 15 \le SGR \end{cases} \qquad (3.9)$$

where:

$$F_3 = -11.087 - 0.8536 \times SGR - 0.0224 \times SGR^2 - 0.0002 \times SGR^3 \qquad (3.10)$$

$$F_4 = -8.4614 + 0.2005 \times SGR + 0.811 \times SGR^2 - 0.0014 \times SGR^3 - 3.5e^{-5} \times SGR^4 \qquad (3.11)$$

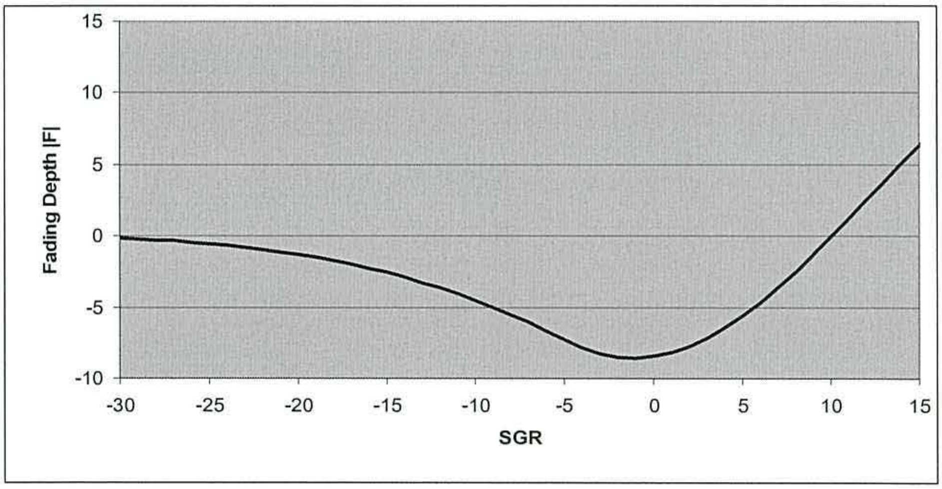

Figure 3.12: Fading depth as a function of skywave-to-groundwave ratio (SGR) [14].

This technique is incorporated into the model when calculating the resulting field strength at night, when the interactions occur between skywave and groundwave.

3.3.2 Atmospheric Noise

In the LF and MF bands, the principal naturally-occurring noise is atmospheric noise. This is caused by multiple thunderstorms and lightning discharges. Distant sources cause noise that is Gaussian-distributed in time. Local sources can cause additional short-term, high-power, spikes. Atmospheric noise is greatest in equatorial regions and noise generated there can greatly raise the noise level at mid latitudes, via skywave propagation [77].

The intensity of atmospheric noise is stochastic and varies with time of day and season of year. The ITU have produced maps of atmospheric noise intensity at 1MHz, six maps per day for each of the four seasons, based on extensive measurement programmes around the globe [78]. By way of example, Fig. 3.13 shows the noise distribution in winter between 0800-1200 hours, local time. Each contour represents the noise strength in dB above thermal noise.

These values may be converted to 300kHz values using the conversion curves shown in Fig. 3.14. The following equation is then employed to calculate the noise field strength at 300kHz figures, with respect to thermal noise:

$$E_n = F_{am} - 95.5 + 20log\left(f_{MHz}\right) + 10log\left(b_{Hz}\right), \tag{3.12}$$

where E_n is the rms noise field strength in a bandwidth, b, at a frequency f_{MHz}; F_{am} is the median noise level taken from the world map, f_{MHz} is the operational frequency (300kHz here); and b_{Hz} is the noise bandwidth in Hz.

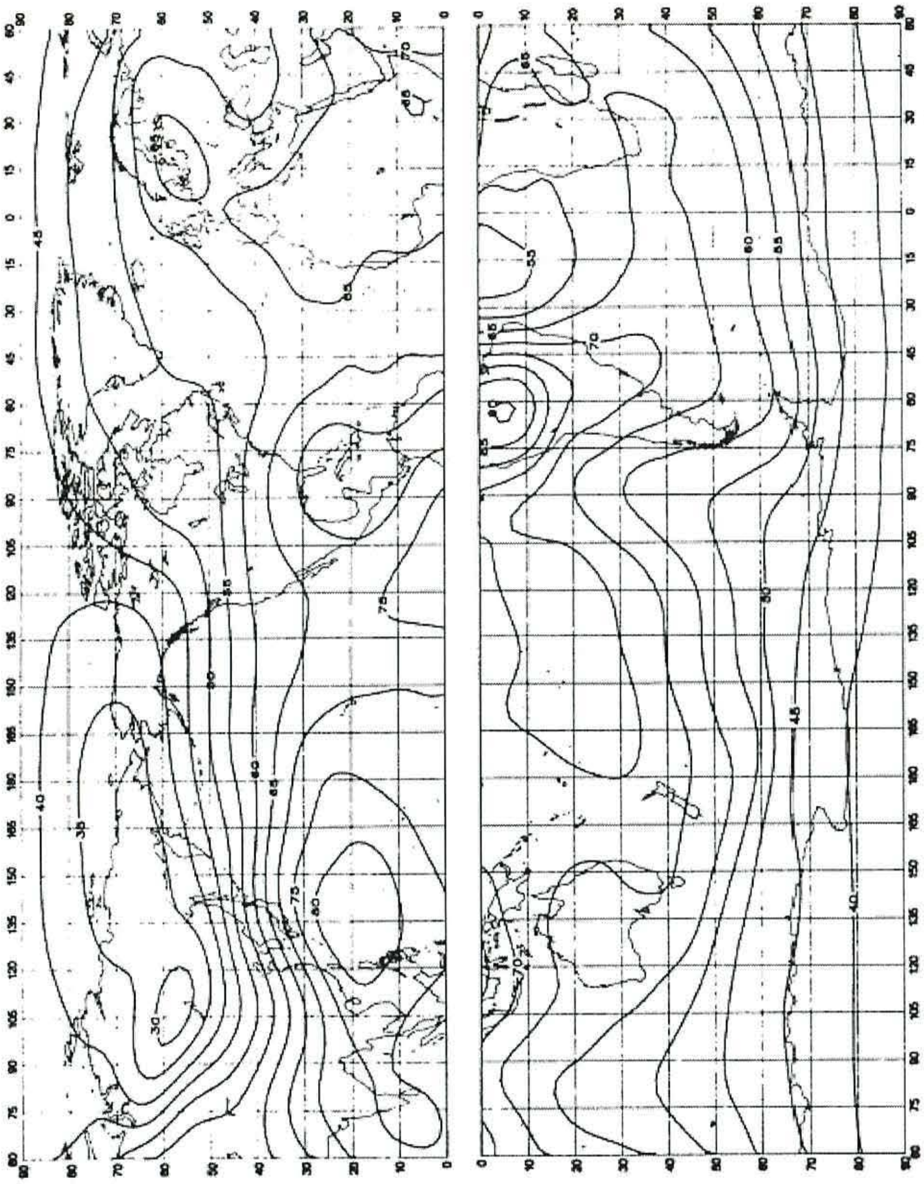

Figure 3.13: Example of the ITU noise world map. The contours represent field strengths in dB above thermal noise at 1MHz, during winter at 0400-0800 local time [75].

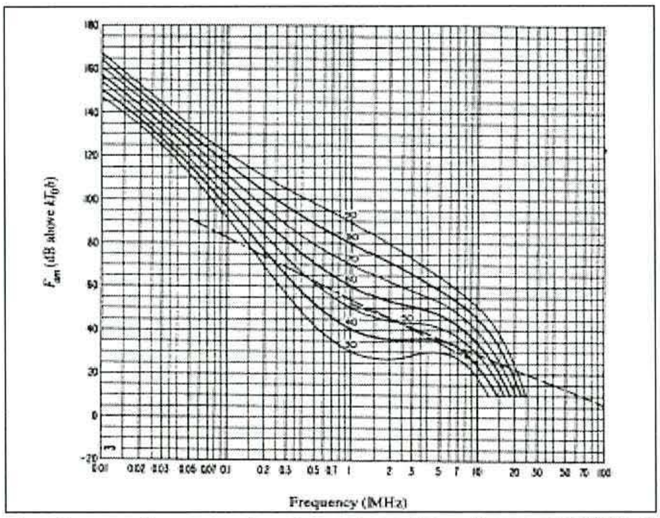

Figure 3.14: Example of curve to convert noise values from those at 1MHz to those at a desired frequency.

Equation 3.12 has been applied point-by-point across the entire region of interest to produce a table of median noise values at a resolution of 10° in latitude and longitude (Table 3.3).

	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
80	48	48	48	49	49	50	50	50	49	48	47	46	44	43
70	53	53	53	53	54	55	55	55	55	55	53	51	45	41
60	54	56	56	58	60	62	65	66	66	63	60	57	50	40
50	55	57	57	59	61	63	65	64	63	61	58	56	56	50
40	60	59	61	63	65	65	65	63	61	58	58	58	59	58
30	65	68	64	66	67	67	66	65	63	63	62	61	66	67
20	67	69	64	65	65	66	66	66	67	67	67	68	72	74

Table 3.3: Median noise values in dB above thermal noise for winter, 0400-0800 period, throughout the EMA and beyond.

There are 24 such tables, one for each combination of time period and season. From these the candidate has derived the field strength values not exceeded 95% of the time throughout the whole year for use in the availability software (Table 3.4). If a finer resolution is required these figures may be linearly interpolated. Both tables encompass an area larger than the European Maritime Area.

	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
80	-3	-2	-4	-4	-4	-4	-3	-3	-2	-3	-3	-4	-6	-7
70	-2	-3	-4	-4	-3	-1	2	4	5	5	4	2	-1	-4
60	-1	-1	-1	1	3	5	9	11	11	10	8	7	2	-1
50	3	3	3	5	7	10	13	13	12	10	9	8	7	4
40	6	6	6	8	11	13	13	13	11	10	9	9	11	13
30	12	11	11	12	13	14	14	13	11	11	11	13	20	24
20	18	14	13	14	17	19	20	19	17	15	17	20	27	30

Table 3.4: Annual average noise values not exceeded 95% of the time, in dBμV/m.

3.3.3. Interference

Up to now only natural factors have been examined: propagation via groundwave and skywave, self-fading, and atmospheric noise. These factors determine the coverage of an individual beacon. There remains another important factor: interference from other beacons. Three types of transmission operate in this frequency band: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). More than 450 beacons within the EMA are crammed into just 64 channels. Inevitably interference occurs, most severe at night when there is skywave propagation over long distances.

The severity of interference experienced at any location depends on the separation of the wanted beacon from the interferer, in terms of both frequency and distance [25]. A receiver's ability to reject unwanted signals is specified by the International Electrotechnical Commission (IEC) in the form of protection ratios (Table 3.5) [68]. These protection ratios set the minimum amounts by which the level of the wanted signal must exceed that of any interferer. For example, should there be interference to a DGNSS beacon from another DGNSS beacon on the same channel, the wanted beacon must have a field strength 15dB greater than the interferer's.

Interference can reach a receiver via both groundwave and skywave propagation. At each location, it is necessary to compute the strength of every one of a large number of potential interferers, arriving via either propagation mechanism. The stronger component of each potential interferer is used to establish whether the protection ratio appropriate to the frequency separation is exceeded. Only if that test is passed is the point deemed to lie within coverage.

	Wanted Signal	Marine (MB)	Aero (NDB)	DGNSS	
	Interfering Signal	Any	Any	MB or NDB	DGNSS
Separation (kHz)	0.0	15	15	15	15
	0.5	-39	15	-25	-22
	1.0	-60	9	-45	-36
	1.5	-60	2	-50	-42
	2.0	-60	-5	-55	-47
	2.5	-	-12.5	-	-
	3.0	-	-20	-	-

Table 3.5 Protection ratios (in dB) that specify the minimum ability of a receiver to reject interference [61] [66,68].

3.3.3.1 Minimisation of interference.

It is up to receiver designers to ensure that their products meet the protection ratio standards. On the assumption that they do so, the band plan is organised (ie beacons allocated channels) in such a way as to minimise mutual interference between stations on the same frequency or adjacent channels. Until recently, the growth in the numbers and powers of beacons in the band plan meant that the band was organised very inefficiently. To remedy matters, Last and Turhan, devised a technique for solving the difficult task of optimising channel allocations [25,79-81]. This method also made use of Poppe's techniques set out above for predicting the levels of the various signals and noise sources at each location.

Last and Turhan's new frequency assignment technique was used to optimise the EMA band-plan on behalf of IALA, ensuring that interference was minimised [82]. The effect of this re-organisation, which came into force across the EMA in September 2001, is that, while interference is still a detrimental factor, it is a good deal less and more consistently distributed between channels. In contrast to the preceding situation in which certain beacons lost almost 90% of their coverage to interference, following the re-organisation, none was expected to lose more than 20%. The new band plan is shown in Appendix B.

3.3.3.2 Verification of optimisation

When reviewing the work on optimisation done by Last & Turhan, it became apparent that since they first developed the optimisation software, the number of DGNSS stations within the EMA had increased, not only in number, but in power too, resulting in greater interference. To quantify this increase in interference: the total numbers of beacons has risen from 408 to 453; the number of exceptionally powerful interferers (≥277km nominal range) has grown from 5 to 125 and, as result, the average power radiated per channel had increased from 5W in the old band-plan, through 17W at the time of optimisation, to 22W. In other words, optimising the band-plan had resulted in beacons' enjoying greater ranges despite the background interference level in the band having risen substantially across the EMA due to the greater number of more powerful stations. Last & Turhan had employed a 2000km limit on the distance at which a skywave signal could cause interference. However, with the increase in beacon powers, this limit was, in practice, exceeded. The most powerful beacon in the EMA, Horta in the Azores, could cause interference up to 4200km away at night.

	DAYTIME		NIGHT-TIME	
Beacon	FOM	CA/IFCA	FOM	CA/IFCA
ANDENES	1.000	(3772/3772)	1.000	(1988/1988)
ASTRAHANSKY	1.000	(383/383)	1.000	(229/229)
BALTIYSK	1.000	(910/910)	0.798	(467/585)
BELLSUND	1.000	(3075/3075)	1.000	(1615/1615)
BJARGTANGAR	1.000	(1102/1102)	0.962	(732/761)
BJORNAYA	1.000	(9248/9248)	1.000	(4535/4535)

Table 3.3: An example of results when processing figure-of-merits (FoM) for each beacon. CA is the number of points remaining within the coverage area, where IFCA is the interference free coverage area.

The candidate discovered this discrepancy in analysing the earlier work on which he was to base his availability calculations. He employed his new-architecture software (see Chapter 4) to re-analyse the effect of interference within the EMA. Table 3.3 shows an example of the resulting figures-of-merit (FoM), that is, the fraction of the interference-free coverage area that remains when interference is present (for example *Andenes* retains 100% of its coverage when interference is present). The result of this investigation was confirmation that the optimisation process performed by Last & Turhan had been a success.

But the data also showed that following the optimisation operation the number of high-powered beacons had increased dramatically. The resulting increase in interference, especially at night, had resulted in a reduction in the coverages of many beacons. As a result of this work, the candidate confirmed the requirement for his own software to be capable of computing skywave interference levels at ranges of up to 4200km from the highest-powered beacons.

3.4 The Bangor Coverage Prediction Software

The Bangor Coverage Prediction Model (BCPM) was developed in the early 1990s for predicting the coverage of marine radiobeacons, taking into account the factors introduced in this chapter. The model produces plots of either the coverage area of a single beacon or the combined coverage area of a system of beacons.

The model works by placing the wanted beacon at the centre of a grid of points, spaced by 0.1° latitude and longitude. This resolution is used as it provides sufficient detail while minimising the sizes of the arrays At each point, the wanted signal's field strength, and the strengths of the atmospheric noise and any interference are calculated, using the techniques explained earlier in this chapter. The wanted beacon's signal strength is compared with the field strength standard in Table 3.1. The signal-to-atmospheric ratio is then calculated and compared to the SNR standard in Table 3.1. The signal-to-interference ratio of each interferer is likewise calculated and compared to the protection ratio for the relevant frequency separation in Table 3.5.

If all the criteria in Tables 3.1 and 3.5 are met, the array point is deemed to lie within coverage. The BCPM then repeats this process for the entire array of grid points around the beacon, building up a picture of the coverage region.

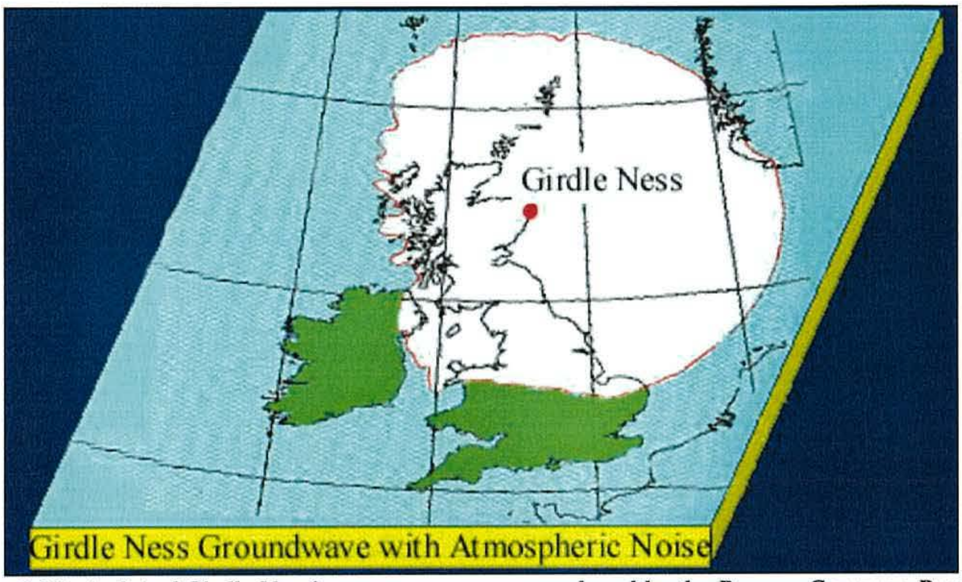

Figure 3.15: A plot of Girdle Ness's coverage area, as produced by the Bangor Coverage Prediction Software. The white region is the region of coverage.

The output identifies the coverage boundary for either a single beacon (eg Fig. 3.15), or a network of beacons (eg Fig. 3.16). As these figures show, the result at each point is a simple binary decision, there is, or is not, coverage. Although the model uses a considerable amount of data to make this decision, the vast majority of it is discarded and no longer accessible. When determining the combined coverage of multiple beacons, each one is processed individually and once its coverage region is calculated, all information for that beacon is discarded.

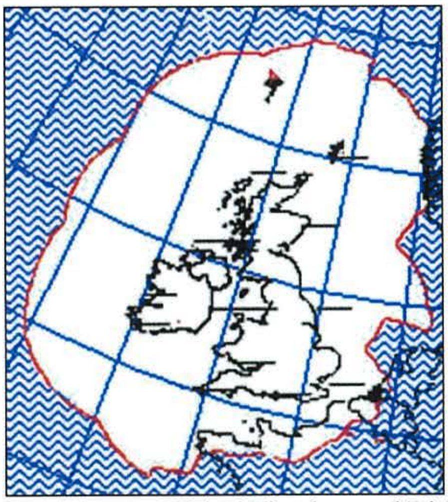

Figure 3.16: Combined coverage area of United Kingdom and Irish beacons produced by the BCPM. The red contour identifies the boundary of coverage provided by all the beacons.

The BCPM handles the various stochastic factors by employing the 95%-ile value in each case. For example, the level of atmospheric noise is the level not exceeded 95% of the time throughout the year. The model also takes into account all the specified factors at night, but only the groundwave components of the wanted and interfering signals, plus atmospheric noise, by day. It has proved a very successful way of predicting the coverage of radiobeacon systems and has been employed in planning various systems.

3.5 Conclusions

The various components that make up the Bangor Coverage Prediction Software have been extensively tested individually and the whole package has been used to help design radiobeacon systems throughout the world. It successfully predicts the coverage areas for single beacons or networks of beacons. However, while establishing each beacon's coverage is an important part of planning a system, it merely shows where the user can expect to receive signals that meet the minimum international standards.

Further research is now needed to investigate the questions of availability and continuity on which this thesis focuses. The various individual stochastic factors that together determine availability and continuity are well described by the analyses embodied in the BCPM. However, the simple software structure of the BCPM is inadequate to support the analysis of multiple simultaneous stochastic events and a more powerful software structure is likely to be required.

Chapter 4

Requirements for predicting availability

4.1 Introduction

Chapter 3 presented the Bangor Coverage Prediction Model (BCPM) and analysed the many factors it takes into consideration. This chapter shows that the BCPM model is inadequate for predicting the service availability and continuity of a radiobeacon system. The software architecture employed needs to be changed fundamentally. A new architecture will be developed and shown to be suitable for these new tasks.

4.2 Understanding availability

Firstly, it is important to clarify that *availability*, to which we now turn, is a quite separate entity from *coverage* with which the BCPM has dealt. One simply cannot say, on the basis of a BCPM analysis, that certain availability standards will be met everywhere within the coverage boundary of a beacon. When considering the effects of stochastic factors such as own-skywave fading, the BCPM calculates the coverage within which the beacon will meet the minimum field strength requirement 95% of the time. Similarly, the 95%-ile atmospheric noise level is used in the model. When computing availability, however, one has to establish whether or not a satisfactory signal is available, say, 99.5% of the time, despite the simultaneous effects of own-skywave fading, atmospheric noise and skywave-borne interference. Clearly, this requires an analysis that can handle multiple stochastic events in much greater depth than does the BCPM.

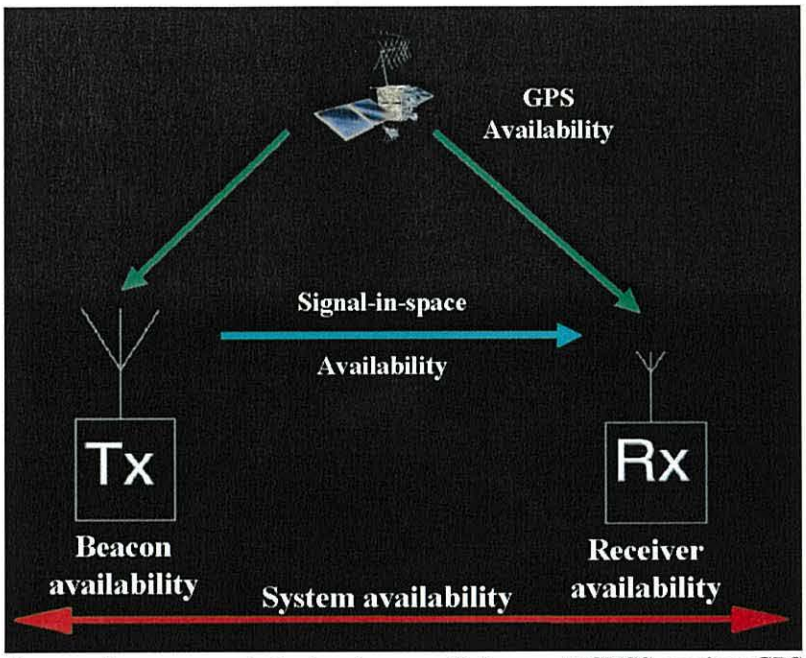

Figure. 4.1: Four main components that make up radiobeacon DGNSS service: GPS, the beacon, its signal-in-space, and the receiver. System availability requires all four to be available.

Fig. 4.1 shows that there are four main parts to radiobeacon DGNSS: GPS, the beacon, its signal-in-space and the receiver. It is important that those factors included within an availability requirement are clearly identified. For instance, a distinction must be made between *service availability* and *system availability*. *Service availability* is the percentage of time a signal at a location is usable. It takes into account the reference station and the signal-in-space only (Fig. 4.2). *System availability* includes service availability plus the availabilities of the GPS service and the receiver. The research in this thesis is concerned with the *service availability;* the model about to be developed will predict this factor and will be used as a tool by service providers.

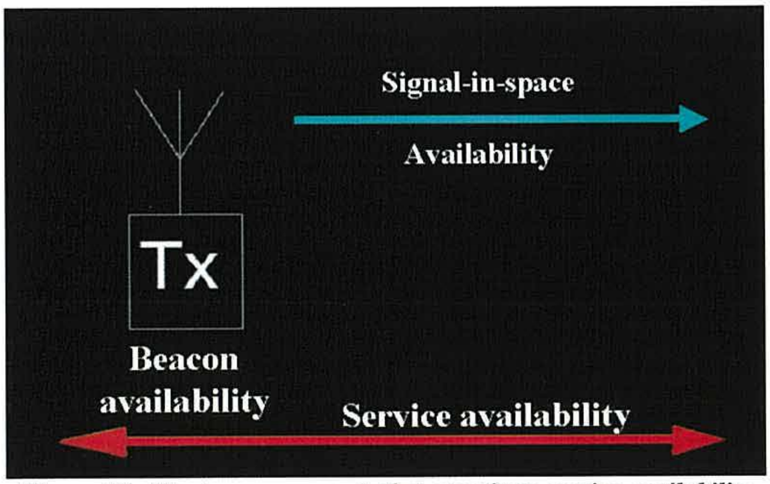

Figure 4.2: The two components that constitute service availability.

Service availability is defined as the percentage of time that a signal at a location is *usable.* Being "usable" means meeting the minimum criteria (the coverage criteria) set out by the ITU [61]. In Europe, these criteria are that the field strength must be not less than 20dBμV/m (or a higher figure specified by the national administration), and the signal-to-noise ratio (SNR) not less than 7dB. In addition, no interfering signal may exceed specified protection ratios that depend on its frequency separation from the beacon's signal. The signal-to-noise ratio (SNR), signal-to-interference ratio (SIR), and field strength are referred to as the "signal characteristics" of that beacon's signal at that location.

To help define the standards a service must meet in order to be deemed "available", all principal documents that set any such standards were identified and reviewed. These were: relevant current resolutions of the IMO, (of which only resolution A.860 was relevant and will be referred to as *"IMO (860)")* [12][15]; documents from the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA), *"IALA (Guide), IALA (Draft Guide)"* [16,83] including recent changes IALA have proposed to the IMO resolution A.815, *"IALA (815)"* [84]; the 1999 US Federal Radionavigation Plan (FRP), *"FRP"* [24] and United States Coast Guard (USCG) documentation, *"USCG"* [58] (both only strictly applicable within the US); and recent proposals for changes to the IMO documentation made by the European Maritime Radionavigation Forum (EMRF) *"EMRF"* [85]. Table 4.1 identifies the factors each document takes into account in determining availability. Thus, all sources include the availability of the beacon ("Beacon"). Most also include the deterministic and stochastic signal-in-space factors listed above that take into account the environment in which the receiver operates ("Environment").

These signal-in-space factors are not always identified explicitly. Rather, several documents make it clear only that the availability specifications they propose apply across the whole of the beacon's coverage area. Thus it is the candidate's view that they must apply in the regions lying just inside the coverage boundary, where the field strength, and the signal-to-noise ratio and signal-to-interference ratio are at their lowest.

The availability model to be developed here will embody the most demanding set of requirements identified in these documents, thus ensuring that the requirements of all documents are met.

Document	Includes	
	Beacon	Environment
IMO (860)	√	√
IALA (815)	√	X
IALA (Guide)	√	√
IALA (Draft Guide)	√	√
FRP	√	√
USCG	√	√
EMRF (App)	√	√

Table 4.1: Comparison of signal availability definitions

4.3 Requirements for predicting availability

An important concept here is that there are areas in which the coverages of neighbouring beacons overlap one another and so provide corrections simultaneously, as shown in Fig. 4.3. This is most likely to be the case by day, when coverages are at their greatest. The service availability at such a location will be greatly enhanced over that provided by a single beacon since, if that beacon fails, the user may select an alternative beacon. In Fig. 4.3 three such beacons, each with its own service availability, provide simultaneous coverage at the location marked by the grey box. The individual service availability of each beacon is calculated in two stages. First, the beacon's broadcast availability (that is, the fraction of time it is on the air) is calculated from its failure rates and repair times. Then the availability of its signal-in-space is calculated at the receiver location, taking into account the values there of the various signal-in-space factors. Finally, the two factors are combined to give the service availability of that individual beacon at the receiver location. The service availability of each of the three beacons, calculated in this way, are then combined to give the overall availability of the DGNSS service at that location.

Now consider in more detail the signal requirements for predicting the service availability of an individual beacon.

One needs to know the probability that the beacon, including all the components associated with it such as its power supply and antenna, is on the air and operating correctly. Then, one needs access to its signal characteristics and their probabilities at each receiver location within coverage. Specifically, one requires the field strengths of the wanted beacon, and those of the atmospheric noise and of each potential interferer. These factors can, of course, be calculated using the methods set out in Chapter 3.

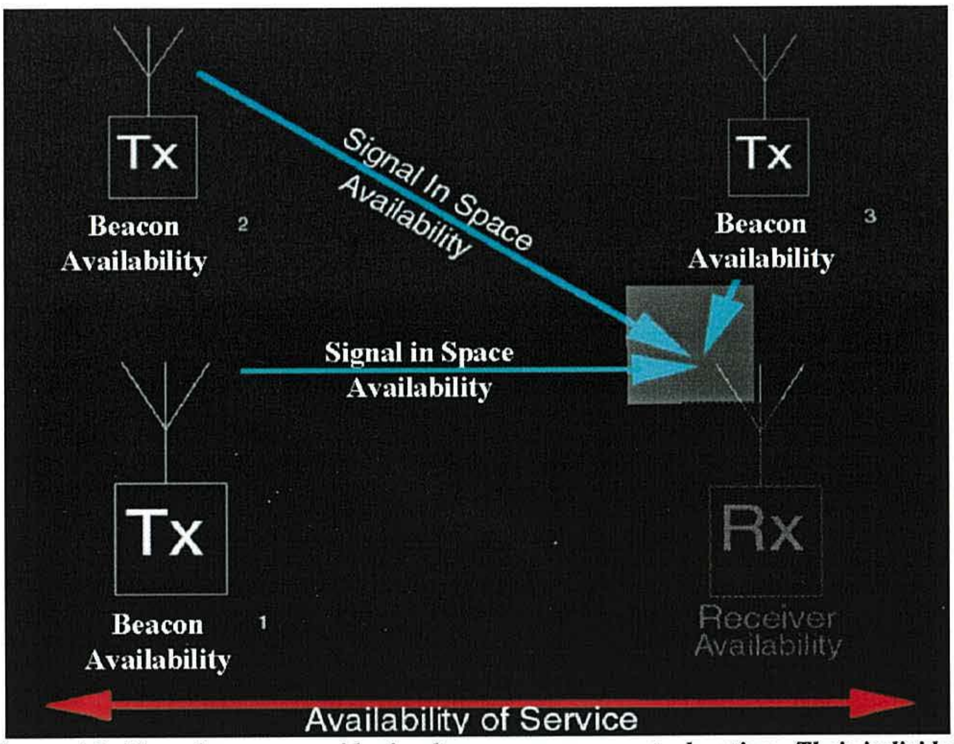

Figure. 4.3: Three beacons provide simultaneous coverage at a location. Their individual signal-in-space availabilities contribute to the service availability.

With multiple beacons, the same process is applied. Now, however, one requires access to the signal characteristics of each of the beacons at each location. Thus, should five beacons provide simultaneous service, the SNR and SIR of each one at each location must be available simultaneously if the service availability there is to be calculated.

4.4 Review of the BCPM

Section 3.4 explained how the BCPM models the coverage of a radiobeacon. The beacon was placed at the centre of a large array of points. At each array point its groundwave and skywave field strengths were first calculated, and then the resulting night-time fading effects.

Also at each array point, the annual average level of atmospheric noise was found and so the atmospheric SNR calculated. Finally, the strongest interference component was identified (a complex process) and the SIR computed. All this data was then used to calculate whether the beacon provided coverage at the array point and the result, a simple binary *yes* or *no,* stored at that point.

Having determined whether a point lies within coverage, the BCPM immediately discards all field strengths, SNR and SIR values. Clearly, software to predict availability will need access to all this information, from all relevant beacons, simultaneously. One could modify the BCPM model to achieve this. But the changes required would involve altering its fundamental structure. In such a situation, it is almost always simpler to create a new model with the required architecture. This new model would, of course, continue to employ the various well-tested functions of the BCPM for computing the field strength, fading, SNR and SIR values. A decision was made to develop this new architecture designed specifically for computing availability and continuity.

4.5 The new architecture

The new architecture will provide simultaneous access to a great deal of information about multiple beacons and their relevant signal characteristics. A decision was made to keep each beacon's information separate, but to store it in a way that would allow it to be accessed rapidly.

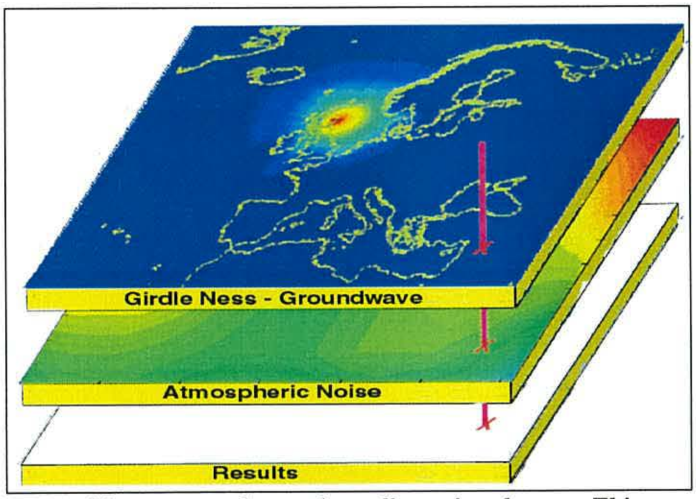

Figure. 4.4 - The new architecture employs a three-dimensional array. This example has just three layers that hold, respectively, the groundwave strength of a single beacon, the atmospheric noise, and (in the results layer) coverage computed using the first two.

As with the BCPM, the new architecture employs large arrays spaced by 0.1° of latitude and longitude. But instead of each array's encompassing the expected area of coverage only, the new arrays will cover the whole region of interest. This change was made in order that the coverage provided by all beacons that lie within this larger area may be considered simultaneously. In the first instance this region will be the European Maritime Area (EMA).

The new arrays are held in a three-dimensional stack. In the simple example in Fig. 4.4 the top level array holds the groundwave field strength distribution of the beacon (in this case Girdle Ness). This array covers the full extent of the EMA. A "groundwave attenuation array" of this kind are generated for every beacon, both DGNSS and interferer, within the EMA. The values in these arrays are (as in the BCPM) be the values of the signal attenuation from the beacon to each location. Signal strength can then be calculated directly from these attenuation values once the beacon's radiated power level is known. Although these are strictly arrays of attenuation values, for simplicity they are referred to as "groundwave field strength" arrays.

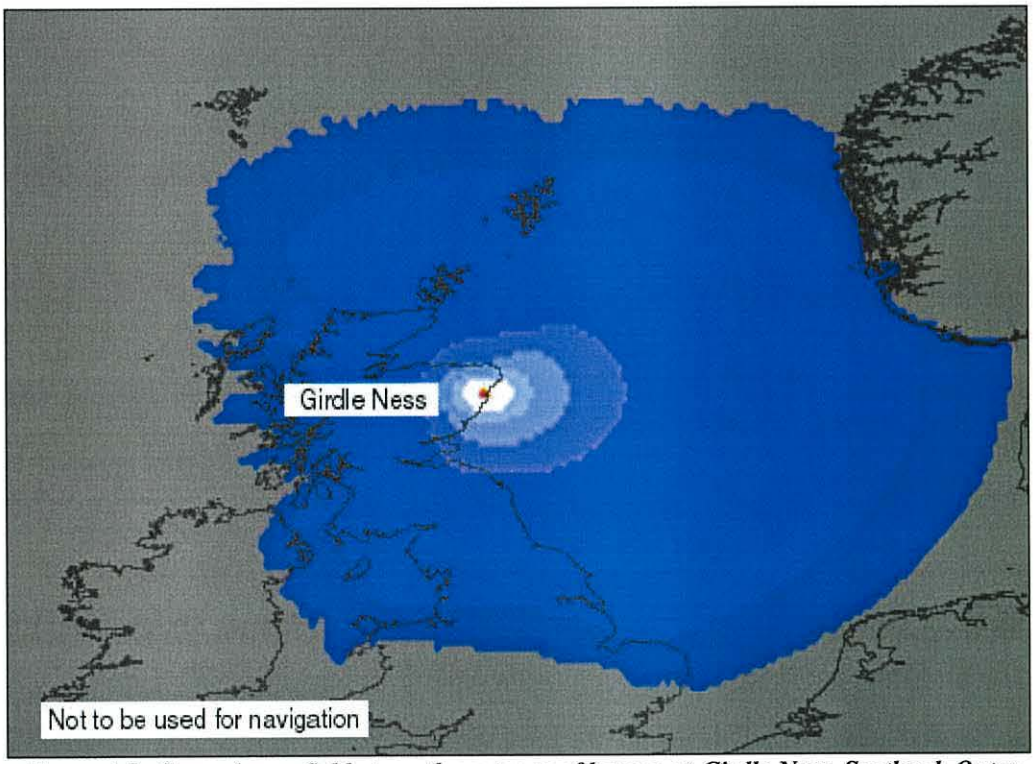

Figure 4.5: Groundwave field strength contours of beacon at Girdle Ness, Scotland. Outer boundary is limit of daytime interference-free coverage computed using top two layers in Fig. 4.4.

The techniques used in the new software model have been adapted from those of the BCPM to add new functionality whilst retaining the coverage-prediction capability of the BCPM itself (Fig. 4.5). The coverage in Fig. 4.5 was predicted as follows. The top-level array in Fig. 4.4 is the groundwave field strength array of Girdle Ness. The second level is the atmospheric noise array. Examining point-by-point the groundwave field strength and the atmospheric noise, the model computes the groundwave signal-to-noise ratio at the point. The model thus has the two values, field strength and SNR, needed to determine whether that point lies within daytime coverage or not. It writes the answer into the corresponding point in the bottom array, the result array. But now of course, in contrast to the BCPM, the new architecture preserves the information used to form those decisions.

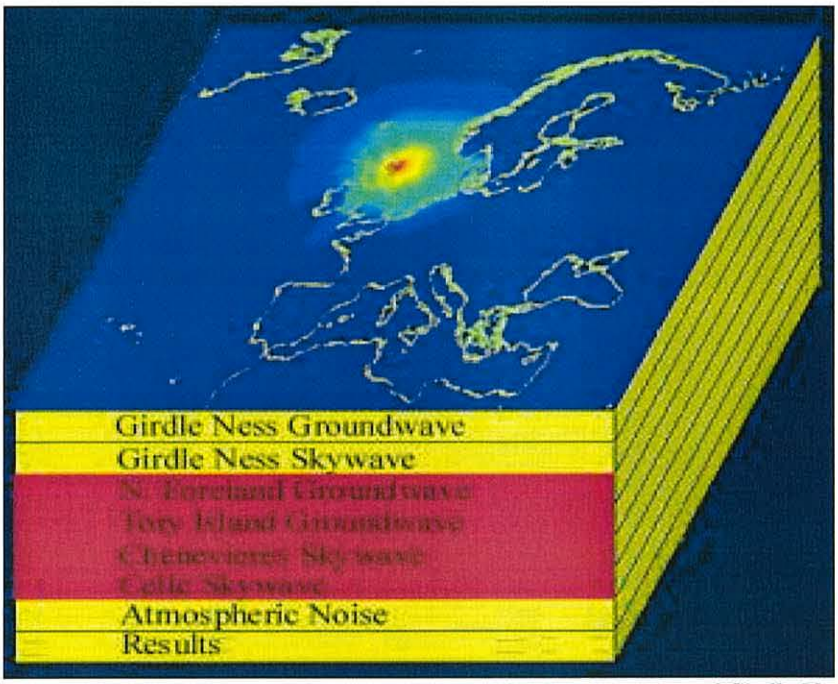

Figure 4.6: Array architecture being used to plot the night-time coverage of Girdle Ness. The top two levels contain the groundwave and skywave field strength distributions of Girdle Ness. The red layers hold potential interferers' field strengths. Atmospheric noise is in the penultimate layer, and results written into the bottom layer.

At night, own-skywave interference is included in the calculation. Thus, the station's skywave array is added to the stack of arrays so that fading can be computed (Fig. 4.6). And when interference needs to be taken into account, the groundwave and skywave arrays of all potential interferer are added; those highlighted in red are example interferers to Girdle Ness.

In this architecture, the process of identifying the strongest interferer and computing the SIR are achieved here by entering the arrays and extracting the pre-stored values for that point. The BCPM did this by calculating and discarding values at each array point. The new approach is much quicker, of course, since the field strength values are all available simultaneously in the stack of arrays. But, more importantly, the raw information remains there so that other questions relating to availability and continuity can be posed later. These examples show clearly the rationale behind the new architecture.

When predicting coverage, the software simply works through the array point-by-point, pulling out groundwave and skywave field strength values, calculating the self-faded signal strength, and then comparing that to the strengths of potential interferers (taken from their individual layers) and atmospheric noise at each location. This process can be likened to pushing a pin through the stack of layers and extracting the data from each layer the pin pierces. If the coverage criteria are met, a positive result is stored in the results layer. This result can be a simple yes or no as with the BCPM. However, the new architecture provides the flexibility to let us store other values at the point, such as faded field strength, SNR or SIR, if required.

This ease of accessing information comes into its own when predicting availability. The availability of a beacon's signal differs from one location to the next. At each location, by working from the stored signal strength, SNR, SIR, and other factors, the beacons availability will be calculated and stored. When considering the overall availability provided by a set of several beacons that act as alternatives to one another, all the information on each beacon is now available simultaneously. This new architecture provides the means for storing and accessing that data. The strength of the new architecture is fully demonstrated when processing the beacons of the entire EMA. In this case, 162 DGNSS beacons are potentially subject to interference from one another and also from the 299 marine and aeronautical beacons. In total, 461 beacons are loaded as separate layers into the array.

But each beacon's signals are propagated by both groundwave and skywave modes. Thus, both layers need to be stored for each beacon: a total of almost 900 layers each covering the entire EMA. Each layer requires approximately 5MB of memory. All can in principle be stored simultaneously. But, to ease the storage requirement, in practice layers are held on hard disk and only stored in RAM when required.

The software is written in Microsoft Visual C/C++ and is less than 400K in size. It takes approximately two minutes to process one beacon on a Pentium 3, 650MHz machine with 256MB RAM. A further description of the software structure is given in Appendix F.

4.6 Verification of new architecture

To verify the operation of the coverage prediction part of the new software model with its new architecture, its results were compared to those calculated manually using ITU methods, and also compared to results generated by the BCPM.

Each of the processes illustrated above was considered: analysis of groundwave propagation, prediction of daytime coverage, addition of skywave propagation and self-fading, and finally calculation of interference. Each was checked by hand calculation against the ITU groundwave propagation curves, and also against the BCPM results. Table 4.2 shows some results from this process. At this stage groundwave propagation alone was being considered. Four check point locations were selected, at various distances from the beacon and involving two types of ground conductivity. The table shows the signal strength values established manually by reference to the "ITU Curves" [69] and by the "New Model" software. The results show that no difference exceeds 1dB. These slight discrepancies are typical of the limitation of the use of the printed ITU curves.

Check Point	Conductivity	ITU Curves dBμV/m	New Model dBμV/m	Difference dBμV/m
1	5000 mS/m	58	58	0
2	5000 mS/m	44	43	1
3	3mS/m	62	61	1
4	3mS/m	39	40	1

Table 4.2: Results of comparing the new software model to the ITU curves, for four different groundwave paths of various lengths and conductivity.

This process was then repeated to check the accuracy of coverage results that included skywave field strength and fading (Table 4.3). Point Lynas is the wanted beacon and the Spanish and Swedish DGNSS beacons, *Capo de la Nao* and *Hoburg* are the interferers.

The groundwave and skywave field strengths of each of the three beacons were extracted from the arrays. From these values, the SGR, and the degree of self-fading (F_term), were determined. Finally, the resulting 95%-ile field strengths were calculated; these are shown in the "New Model" column. The "Calculated" column gives the corresponding figures calculated manually from ITU curves [69] and by applying the fading method developed by Poppe [14]. Again, the two agree within 1dB.

Beacon	Curves and BCPM					New Model dBμV/m	Diff dBμV/m
	Ground dBμV/m	Sky dBμV/m	SGR	F_term dBμV/m	Calculated dBμV/m		
Lynas	35	26.8	-7	-6	29	30	1
C_DE	N/A	12	N/A	N/A	12	11	1
Hoburg	N/A	14	N/A	N/A	14	14	0

Table 4.3: Results of night-time coverage with interference. Point Lynas (Lynas) is the wanted beacon. The Capo_de_la_Nao (here "C_DE") and Hoburg beacons are potential interferers.

Roberts *et al*, [86] have independently compared final coverage results produced by the new software, with all night-time factors in operation (Fig. 4.7), with corresponding predictions produced by the BCPM (Fig. 4.8), for the beacons along the Norwegian coastline. In Fig. 4.8, the red contour line shows the edge of coverage predicted by the BCPM. The corresponding line in Fig. 4.7 is the outer contour. From these two plots it can be seen that the coverage calculated for each beacon with the new software, matches that calculated with the original BCPM (red contour). Comparing these two plots also illustrates the increased flexibility of the new software: the BCPM simply produces a coverage boundary. The new software gives additional information, in this example beacon selection (See Chapter 5).

Thus, the functionality of the old BCPM has now been transferred into the new software model with its new, improved, architecture. The new software model has been verified through tests against both the BCPM and the ITU curves to ensure that it is producing correct results. Details of further verification are shown in Appendix C.

Having shown that the new software does indeed reproduce the same results that the BCPM does, it can now be further developed to model availability and continuity.

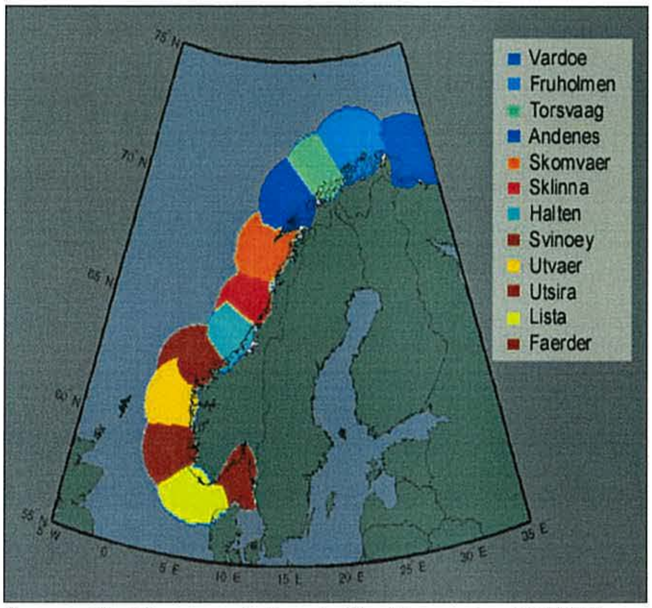

Figure 4.7: New software: Best beacon choices in the Norwegian DGNSS coverage region, using the 'post-SA' strategy.

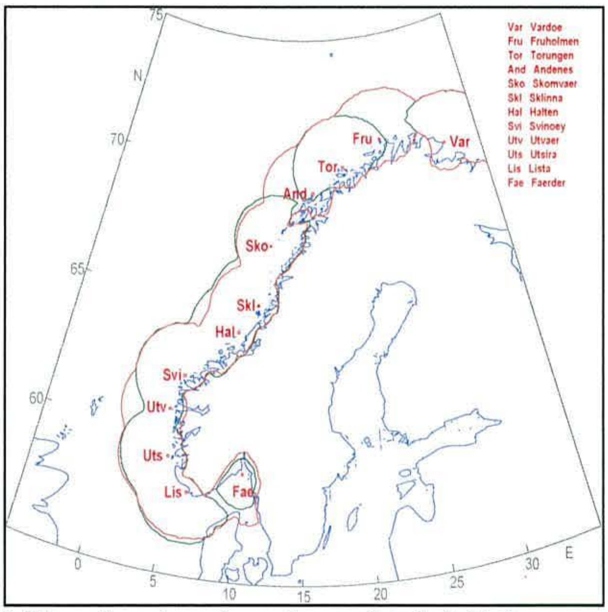

Figure 4.8: BCPM: The red contour shows the predicted night-time coverage of Norwegian DGNSS radiobeacons [86]

4.7 Conclusions

This Chapter has shown that coverage and availability are different entities and that being within the predicted coverage region of the beacon does not mean that the availability requirement has been met. *Availability* also involves the availability of the beacon itself as well as that of the signal-in-space. The service availability of a beacon is calculated using its broadcast availability and also considering the propagation of its signal. Wherever more than one beacon provide simultaneous coverage, the service availability at each location is a function of the availabilities of all the beacons.

The requirements of a software model for computing the signal propagation factors in availability have been analysed and compared to those offered by the BCPM. The BCPM has been shown to be unsuitable for predicting multi-beacon availability since it focuses on each beacon separately and then discards all information except the result. A new architecture has been developed that overcomes this drawback. By combining the new architecture with the functions of the BCPM, all the individual propagation factors can be calculated as before in the tried-and tested manner. But now the results of computations are stored for subsequent use in availability and continuity calculation.

New coverage software, employing this new architecture has been developed and its operation verified by comparison with both results computed using the BCPM and ITU methods of calculating field strengths. This powerful new software tool can already predict coverage, but more importantly, it can form the basis for software to compute availability and continuity. However, it turns out that the new software architecture also opens up another very important area of application: the identification of the best beacon for use at any location. This application will be explored in Chapter 5. Then, in Chapter 6 we will return to the computation of the availabilities of individual beacons and groups of beacons.

Chapter 5

Beacon selection

5.1 Introduction

The previous chapter introduced a new, powerful, software model. This model employs an architecture that provides information on all parameters of all beacons at all locations simultaneously. It forms an excellent tool for investigating an important question, different from that of availability, but closely related. This question, which had been discussed for some time at Bangor, was that of beacon selection: simply, which is the "Best Beacon" to use at my location?

With more and more beacons being introduced into the coastal regions of the EMA and other parts of the world, there is a high probability that a user will be able to receive more than one station simultaneously, especially by day. Each such beacon carries its own corrections. This raises an interesting and important question: which beacon to choose. With many receivers, the user must select the station manually, but there is little guidance as to how to make that choice. Other types of receiver perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

The new software model, by providing all the key information on all beacons simultaneously, provides precisely the framework within which the choice of beacon can be examined. In this chapter the new model is used to study the two existing selection methods. Their results are then compared and the regions within which they make different selections are identified. Then the question of beacon selection is re-analysed and two novel improved approaches are proposed, which are then modelled and evaluated.

Throughout this work it is assumed that each beacon contains the same hardware of identical quality and therefore selection is determined on the needs of the mariner when receiving correction messages.

5.2 Modelling existing beacon selection strategies

Currently two strategies are commonly employed in commercial DGNSS receivers for selecting the beacon to use: the *nearest beacon* and *strongest beacon* strategies. When a receiver employs the *nearest beacon* strategy, it ignores all attributes of the beacon's signal, simply choosing the closest station. Thus it will select a nearby weak station – possibly one whose signal has arrived over a land path of high attenuation - and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case, the more distant beacon's signal would have a higher SNR than the nearest one. So choosing the nearest signal in this way may well result in more data errors, and so greater delays in receiving correction updates.

In contrast, selecting the station using the alternative *strongest beacon* strategy would mean that the stronger, more distant one was chosen. However, this might result in greater position errors due to increased spatial dilution of precision!

The new software was employed to map the choices of beacon made by these two strategies and allowed us to determine whether, in practice, they led to significantly different choices [87].

5.2.1 Modelling the nearest beacon strategy

The modelling process was first run using the 16 beacons installed, or currently planned, by the General Lighthouse Authorities (GLAs) of Great Britain and Ireland. The first task is to compute the coverage area of each station. Then, point-by-point throughout these 16 coverage areas, the geographically-nearest beacon is identified. When all points have been examined, an output plot is produced (Fig. 5.1), with a different colour used to distinguish the area within which each beacon has been chosen.

Fig. 5.1 distinguishes between the extent of coverage by day (outer boundary) and by night (inner, lighter, region). The night-time coverage is, of course, less than the daytime because of self-fading due to skywave cancellation of the beacons' signals.

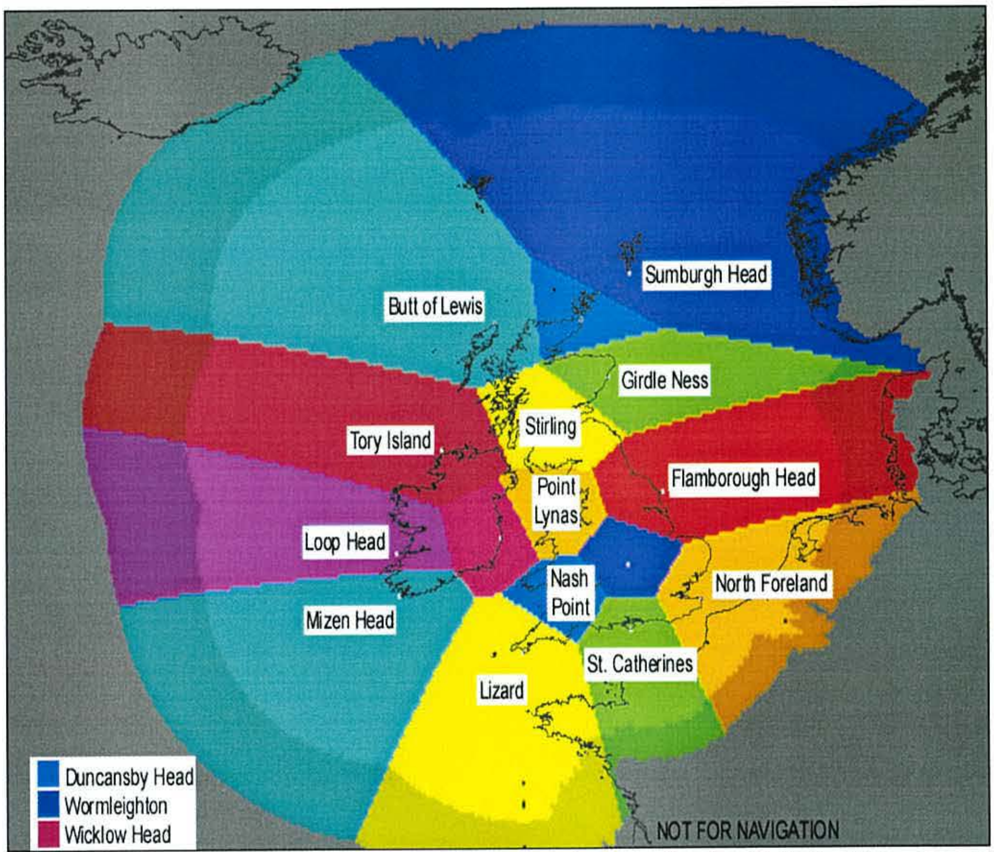

Figure 5.1: Beacon selection using* nearest beacon *strategy, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.

This form of diagram was designed to provide the information in a convenient and efficient fashion to those navigators who must input the choice of beacon into their receivers manually. It tells them the beacon to use (by day or night), where on a voyage they should change beacon selection, and where they should cease to rely on coverage from the DGNSS system.

Since this selection is based solely on distance, the boundaries between adjacent areas are the straight lines along which pairs of neighbouring beacons are equidistant. It is interesting to compare the sizes of the coverage areas of the various GLA stations: Sumburgh Head, for example, serves a much larger region than does Nash Point. This is partly explained by its greater nominal range, 370km as compared to 277km, but more by the fact that Nash Point's neighbours are simply much closer to it than are Sumburgh's.

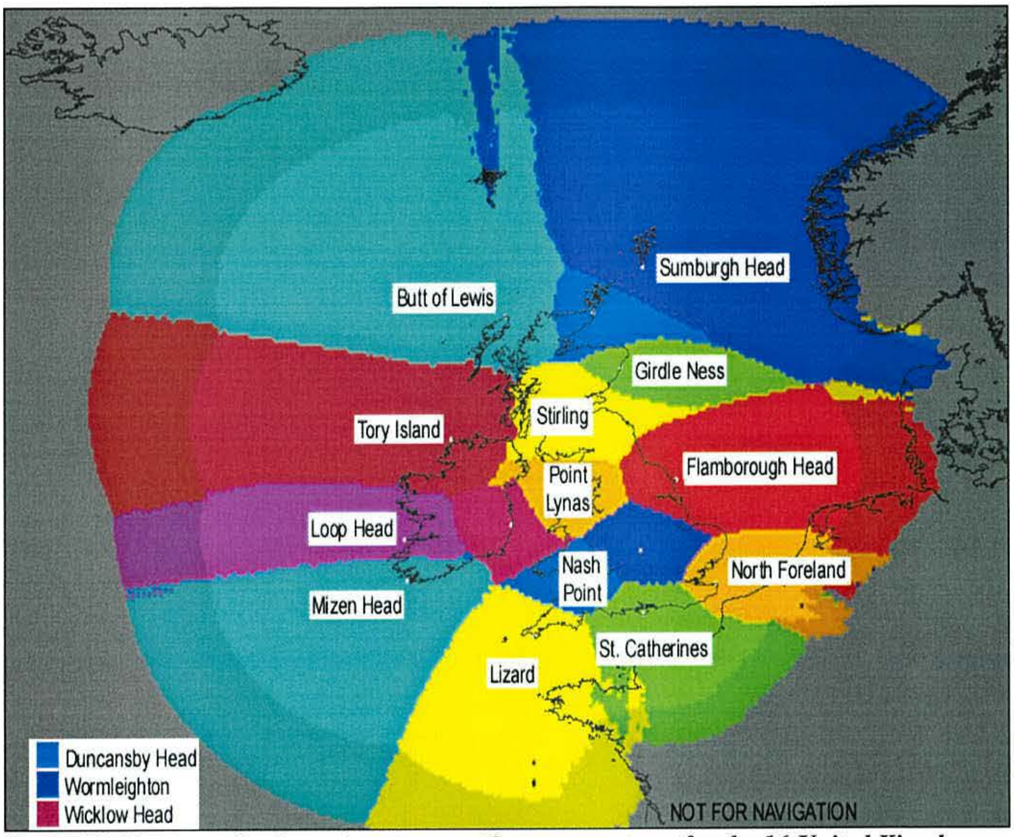

Figure 5.2: Beacon selection using* strongest beacon *strategy, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.

5.2.2 Modelling the strongest beacon *strategy*

The same process was then employed to model the *strongest beacon* strategy; this time the beacon with the strongest signal at each point was identified (groundwave by day, faded skywave by night). The result is shown in Fig. 5.2.

Now the boundaries between the areas served by adjacent beacons are much more complex, because they take into account the complex nature of signal attenuation over land. A splendid example can be seen north of the Faroe Islands. The islands cause severe attenuation of the signal from Butt of Lewis. So the Sumburgh signal, which arrives via an all-sea path, is the stronger.

The beacons this strategy chooses appear to be significantly different from those chosen by the *nearest beacon* strategy. (*Nearest beacon* is the most commonly-used strategy in automatic receivers and so will be used as the basis for comparisons throughout this chapter). The yellow areas in Fig. 5.3 are the regions in which the two strategies produce different results; they constitute 15% of the total daytime coverage.

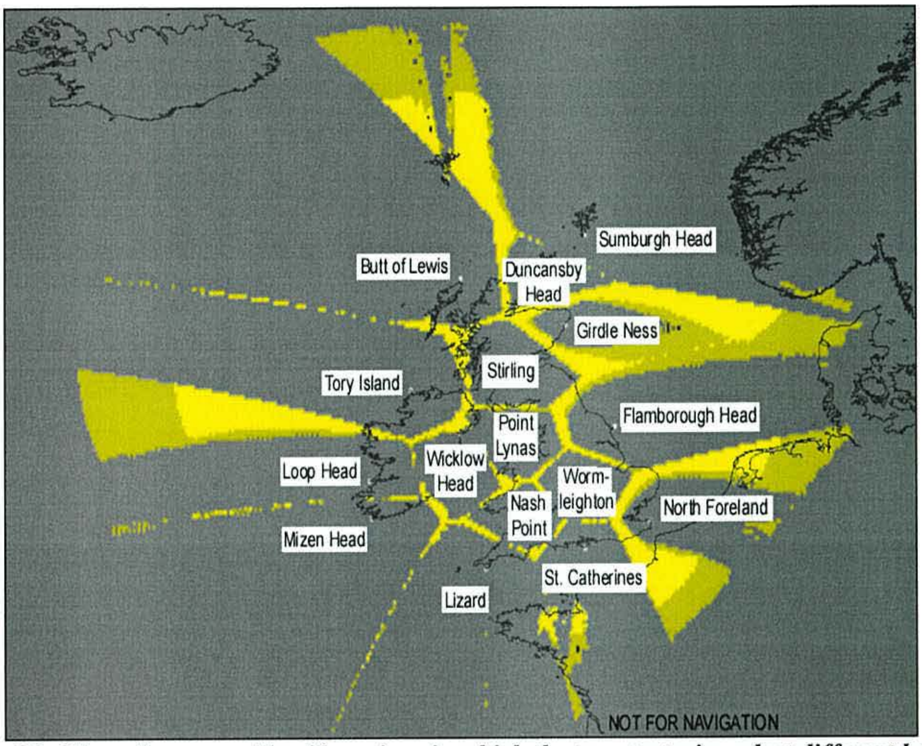

Figure 5.3: The yellow areas identify regions in which the two strategies select different beacons.

To understand the reasons for the areas of difference, consider the large region west of Ireland that straddles the Tory Island/Loop Head boundary. Here the signal from Tory Island is the strongest, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head. But even where two stations of equal power do compete, the *nearest beacon* strategy frequently selects the weaker signal. Consider the inland section of the yellow area that straddles the Duncansby Head/Girdle Ness boundary. Fig. 5.1 shows that Girdle Ness is the nearest beacon here. But its signal arrives via a land path of relatively high attenuation. The signal from the slightly more distant Duncansby Head station arrives over a sea path and is the stronger.

5.2.3 Review of current selection strategies

Fig 5.3 has shown that in many regions, the *nearest beacon* strategy fails to select the station with the strongest signal. The consequences of simply choosing the *nearest beacon,* as many receivers do, are a lower SNR, a higher message error rate, and a greater message latency, than the *strongest beacon* would offer. When SA was active, message latency was the major constraint: the greater the latency, the greater the pseudo-range error that would build up before the next correction was received, and so the greater the resulting position error.

The logical conclusion of this argument is that one should always choose the beacon whose signal has the highest signal-to-noise ratio. But there is more to maximising SNR, than just using the strongest signal; realising this led to a novel selection technique based on maximising signal quality.

5.3 Beacon selection by signal quality

In the two selection processes employed in automatic receivers and analysed above, the only *noise* taken into account is atmospheric noise. Since its level at any time is essentially the same on all channels across the radiobeacon frequency band, choosing the *strongest beacon* automatically gives the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – the dominant factor for radiobeacon coverage in Europe at night [25]. One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength, but on a different frequency, might have much less interference, and so a higher SNR. Thus, one should take into account when selecting a beacon not only atmospheric noise, but also interference. The *overall SNR* should be used as the measure of quality: that is, the ratio between a beacon's signal strength and either the atmospheric noise or the interference, whichever is the greater. That is the new *quality strategy*.

Our software model provides all the information needed to assess beacons' SNRs fully: the groundwave and skywave strengths of the wanted beacon, the atmospheric noise level, and the strengths of all interfering components on all channels. Thus, the true SNR of each beacon's signal can be computed at each point, so allowing the Best Beacon there to be identified according to this *quality strategy*. Fig. 5.4 shows the results for the British Isles beacons. This figure is plotted under worst-case conditions: at night, when interference capable of reducing coverage can be received via sky-wave propagation. In consequence, not only is night-time coverage smaller than by day, but also the effect of interference on the choice of beacon is greatest.

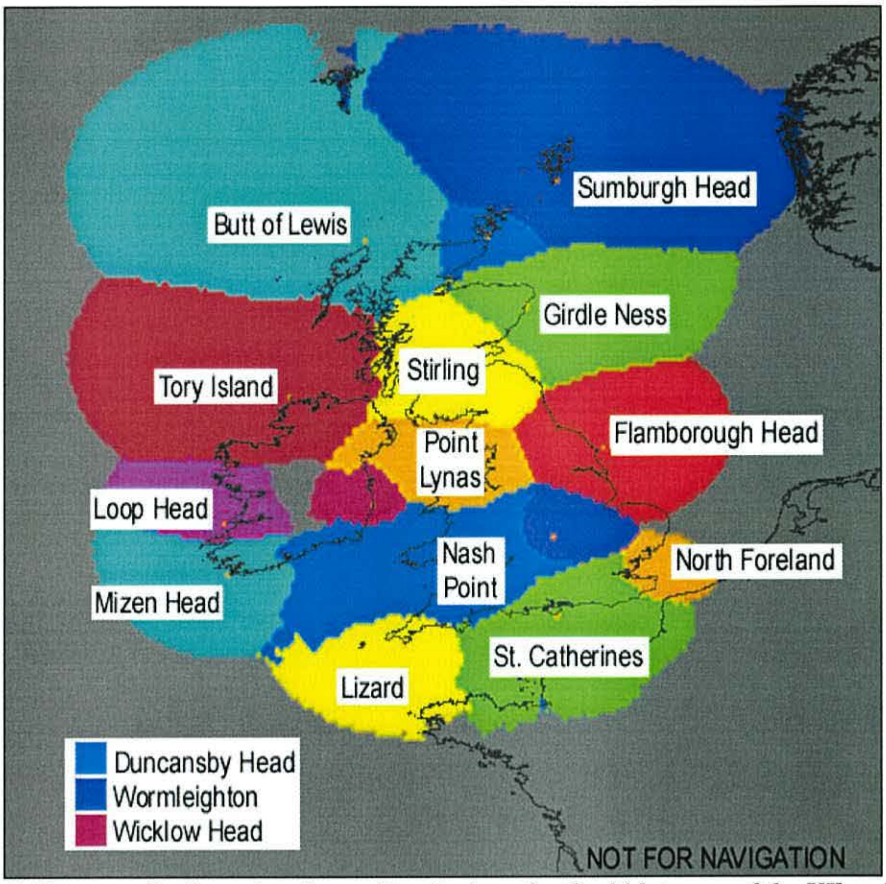

Figure 5.4: Beacon selection using the* quality strategy *for the 16 beacons of the UK and Ireland, under night-time conditions with skywave interference.

In marked contrast, the *nearest beacon* strategy – again used as the basis for comparison – simply ignores interference. In the yellow areas of Fig. 5.5, which total 14% of the night-time service area of the system, the new *quality strategy* has chosen beacons of higher SNR than did the *nearest beacon* strategy. Clearly, the simple *nearest beacon* approach fails to provide the user with the highest quality signal over substantial and important sea and land areas.

5.3.1 Review of the quality selection method

Fig 5.4 shows that the *nearest beacon* selection strategy may select a weaker signal with a greater bit error rate (BER) than the *quality strategy*. However, in May 2000, selective availability was set to zero. This made a fundamental difference to the criteria determining the choice of Best Beacon. Post-SA, the dominant position errors in raw GPS became the uncorrected parts of signal delays in the ionosphere and troposphere. Both these types of error change much less rapidly than did the previously-dominant SA.

Therefore, correction messages remain valid for much longer periods of time; indeed, they may be usable for tens, even hundreds, of seconds [18]. So the effect of latency in the reception of corrections on position error is markedly reduced. Much lower beacon SNR values can be tolerated than before, since missing occasional messages matters so much less. Further, receiving the station with the highest SNR, or even the strongest station, would now appear to be much less important than before.

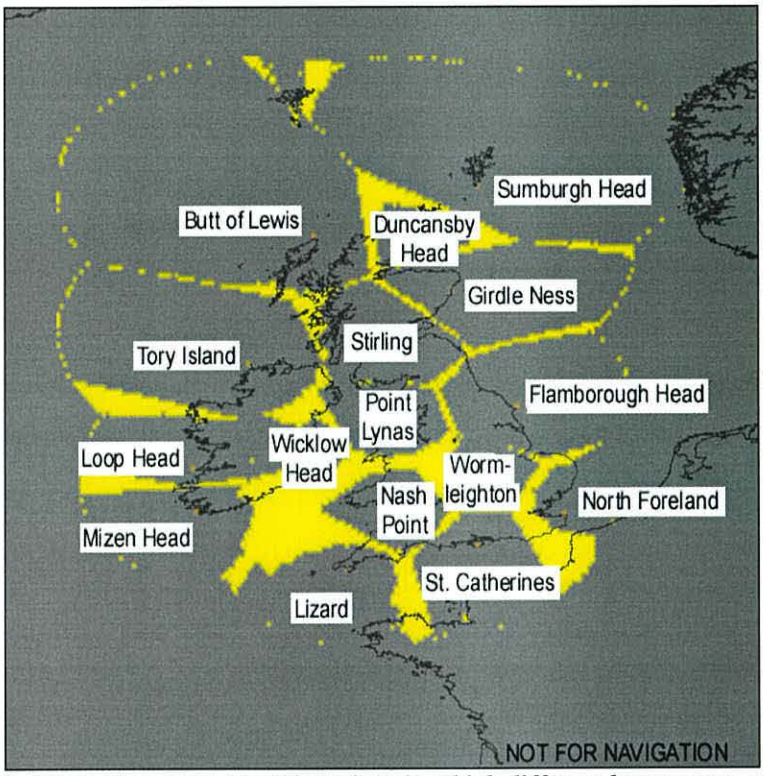

***Figure 5.5:** The yellow areas identify regions in which different beacons are selected by the new* **quality strategy** *and the conventional* **nearest beacon** *strategy.*

On the other hand, as the separation between reference station and receiver increases, the dominant error source in *differential* operation soon becomes spatial dilution of precision. To be strict: this is not an *error* source itself, but rather the obvious result of the user and the reference station experiencing different atmospheric delays. Whatever: it would appear that a simple *nearest beacon* selection strategy is all that is now required.

However, the situation is complicated by a third factor! Correction messages also carry alarms to warn the user of unhealthy satellites, or failures of reference stations. Indeed post-SA, enhancement of integrity is a much more important benefit of differential operation for many users than enhancement of accuracy.

So it may not, in fact, be acceptable to choose a nearest beacon with minimal spatial dilution but low SNR, since this might result in increased message latency and, possibly, an excessive time-to-alarm. In order to resolve this issue, time-to-alarm specifications were studied.

5.4 Time-to-alarm specifications

The time-to-alarm (TTA) specifications in the various international, and US national, radiobeacon DGNSS standards were reviewed. Table 5.1 shows the requirements set by the five governing authorities who set TTA standards: the International Maritime Organisation (IMO); the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA); the International Electrotechnical Commission (IEC); and, in the United States, the United States Coast Guard (USCG) and the US Federal Radionavigation Plan (FRP) [12,15,24,58,68,84]. There are quite a number of significant ambiguities in these statements, and discrepancies between them! These are highlighted in Table 5.1 using colours [88].

The first ambiguity (highlighted in blue) is as follows: IMO A.815 and IALA speak of a warning being "provided to users", and the FRP states that "users will be notified", within the TTA. Does this mean that the user's receiver will *display* a warning within the TTA, as users might reasonably expect?

Or does it mean simply that the reference station will *transmit* a warning, as some administrations appear to believe? The difference is very significant: it is the time the warning takes to pass through the transmission system and for the receiver to respond to it. This delay may be several seconds. Also, its duration depends in part on a latency determined by the SNR, and hence on the beacon selection strategy employed.

The USCG document appears to define TTA in both ways! In the *Definitions* section, the TTA lasts until "the broadcast of the alarm". But in Chapter 4, the TTA lasts until "the user equipment suite/user is alarmed".

Authority	Statement regarding TTA
IMO (A.815)	A warning of system malfunction should be provided to users within 10s.
IMO (A.860)	Time to alarm *is* the time elapsed between the occurrence of a failure in the system and its presentation on the bridge. Time-to-alarm ≤10s
IALA	A warning of system non-availability or discontinuity should be provided to users within 10s.
IEC	While in manual mode and the manually selected station is unhealthy, unmonitored, or signal quality is below threshold, then an alarm shall be activated.
USCG	[*Chapter 4*] (*Time-to-alarm is*) the time from when a protection limit is exceeded to when the user equipment suite/user is alarmed by the broadcast. (It shall be) less than 2s for 200bps transmission rates, 4s for 100bps transmission rates and 8s for 50bps transmission rates. [*Definitions*] Time-to-alarm: The maximum allowable time between the appearance of an error outside the protection limit at the integrity monitor and the broadcast of the alarm.
FRP	Integrity of the Maritime DGPS service operated by the USCG is provided through an integrity monitor at each broadcast site. Each broadcast site is remotely monitored and controlled 24 hours a day from a DGPS control centre. Users will be notified of an out-of-tolerance condition within 6s.

Table 5.1: Time-to-alarm definitions and specifications.
Colours indicate discrepancies and ambiguities.

As far as the IMO is concerned, and also IALA which bases its document on IMO, this ambiguity can be resolved by IMO A.860. This defines the time-to-alarm as "the time elapsed between the occurrence of a failure in the system and its presentation on the bridge" [15].

A second ambiguity (shown here in green) is whether the "system malfunction" in IMO A815 means precisely the same as IALA's "system non-availability or discontinuity", or the IEC's "selected station is unhealthy, unmonitored, or signal quality is below threshold", or the USCG's "protection limit is exceeded", or the FRP's "out of tolerance condition"! To add to the confusion of terms, the IEC employ yet one more statement when dealing with automatic receivers. These multiple ambiguities concern the *causes* of alarms only and so, happily, have no implications for our choice of beacon selection strategy. The resulting confusion could, however, be significant for administrations who operate marine radiobeacons.

A major quantitative discrepancy (shown here in red) concerns the time-to-alarm limit itself. For 100bps transmission, IMO A.815 and A.860, and IALA, all specify 10s. The USCG specify 4s, the FRP 6s, while the IEC give no specification! Clearly, the USCG's 4s, timed from when the protection limit is exceeded to when the user's equipment or the user is alerted, is the most stringent of the alternative TTAs and so demands the highest SNR.

Finally, only the USCG specify a maximum range (300 statute miles) at which a radiobeacon's signals should be used without warning.

The candidate has chosen to interpret these confusing specifications as follows in his analysis. The maximum TTA will be that experienced by the receiver, in accordance with IMO A.860. This is the most conservative assumption – but also the common-sense one! It means that the TTA must include latency delays due to noise and interference. Then, the IMO/IALA 10s TTA requirement will be used when assessing beacon selection strategies and making coverage predictions in Europe. Different values would be required for USCG systems that meet the FRP requirements.

5.5 Beacon selection by the Post-SA *strategy*

A satisfactory post-SA beacon selection strategy should embody these interpretations. A simple *nearest beacon* strategy would not guarantee that the TTA requirement was met. A *quality strategy* would not minimise spatial dilution. So the candidate has proposed a novel "*post-SA strategy*", based on the following principle: *the beacon to be selected is the nearest one that can meet the quality measure required for a 10s TTA [89].*

Happily, there is solid information here on which to decide what minimum SNR is needed to ensure that this TTA criterion is met. Measurements relating the signal word error rate to SNR [14] have established that 7dB minimum *signal-to-noise* will result in latency sufficiently low to give a high probability of successful message reception within 10s.

Indeed, this minimum SNR was included in the specification of beacons originally (in the SA era) precisely in order to achieve the 10s message updates necessary for acceptably-low position errors [68]. Enge *et al*, [90] show how the SNR affects position errors. So our post-SA strategy chooses to retain this minimum SNR.

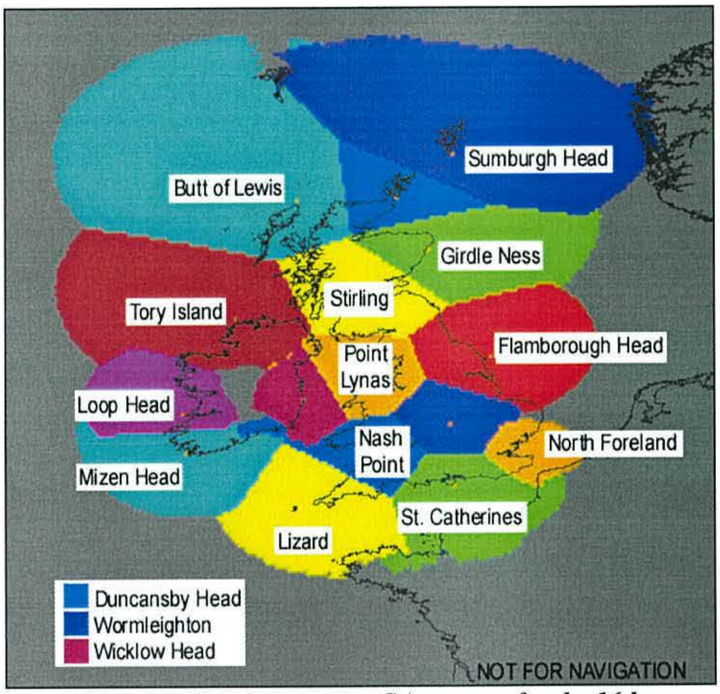

Figure 5.6: Beacon selection using the new post-SA strategy for the 16 beacons of the UK and Ireland, under night-time conditions with interference.

The result of applying this strategy to the 16 British Isles beacons is shown in Fig. 5.6. This figure is again plotted under worst-case conditions: at night, with interference. The results are strongly influenced by the differences of interference levels on the various beacons' channels. For example, the coverage of North Foreland is reduced by skywave interference from a distant station in the Mediterranean region. As a result, St. Catherine's is selected as the best beacon to use when following some of the busiest sea-lanes in the English Channel, even though North Foreland is the nearest beacon. This point is clearly illustrated in Fig. 5.7 in which the yellow areas are those where the *post-SA strategy* and the *nearest beacon* strategy give different results. Within these yellow regions, the nearest beacon should not be used at night since its signal actually fails to meet the time-to-alarm criterion.

5.5.1 Review of Post-SA selection method

Our new post-SA strategy happily turns out to be very similar to one proposed by the IEC recently [68]. However, whereas the IEC take only the signal-to-*atmospheric* noise ratio into account, our strategy ensures that *interferers* also do not exceed the minimum protection ratios. This new selection strategy selects the beacon that provides the greatest accuracy (the nearest), whilst ensuring the time-to-alarm requirements are met.

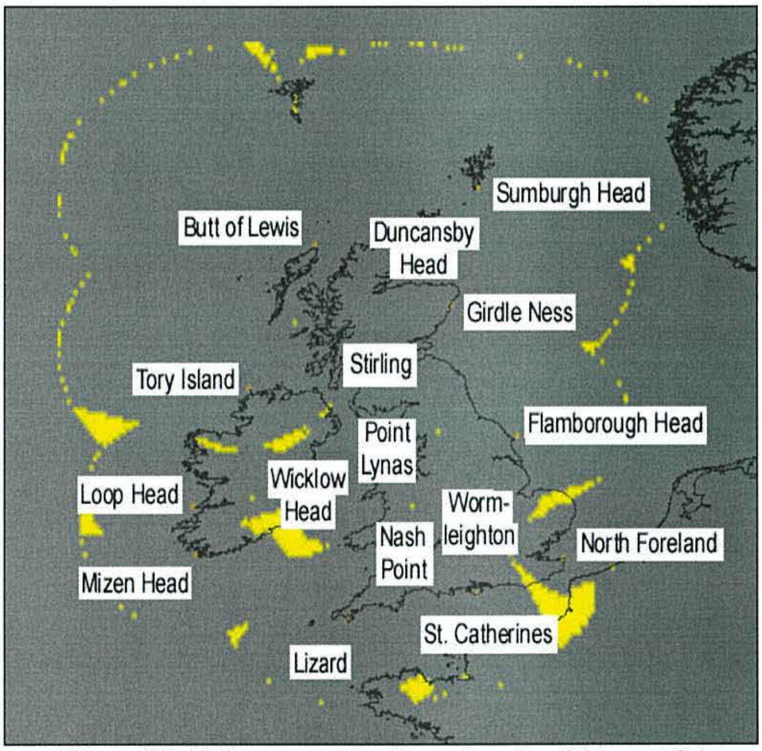

Figure 5.7: Yellow areas identify regions in which post-SA and nearest beacon strategies select different beacons.

5.6 Alternate beacons

Having identified the Best Beacon, the user also needs guidance as to which alternate station to select should that beacon be unavailable because of a scheduled or unscheduled outage. The new software also allows us to provide that guidance. The same process as for choosing the Best Beacon is employed. But this time the second-best beacon, not the best, is identified. The *alternate beacon* results generated using the new *post-SA* strategy are presented in Fig. 5.8.

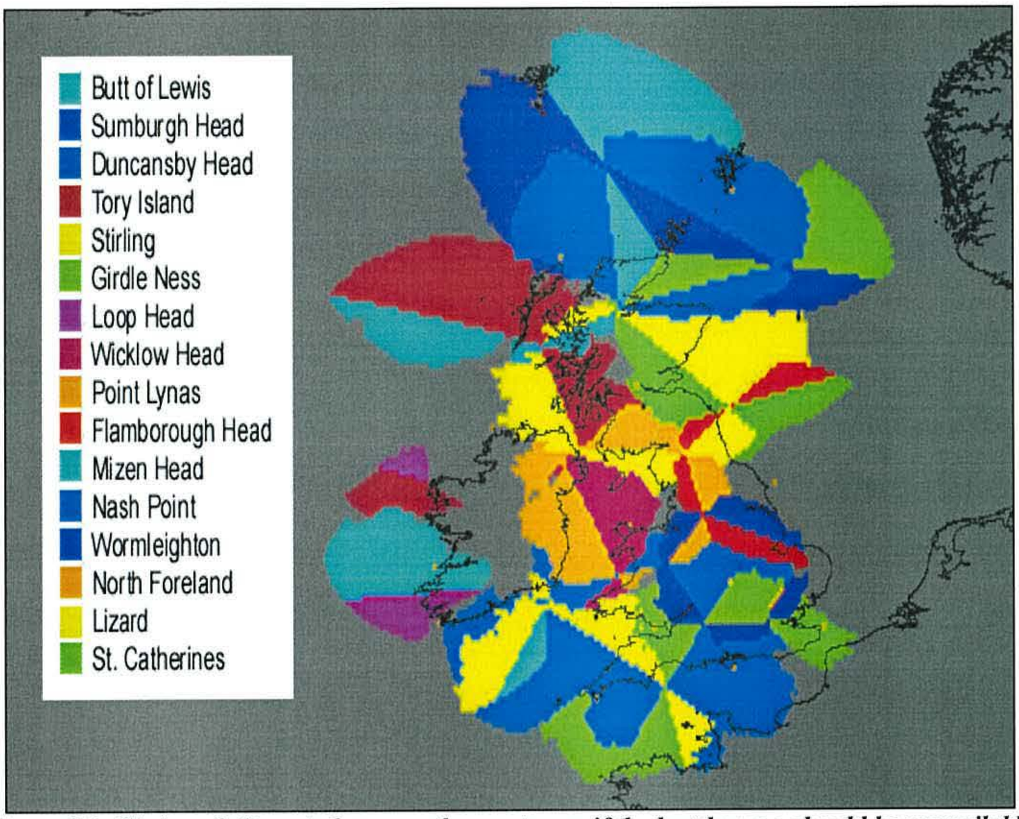

Figure 5.8: Choice of alternate beacon - the one to use if the best beacon should be unavailable. The post-SA strategy has been employed.

The maps shown in Figs. 5.3, 5.4, 5.6, 5.8 and 5.10 are in a format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. To allow "automatic" receivers to employ the same information, the data is also produced in a tabular form that manufacturers can store within their receivers. Table 5.2 shows part of this data set: at each location, specified by latitude and longitude, the Best Beacon (here termed the "Primary") is computed using the *post-SA strategy* and listed. The alternate is also listed, as "Secondary".

60 -	NASH_POINT		
61 -	WICKLOW_HEAD		
62 -	POINT_LYNAS		
	:		
Lat: 53.2	Lon -4.1	Primary- 62	Secondary- 61
Lat: 53.2	Lon -4.0	Primary- 62	Secondary- 61
Lat: 53.2	Lon -3.9	Primary- 62	Secondary- 61
Lat: 53.2	Lon -3.8	Primary- 62	Secondary- 61
Lat: 53.2	Lon -3.7	Primary- 62	Secondary- 61

Table 5.2: Part of a tabulated data set for beacon selection, employing the post-SA strategy.

5.7 Beacon selection across the EMA

The Best Beacon studies have so far focussed on the small set of 16 beacons installed in the British Isles. Now the software can be used to compute the result of applying the new *post-SA strategy* across the entire European Maritime Area (30-72°N, 30°W-55°E). Fig. 5.9 shows the daytime results: for the first time the combined coverage of all 161 differential GNSS radiobeacons across the EMA is shown, also identifying point-by-point the radiobeacon with the lowest spatial dilution whose signal meets the time-to-alarm criterion; the Best Beacon.

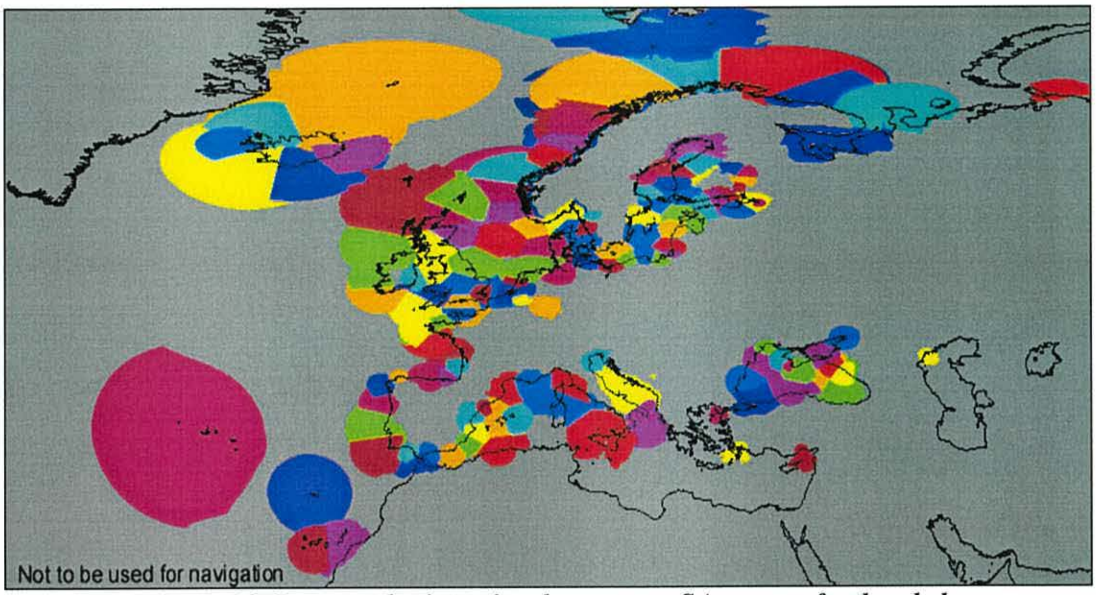

Figure 5.9: Beacon selection using the new post-SA strategy for the whole European Maritime Area (daytime, with interference).

5.8 Redundancy

An important part of this study and a necessary staging post in the availability calculations (see Chapter 7) is to employ the new software to calculate the number of beacons that simultaneously provide coverage at each location. Figures 5.10 and 5.11 show the results for day and night respectively: orange identifies locations covered by a single beacon, yellow dual coverage, and so on as indicated in the legend.

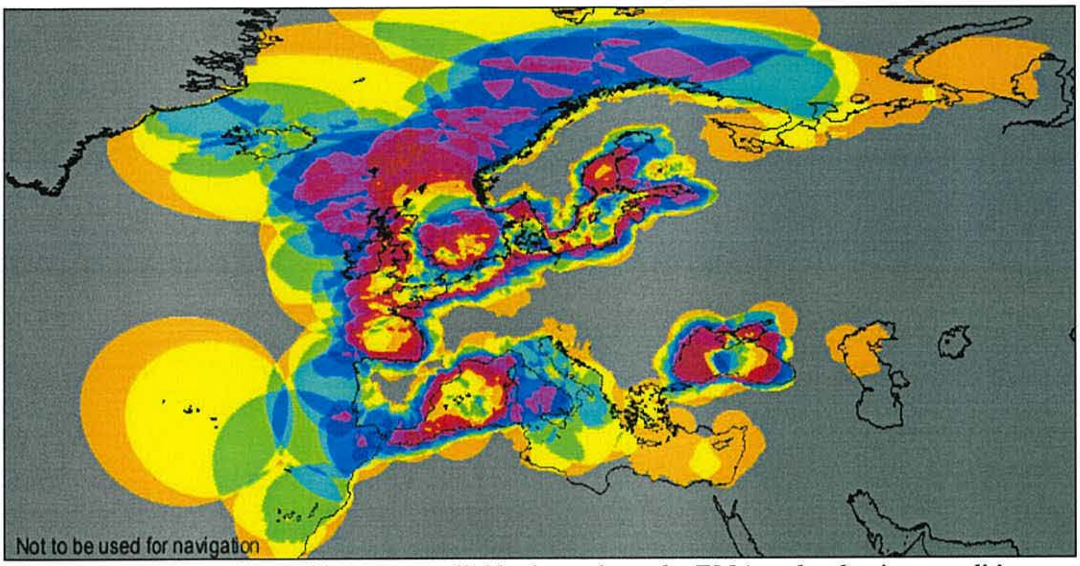

Figure 5.10: Numbers of beacons available throughout the EMA under daytime conditions. Orange = 1, Yellow = 2, Green =3, L. Blue = 4, Blue = 5, Dark blue = 6, Purple =7, Magenta =8, Dark red =9, Light red = 10. In areas where more than 10 beacons provide simultaneous coverage, the colours are re-cycled, so Orange =11.

By day, parts of the North Sea, the Mediterranean and the Atlantic (just off the French coast), have multiple overlapping coverage and repeat colours. The number of beacons providing simultaneous coverage varies greatly from place to place and by day and night. Naturally, there is only a single beacon along the coverage boundaries. The maximum number of beacons providing simultaneous coverage is 23 beacons by day, in the North Sea!

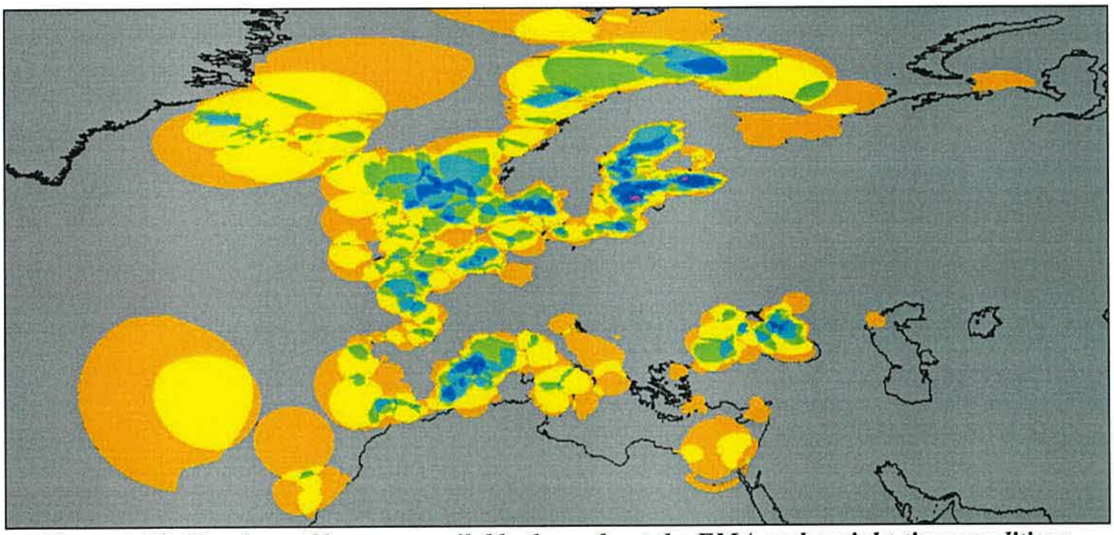

Figure 5.11: Numbers of beacons available throughout the EMA under night-time conditions. Orange = 1, Yellow = 2, Green =3, L. Blue = 4, Blue = 5, Dark blue = 6, Purple =7, Magenta =8, Dark red =9, Light red = 10.

5.9 Conclusions

Our new software architecture has allowed us to model and compare beacon selection methods. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a *quality strategy* has been proposed and studied in which the Best Beacon is deemed to be the one with the highest ratio of signal-to-atmospheric noise, or interference.

With the ending of SA, however, the constraints on beacon selection have changed dramatically. A new strategy has accordingly been proposed in which the Best Beacon is the nearest one, with the least spatial dilution, whose signal quality meets the time-to-alarm requirements. The candidate has revealed, and here discusses, the unfortunate multiple ambiguities in the TTA specifications of different international and national bodies. He has then made his own interpretation of the requirement: the user must be made aware of a fault within 10s of its occurring. Happily the new post-SA strategy turns out to be similar to one being considered by the IEC, although an important difference between the two is identified.

The results are presented in a pictorial form designed to be convenient for users who are obliged to enter the choice of beacon into their receivers manually. The results for both the British Isles and the whole European Maritime Area have been produced. An example is also presented of the data in a tabular form that can be built into receivers at the time of manufacture. Both forms of presentation indicate not only the choice of Best Beacon, but also the alternate to be employed when the best station is unavailable.

Moreover, in this chapter the power and flexibility of the new software architecture has been demonstrated. Having completed our analysis of beacon selection, Chapter 6 returns to the subject of availability.

Chapter 6

Availability

6.1 Introduction

As shown in Chapter 4, availability is defined as the percentage of time that a signal at a location is usable. Being "usable" means meeting minimum criteria for coverage set out by the ITU [61]. As with coverage, the ITU stipulate a minimum availability requirement. Other national and international bodies have their own standards, which often conflict, as shown in Chapter 7. This chapter examines methods of calculating availability and the different factors involved.

6.2 Current methods of calculating availability

Chapter 4 showed that a reference station's service availability is a function of the beacon's broadcast availability and the availability of the resulting signal-in-space. Then, at locations where multiple beacons provide coverage, the service availability is a function of the availabilities of each individual beacon.

In order to model this situation, a methodology that will enable both the individual beacon's availability and the service availability to be calculated at each location is needed. Three current methods are examined, each with its own methodology, and evaluated on the basis of its suitability for modelling the radiobeacon DGNSS service.

6.2.1 Probabilities

In 1999 Specht *et al [19],* from the Polish Naval Academy, studied the availability of the DGPS radiobeacon signal using an analytical method.

His study took into account fix accuracy, reliability of each component, signal transmission, integrity, fix rate and message type. His approach was to model the service analytically, starting with the classic availability calculation:

$$Availability = \frac{MTBF}{MTBF + MTTR}, \tag{6.1}$$

where MTBF is the *Mean Time between Failures* and MTTR, the *Mean Time to Repair*. Then, Specht derives A_{DGPS}, the availability of the differential GPS service from A_{GPS}, the availability of GPS itself and A_{LDAS}, the availability of the Local Differential Augmentation GPS Service (*LDAS*):

$$A_{DGPS} = A_{GPS} \cap A_{LDAS}, \tag{6.2}$$

where the symbol "$\cap$" represents a logical AND function, since both must be available. He then splits the availabilities A_{GPS} and A_{LDAS} into their constituent components (Fig. 6.1).

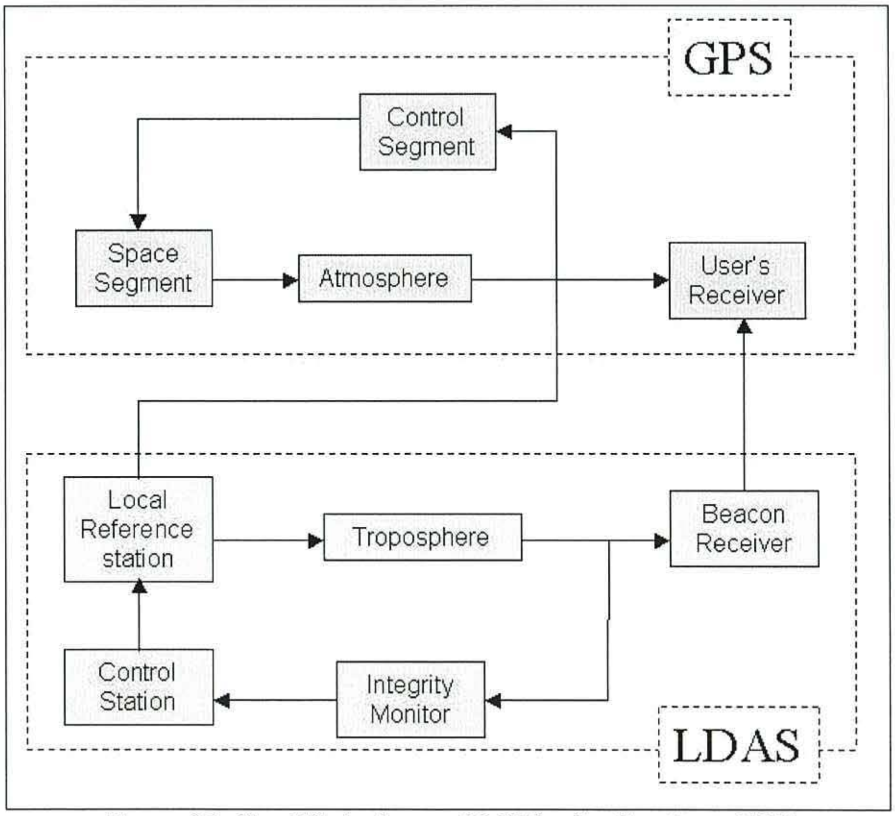

Figure 6.1: Simplified scheme of DGPS, after Specht et al [19]

Specht, having defined this structure for calculating the availability of differential GPS as a whole, focuses on the availability of the transmissions at the DGPS reference station as the key element. In doing so, he considers messages of both Type 1 and Type 9-3; in this review of his work, only Type 9-3 messages are considered as there are consistently used throughout the EMA.

The basis of Specht's analysis is to calculate the probability that two RTCM messages are correctly transmitted to the user's receiver during a specified time period. Whilst no explanation for this is given, the candidate believes two RTCM messages are defined because four different PRCs are required in order to calculate a 3D position and two different RTCM type 9-3 messages are required to provide these corrections. As a Type 9-3 message is of fixed length, the probability of correct reception is identical for each set of three satellites, using:

$$Pd = (1 - BER)^{L_{9-3}}, \tag{6.3}$$

where, Pd is the probability of a correct reception, L_{9-3} is the message length in bits and BER is the bit error rate. Specht then calculates the number of messages that are transmitted in a specified period of time, using:

$$n = \frac{T_{\max} \cdot R}{2 \cdot L_{9-3}}, \tag{6.4}$$

where T_{max} is the length of time interval, R is the baud rate and L_{9-3} is the message length in bits.

Specht applies a criterion that at least one of the two RTCM messages should be received correctly within the time period T_{max}. Specht states that the probability of this occurring is given by:

$$q_s = q_d^{\,n}\left[\sum_{k=0}^{n}\binom{n}{k} p_d^{\,k} q_d^{\,n-k}\right] + q_d^{\,n}\left[\sum_{k=1}^{n}\binom{n}{k} p_d^{\,k} q_d^{\,n-k}\right]. \tag{6.5}$$

The candidate interprets the terms in this equation as follows: q_s is the probability of failure to receive either message; q_d is probability of missing one set of messages; p_d is the probability of a correct transmission; and n is the number of messages transmitted in the specified time period. Specht then simplifies this to:

$$q_s = 2q_d^{\,n} - q_d^{\,2n}. \tag{6.6}$$

In this way, Specht calculates the availability of two successive DGPS transmissions. His result, in Fig. 6.2, shows the availability of receiving two successive DGPS transmissions, expressed as a fraction, as a function of bit error rate (BER). The figure includes a comparison between Type 1 and Type 9-3 messages. It shows that Type 9-3 messages give a greater availability than Type 1 messages over a wide range of BER values. This conclusion agrees with the results of previous work done by Enge *et al* [90].

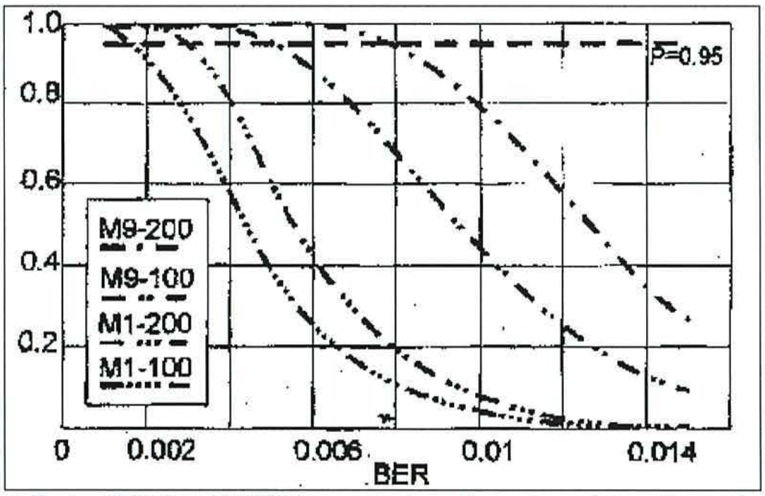

Figure 6.2: Availability of DGPS transmissions for various data rates and message Types, after Specht et al [19]. Curve M9-100: Type 9-3 messages at 100bps.

6.2.1.1 Review of Specht's work

This work by Specht *et al* allows them to estimate the availability of a DGNSS transmission. However, Specht's definition of "availability" differs significantly from our "service availability". Specht *et al* start by identifying the radiobeacon differential service including the reference station, integrity monitor, GPS control stations and the user's receiver.

The research presented in this thesis, in contrast, the availability of the differential service is considered (Chapter 4.2); for that reason the user's receiver is excluded. Specht investigates the entire DGPS service (A_{DGPS} in Equ. 6.2) and then proceeds to calculate the availability of DGPS transmissions, taking into account message types and bit error rates.

His approach only refers to the reception of the RTCM message; it does not include the availability of the reference station. It also takes into account the reception of two sequential messages with corrections for different sets of satellites. The reason for this specific requirement is unclear, a possible reason for considering two sets of corrections is that four PRCs are required for a 3D position fix, which would provide the greatest positional accuracy and would require two different type 9 messages to be received. This method does not take correction messages received from multiple beacons into account.

To conclude, Specht *et al's* approach is suitable for comparing the probability of receiving DGPS transmissions of different message types and baud rates. However, this method is not best suited for the service that the candidate has set out to model. The technique set out by Specht *et al*, would soon become extremely complicated when modelling corrections received by multiple stations, as this method would require knowledge of which message contained corrections to which satellite. Therefore, an alternative approach was required.

6.2.2 Markov Analysis

The Analytical Sciences Corporation (TASC) have developed a set of availability standards used by the USCG in connection with navigation systems that include radiobeacon DGPS [20,91,92]. TASC analysed requirements for harbour entrance and approach navigation, considering several systems and analysing the availability of a navigation service employing these systems, with and without backup systems.

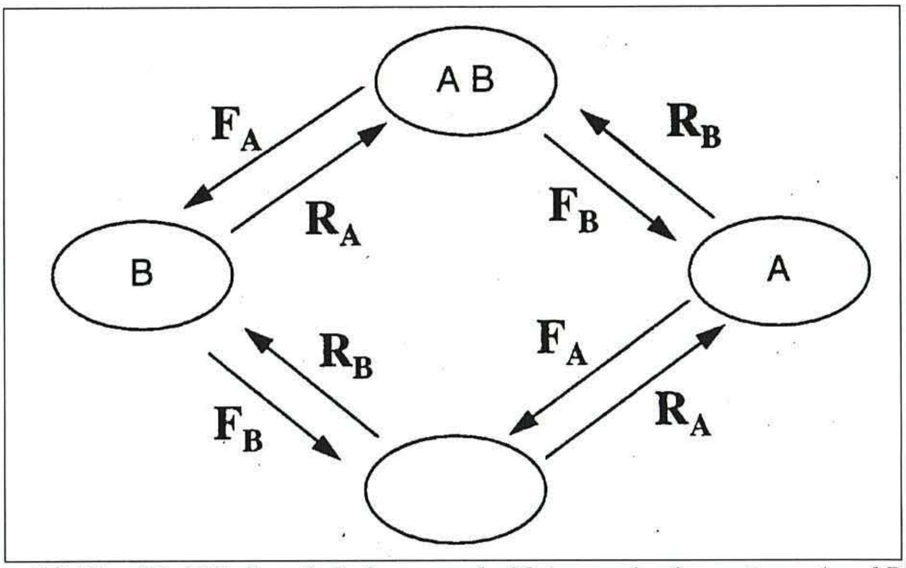

Figure 6.3: Simplified Markov chain for a vessel with two navigation systems, A and B. [20]

The methodology TASC employed was the Markov analysis, through the use of a Markov Chain and Markov Process. These methods are basically the same and work by splitting a system into a number of states. Consider; by way of example, the simplified Markov chain shown in Fig. 6.3. Here a vessel has two pieces of navigational equipment, A and B. State 1 (top centre) is defined as "both navigation operational". In the other states, either A has failed and only B is operational, or *vice versa*, or both pieces of equipment have failed. The transition lines marked with 'F' or 'R' are the *failure* and *recovery* rates. These rates are calculated using equations 6.7 and 6.8, in which '*i*' is the item in question, ie A or B:

$$F_i = \frac{1}{MTBF_i} \tag{6.7}$$

$$R_i = \frac{1}{MTTR_i} \tag{6.8}$$

A Markov chain like this is typically used to estimate the chance of an incident's occurring in a static system; in Fig. 6.4, an incident is represented as a further state, linked to the rest of the chain by transition lines with associated incident transition rates, I_i. In this example it is assumed that, once the incident has occurred, there is insufficient time to recover, and vessel operation is finished. Thus, there are no figures for rates of recovery from incidents.

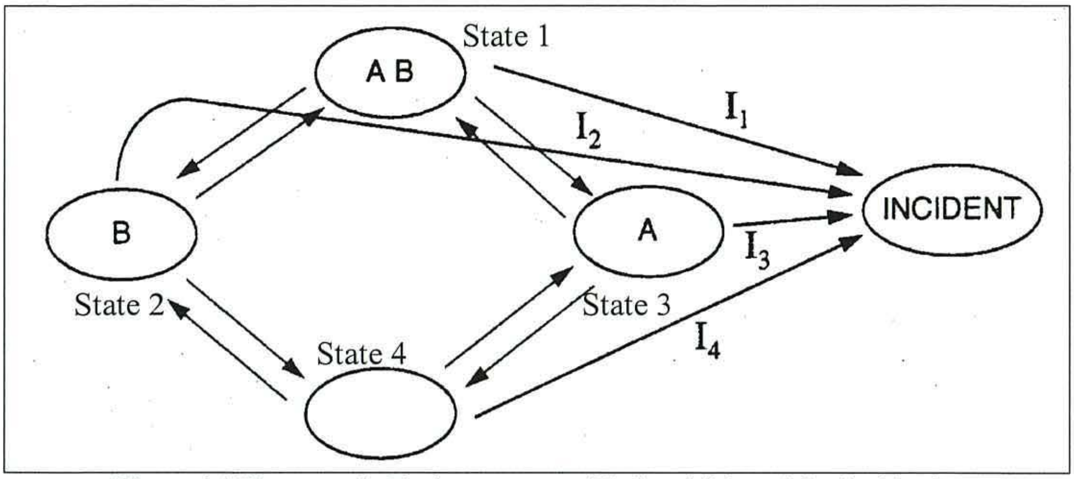

Figure 6.4 The example Markov process, with the addition of the 'incident' state and transition lines.

TASC evaluate the system at discrete time intervals as in most situations the channel width will vary with time as the vessel operates a given route, and the probability of failure changes. This is approximated by using the following equation to evaluate the model at discrete time intervals (Δt):

$$P(t+\Delta t) = P(t)e^{\Lambda(t)\Delta t}\,. \tag{6.9}$$

Where, $P(t+\Delta t)$ is the initial probability at each discrete time interval and is set to the last calculated probability vector $P(t)$ and the transition matrix is:

$$\Lambda = \begin{bmatrix} \lambda_{11} & F_A & F_B & 0 & I_1 \\ R_A & \lambda_{22} & 0 & F_B & I_2 \\ R_B & 0 & \lambda_{33} & F_A & I_3 \\ 0 & R_B & R_A & \lambda_{44} & I_4 \\ 0 & 0 & 0 & 0 & \lambda_{55} \end{bmatrix} \tag{6.10}$$

The entries in this matrix refer to the probability of being in each state. For example, the probability of being in state 1 and moving back to the same state corresponds to the λ_{11} element. The probability of being in state 2 (system A has failed and only system B is available) is given by F_A. Once this matrix has been filled, the probability of a failure can be calculated.

TASC built up the complex Markov process in Fig. 6.5, which represents several navigation systems aboard a test vessel. Differential GPS is the primary navigation source, radar the primary backup, and stand-alone GPS as the third option. The states in the figure represent all possible combinations of failures. Each of the F_{XX} transitions, representing the transitions between states, is assigned a probability equivalent to the appropriate probability of failure or of repair of the item in question. I_{XX} items are 'incident' rates; for example, I_{DGPS} is the probability of the vessel failing to remain within the channel of water within which it should be sailing once DGPS has failed.

State 1, with all systems operational, is assumed as the starting state. From there, the state may change to any state from State 2 to State 5. By proceeding through the network, TASC estimate the probability of being in any other state. The changes of states depict the order in which items fail and the consequences of their failing in a particular order.

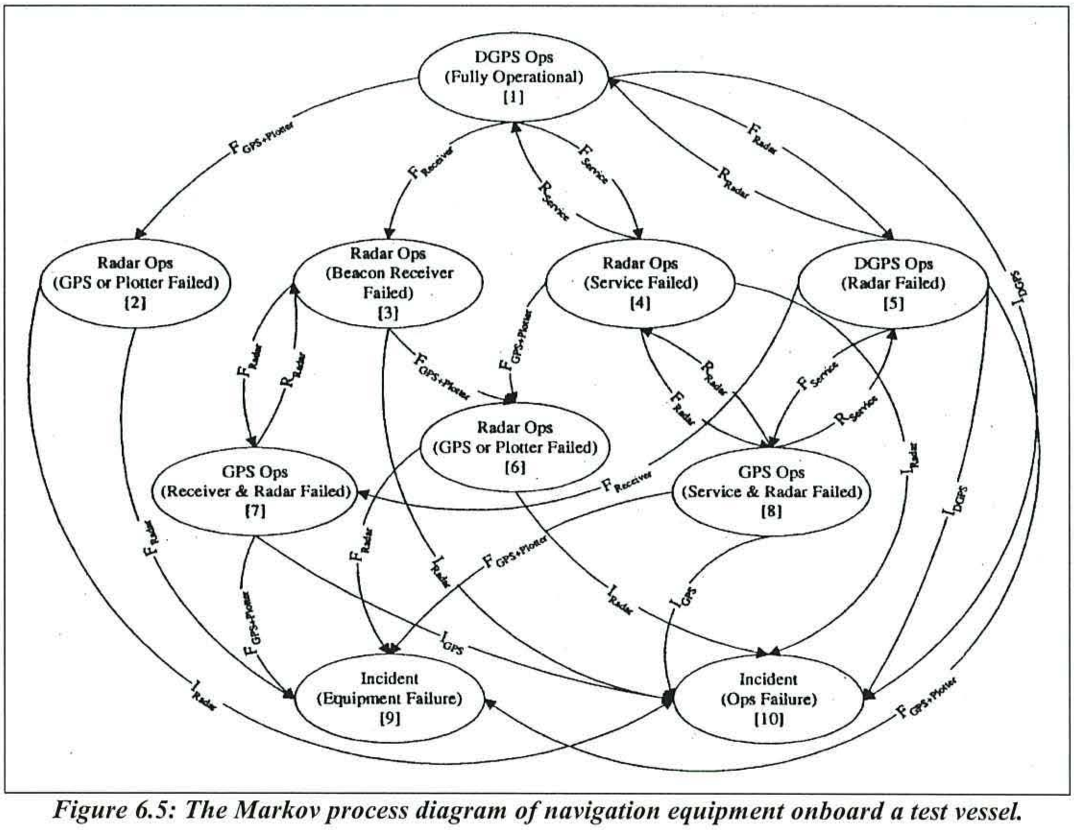

Figure 6.5: The Markov process diagram of navigation equipment onboard a test vessel.

This equation proposes that for each discrete time interval being considered, the initial probability of failure continues on from the previous time interval considered.

Based on results calculated for several ports in the United States using this Markov method, TASC developed sets of guidelines for the USCG, one to be applied in *typical* harbours and approach waterways and the other in *challenging* ones. It is evident that the Markov Chain is a powerful method of calculating availability, especially when the order of failures is important or if there is a time domain on which to model the availability.

6.2.2.1 Review of Markov analysis.

The benefit of a Markov analysis is that it lets one estimate the probability of each possible state of a complex system arising. It can be employed in both static and time-dependent analyses. From static analysis, a single availability figure may be calculated. Time-dependent analysis, run for a sufficiently long period, gives availability figures for each of the possible states.

The service availability we are exploring, computed over a sufficient period, will not be time-dependent. So a time-dependent Markov chain analysis would not be appropriate. A static Markov chain analysis is very complex and is most suitable for much more complex systems than ours. Also, it is best at dealing with the order in which failures occur, a feature not required in our model.

In summary, Markov Chain analysis is a powerful technique for modelling complex systems where the order of events is significant. But we wish to analyse a relatively simple (though demanding) system that does not depend on the sequence of failures. A different approach is required.

6.2.3 Fault tree analysis

Another widely-used method of calculating availabilities in systems with multiple failure mechanisms is Fault Tree Analysis (FTA).

An FTA represents the logical structure of a set of events whose individual failures can result in the failure of a system. It presents a diagrammatic view of the system being modelled. Producing a fault tree forms a relatively simple introduction to a complex system. It enables the user to identify key areas of weakness and see where they lie within the larger picture [93].

As an example, Fig. 6.6 represents failure modes of an electrical circuit [94]. The main event, an overheated wire, is at the top of the diagram. Below are the various circumstances that could cause this wire to overheat: for example, a fuse being unable to open (G1), or a shorted motor (G2). Three such possible causes are inter-related by an OR function. Each of these three blocks is then broken down into causes. For example, G1 can be due to causes B1 or B2. Once the entire fault tree has been mapped out in this way, a probability of occurrence is assigned to each possible cause, as in Markov analysis. That done, the probability of the wire overheating can be calculated, working upwards from the bottom of the fault tree.

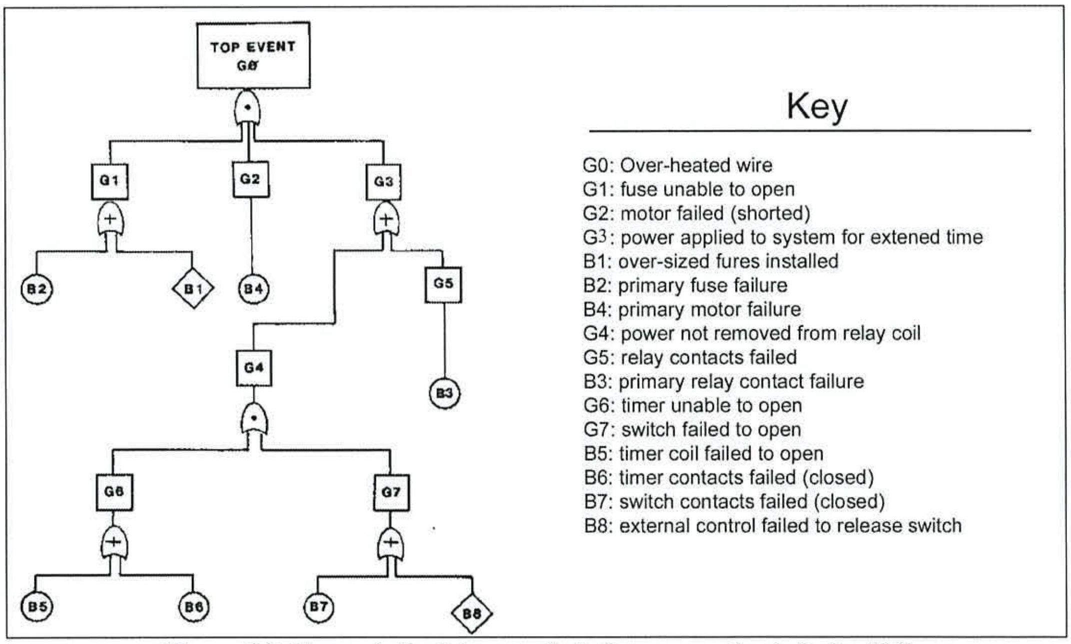

Figure 6.6: Example fault tree analysis for an over-heated wire [94].

Expressing this probability mathematically [94]:

$$P(wire\,overheating) = \prod_{i=1}^{N}(1-U_i)\,, \tag{6.11}$$

where U_i is the probability of each event i occurring, N is the number of events on that level, and Π is the product function.

That is, the probability of the wire overheating is the product of the probability of these individual events occurring. An important implied assumption here is that the various failure events are independent and not correlated.

Fault tree analysis is a simple but effective approach, which allows a complex system to be modelled and potentially difficult areas highlighted. However, unlike a Markov chain, it cannot model failures that are sequential in time, or model a system at discrete time intervals [93].

6.2.3.1 Review of Fault tree analysis

Fault tree analysis seems an ideal way of modelling a system, like ours, that doesn't use sequential events or require discrete time intervals and where failures can be due to multiple causes. By breaking our system down into components, unexpected complications can be identified. Using an FTA would require all the separate events which can cause non-availability to be established, together with their individual probabilities.

6.3 Conclusions on choice of method

From these three different methods, the most suitable for our needs is the fault tree analysis. Specht's probabilities method, although suitable for calculating the service availability of a single beacon, was rejected since his derivation is so unclear and because one needs to consider the effects of multiple beacons. Markov chain analysis is too complex for our needs and its ability to model sequential failures or time dependencies is not required.

The FTA is a clear, concise, and simple to use method. A further benefit is that it focuses our attention on the need to ensure that the events that cause non-availability are independent and non-correlated – something that would need to be done whatever model was used. The FTA was chosen as the method to be used and will form the structure for our new availability software model.

6.4 Events to be included in the FTA

Chapter 4.2 and Section 6.2.1 identified many of the multiple factors that can lead to loss of availability of the radiobeacon DGNSS service. The inter-relationships between these factors and the entire radiobeacon service will now be represented using the FTA convention (Fig. 6.7). This diagram illustrates the complexity of the problem. However, it is poorly matched to the information actually available to us. For example, service providers monitor their reference stations and transmitters continuously. As a result, they have reliable data on MTBF and MTTR values, which we could use. Thus, it is unnecessary for us to break down station failures into their detailed causes. We can concentrate on the reference station and the environmental factors that affect the availability of the signal-in-space, that is, on the factors that determine the service availability of the radiobeacon differential service.

Further, since availability will only be modelled within the *coverage* region of a beacon, all of the individual factors that can affect availability have already been examined in predicting *coverage*. These factors can be split into two distinct, groups: deterministic and stochastic.

6.4.1 Deterministic events

"A deterministic process is defined to be a process whose future can be predicted perfectly from its past"[95]. For example, groundwave propagation is deterministic; once the field strength at a point has been calculated (eg using Fig. 3.2), it does not alter. In fact, all relevant deterministic events have been taken fully into account in the course of predicting coverage.

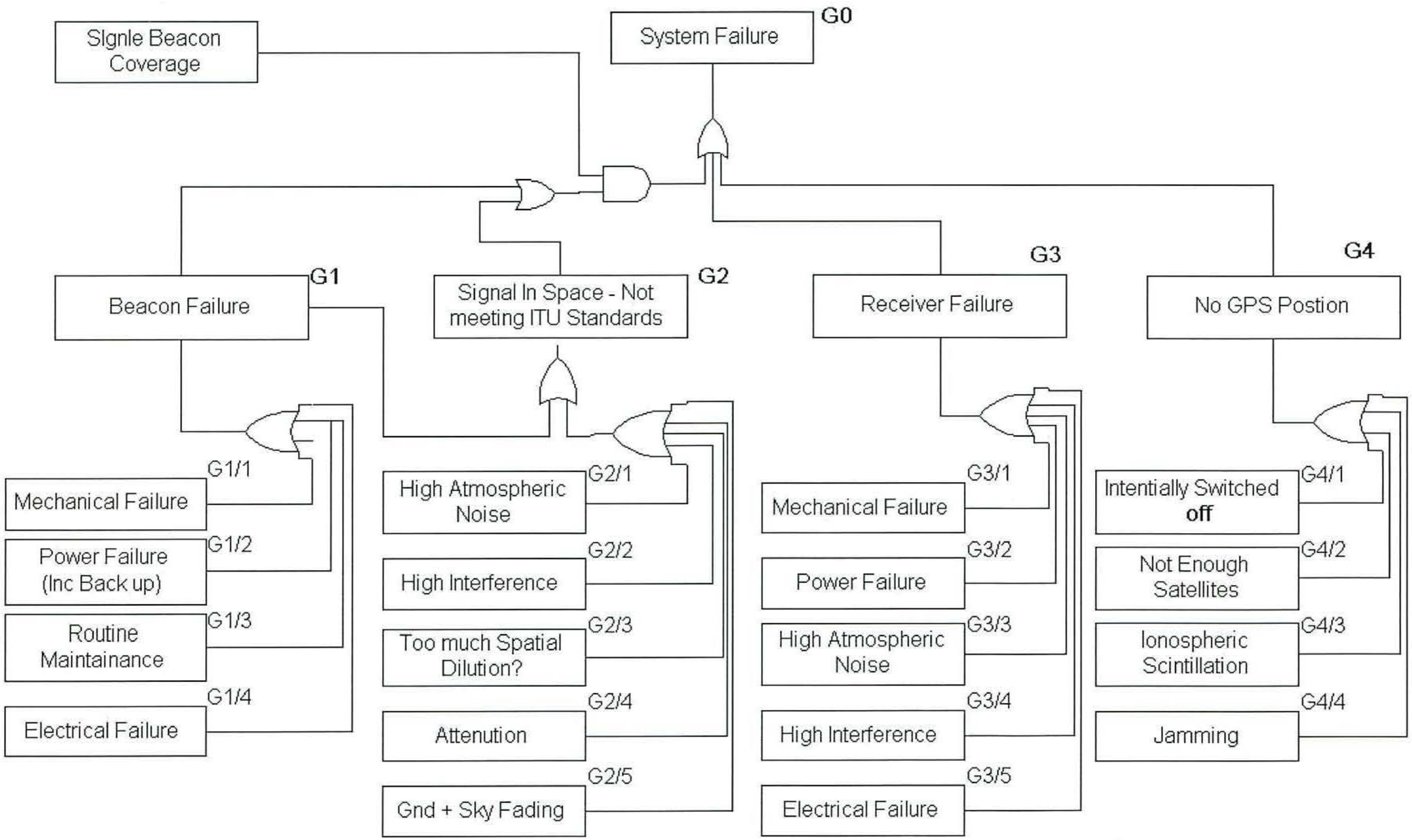

Figure 6.7: First level fault tree for the radiobeacon DGPS service

6.4.2 Stochastic events

Stochastic factors vary with time, in a random way. (The term *stochastic variable* is an alternative term for a *random variable.* The word *Stochastic* derives from a Greek word meaning to 'guess at' [95]). An example of a stochastic variable is atmospheric noise [78]. Since, at any location and time, the level of this noise in the short term is determined by many independent spikes, occurring randomly over a large area, the level of atmospheric noise is stochastic (Fig. 6.8).

Stochastic events such as this require the use of statistical methods. In the example of atmospheric noise, the very large amounts of data that have been analysed by ITU - covering all times and seasons and many locations - enable field strength to be predicted. The results are expressed as mean values supported by probability distributions. Thus, one can say with confidence what level of noise should not be exceeded for a given percentage of the time and what is the probability of failure due to the SNR falling below a given threshold.

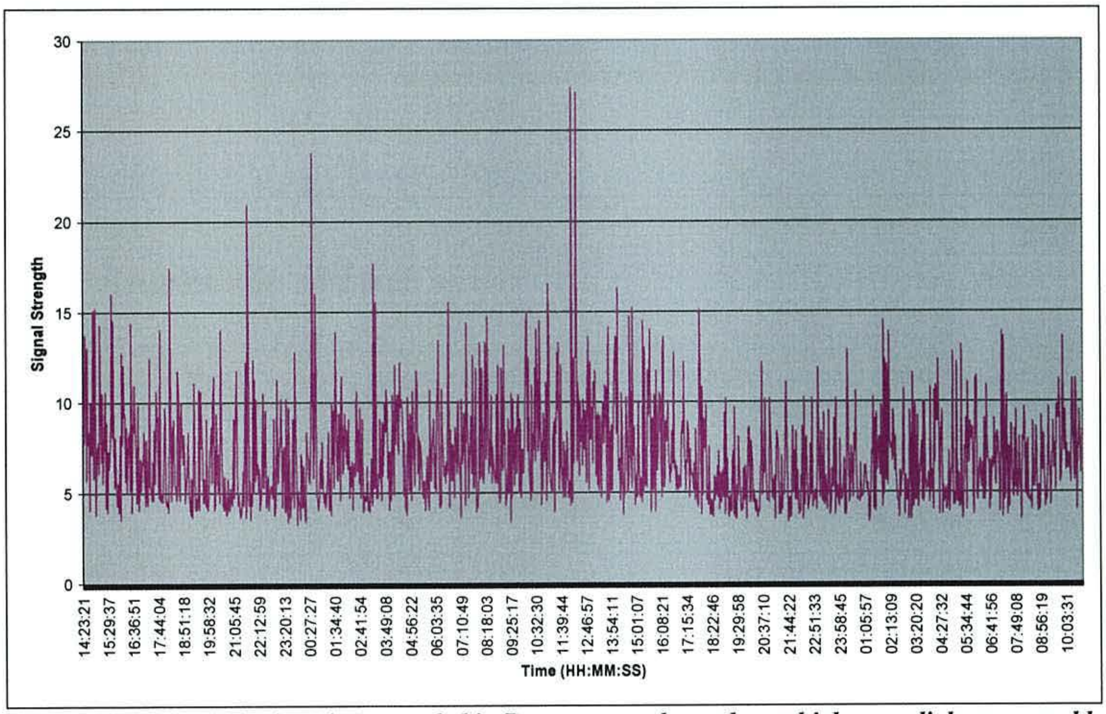

Figure 6.8: Atmospheric noise, recorded in Bangor on a channel on which no radiobeacon could be received. The random spikes range in amplitude from below 5 dBµV/m to 27dBµV/m.

The result of removing all unnecessary events, including the deterministic ones, from the FTA is greatly to simplify the diagram (Fig. 6.9). Only the stochastic signal factors and the beacon's availability remain.

By day, when there is no significant skywave propagation, it is simplified even further, shrinking to include simply the effects of beacon failure and atmospheric noise.

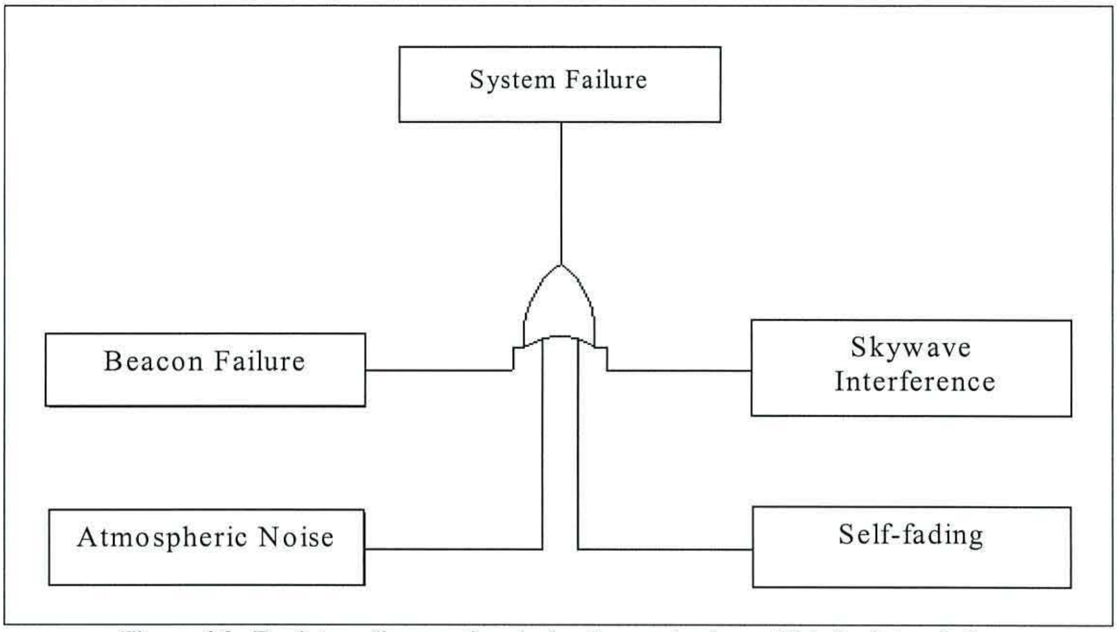

Figure 6.8: Fault tree diagram for stochastic events alone. This fault tree is for night-time conditions; by day there is no skywave propagation, so only beacon failure and atmospheric noise remain.

6.5 Development of the FTA

When first considering the use of an FTA, it was envisaged that the availability calculations would be carried out by using a commercial FTA software package. The *Fault Tree Plus* commercial software [96] was obtained and the full fault tree of Fig. 6.7 entered into it. As the fault tree was progressively simplified, the commercial software was still employed. Eventually, it became obvious that the same calculations could simply be written into the software of the model used to determined availability.

The availability analysis contains two parts: one analyses the availability of a single radiobeacon plus its signal-in-space; the other analyses the service availability provided by multiple beacons that provide signals simultaneously.

6.5.1 A single beacon

For a first attempt at modelling availability, the conditions that are found at the edge of coverage were applied to every location within coverage. That is, the 95%-ile values employed to establish coverage were used. Availability calculations were then carried out, first using the commercial software, then using code intended for use in the new availability model. Comparing the results allowed the new software to be verified. First, the availability of the signal-in-space from a single reference station was calculated [94,97]:

$$\textit{Single station availability} = \prod_{i=1}^{N}(1-U_i), \tag{6.12}$$

where N is the number of events being processed (2 events by day, or 4 by night) and U_i is the probability of each event's causing non-availability of the service. An "event" in this context means either a reference station failure or excessive atmospheric noise (the daytime pair), or excessive self-fading or skywave-borne interference (the additional night-time factors).

Table 6.1 shows the individual probabilities of the four events used in calculating the availability of the signal-in-space from a single beacon under day and night conditions. These are the edge-of-coverage, or coverage predicting, values. The beacon availability figure is 0.005, a value taken from the IALA guidelines [16]. The other three variables are each assigned the value of 0.05, which corresponds directly to the 95% probabilities of self-fading, atmospheric noise and skywave interference used in predicting coverage.

The resulting availability values, computed using the figures in Table 6.1, are shown in Table 6.2.

	Beacon	Atmospheric noise	Skywave interference	Self-fading
Prob. of occurrence	0.005	0.05	0.05	0.05
Day	0.005	0.05		
Night	0.005	0.05	0.05	0.05

Table 6.1: Probabilities of occurrence of individual stochastic events that can cause loss of service. These are edge-of-coverage values. Note difference between day and night conditions. A blank field in this table means "not applicable".

	Availability	
	New software	Commercial software
Day	0.9453 (94.5%)	0.9451 (94.5%)
Night	0.8531 (85.3%)	0.8530 (85.3%)

Table 6.2: Availabilities calculated using new software, and commercial software. These figures are for the signal-in-space from a single beacon, using the edge-of-coverage probabilities in Table 6.1.

The results from the new software match those from the commercial software very closely indeed, confirming that the new code is operating correctly.

6.5.2 Availability with multiple beacons

Now the calculation is expanded to estimate the availability of the DGNSS service at a point that lies within the service areas of a number of beacons (Chapter 5 showed that this is very frequently the case):

$$Availability = 1 - \prod_{i=1}^{N}(1 - Q_i), \tag{6.13}$$

where N is the number of signals that can be received simultaneously, and Q_i is the availability of each individual signal-in-space, *i*. This calculation assumes that the availability of each individual beacon's signal is the corresponding single-beacon figure from Table 6.2.

	New software		Commercial software	
No. of beacons	Day	Night	Day	Night
1	0.94525	0.85309	0.94525	0.85309
2	0.99700	0.97842	0.99696	0.97618
3	0.99984	0.99683	0.99983	0.99627
4	0.99999	0.99953	0.99999	0.99942

Table 6.3: Availability of service from a single beacon and from multiple beacons.

The results (Table 6.3) show that the service availability increases rapidly with the number of beacons, as would be expected. Again, the commercial software verified the results computed by the new software. That done, the commercial software was deemed to be needed no longer; since it had only been hired, it was returned!

6.6 Correlation of stochastic events

Equations 6.12 and 6.13 are only valid if the events that cause non-availability are independent of each other, i.e. non-correlated. The results would be incorrect if the factor that caused the signal from one beacon to fail applied simultaneously to the other beacons, since they could no longer be used as fall-backs for each other. At first sight, one would expect this to be the case: if, for example, a mariner should lose the service from a beacon due to a rise in atmospheric noise, that increase might very well affect all signals available to him. A measurement programme was set up to investigate whether this was indeed the case.

Three factors are examined: the correlation coefficients associated with atmospheric noise, skywave interference and self-fading. Beacon availability was excluded, since no known mechanisms have been observed that cause the simultaneous failures of beacons, separated as they are by many tens or hundreds of kilometres. Also, scheduled maintenance of beacons is invariably timed to ensure that adjacent beacons are not off-the-air simultaneously.

The first factor investigated was atmospheric noise. The question was: what is the correlation between the noise on two frequencies (the back-up beacon would inevitably be on a different frequency from the one it was supporting). A spectrum analyser was set up connected to a PC (Fig. 6.10).

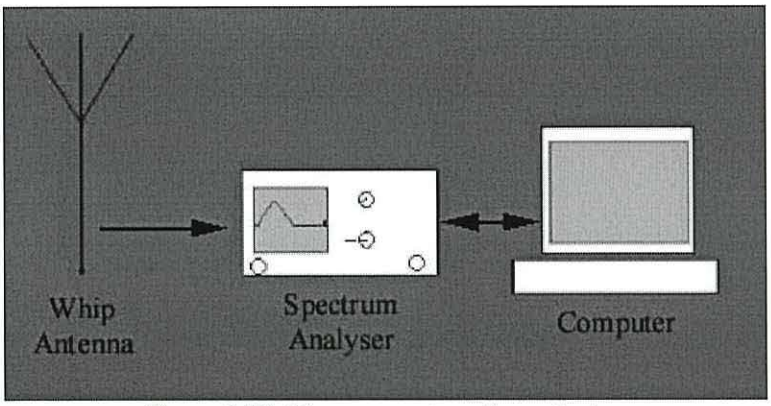

Figure 6.10: Measurement equipment set-up

The PC would switch the analyser to a frequency and record the field strength it measured there. By switching back and forth rapidly between two frequencies over a sufficient period, the degree of correlation could be estimated.

The frequency channels used were carefully selected so that they were sufficiently separated in frequency to show the effects across the band, and were also clear of any signals with field strengths sufficient to prevent the level of atmospheric noise being measured (Table 6.4). The spectrum analyser was carefully calibrated before the experiment, using a precision loop antenna to establish a calibration factor that would allow field strength values (in dBμV/m) to be computed from the signal level values at the analyser's input (in dBμV).

The second factor was self-fading. Again the question was: what is the correlation of a reduction in the field strength of two beacons experiencing self-fading on different frequencies (as before the back-up beacon will inevitably be on a different frequency from the first). In other words, if our primary beacon is lost in self-fading, should we expect the backup beacon to be lost, too. The same hardware and experimental process were used as for the atmospheric noise measurements. Again the frequency channels employed (Table 6.4) were carefully chosen to ensure that only beacons at suitable ranges from the measurement site were used. In this way a substantial degree of self-fading was achieved. These channels were checked to ensure that the beacons whose fading was to be observed (Lizard and Flamborough Head) were sufficiently stronger than any potential co-channel interferers to ensure accurate readings. The experiment was, of course, conducted at night.

The third factor was skywave propagation. The question this time was: what is the correlation between the strengths of the signals received from two distant, skywave, interferers on two different frequencies. This question was raised to ensure that any changes to the interference experienced by the first beacon, would not be expected to be experienced by the back-up. A pair of channels was chosen (Table 6.4) each of which offered a single distant station, received via skywave only. These stations (Gatteville and Roches Douvres) were sufficiently stronger than other stations to ensure accurate readings. Again the setup and procedure above was employed. These measurements, too, were conducted at night.

In these tests, the recorded data was not continuous nor could the two frequencies of each pair be monitored truly simultaneously.

This meant that very short-term noise spikes would be missed and so would the fact that they were correlated between frequencies.

Indeed, local thunderstorm noise bursts would be expected to be correlated in this way. However, the point of these measurements was to ensure that there was no significant correlation between conditions on pairs of channels that would prevent one beacon acting as an effective back-up to another. Since spikes of less then a few seconds duration would not cause signal losses of sufficient importance to cause either a user, or an automatic receiver, to switch from a primary beacon to its back-up, they can safely be ignored, as here. The fact that the signals were not recorded continuously, but were sampled, is also not significant in view of the very large numbers of samples recorded and analysed.

All these measurements were made for 30 days in March and April 2001, the measurements for the three different tests being interleaved over a period of 12 seconds. Once all data had been recorded, Microsoft Excel was used to calculate the correlation co-efficient between each pairing. Table 6.4 shows the frequencies used for these measurements. The right-hand column shows the results: a set of three correlation co-efficients, one for each parameter. A correlation co-efficient takes a value of: 1 if the events are synchronised, rising and falling together; 0 if they are uncorrelated; and -1 if they are synchronised but move in opposite directions.

	Frequency A/kHz	Beacon used	Frequency B /kHz	Beacon used	Correlation
Atmospheric noise	285.5	None	317.5	None	-0.001
Self-fading	284.0	Lizard	302.5	Flamborough	0.012
Skywave interference	297.0	Gatteville	308.0	Roches Douvre	0.1

Table 6.4: Results of measurements to ensure failure of one beacon does not mean failure to all.

The measured correlation between the atmospheric noise on the two frequencies was –0.001, an extremely low value. That is, there was negligible correlation. There was again a low correlation, 0.012, between the degree of self-fading of the signals from two stations on different frequencies. Finally, the correlation coefficient between the skywave interference received from two distant stations on separate frequencies was

again low, 0.1. The conclusions were clear: there would be negligible correlation between the loss of one station and the loss of one or more backup stations.
Thus it was acceptable to employ the methods of equations 6.12 and 6.13 in computing the availability of the service at each location.

6.7 Conclusions

In this chapter, the need is identified for a method of calculating service availability. Three candidate methods are analysed: Specht's approach, using a Markov Chain, and using Fault Tree Analysis. The Fault Tree Analysis was selected as the most appropriate for use in the model.

A fault tree, encompassing many events, was developed for radiobeacon DGNSS signal availability. These events could be split into two distinct groups: deterministic and stochastic. Deterministic events, such as groundwave interference, remain constant with time and have already been taken into account when predicting coverage. Thus they can be excluded from service availability calculations. Stochastic events, however, vary randomly with time and must be included in calculations of service availability.

With the factors that affect the service availability identified, a simpler fault tree was developed. It soon became apparent that it was unnecessary to use a commercial software tool to predict availability; rather the calculation could be included within the new software once it had been verified against the commercial software.

A measurement programme was then conducted to ensure that the stochastic events that cause non-availability are independent and non-correlated. Large numbers of pairs of measurements were recorded and analysed. The results showed that there was negligible correlation between the levels of atmospheric noise, self-fading, and skywave interference between pairs of channels. Thus, should a user's primary beacon become unavailable due to any of these events, a back-up beacon on a different channel would be a viable alternative.

With the factors which can affect the service availability identified and the methodology both chosen, and built into and tested in the new software, the next stage is to start modelling the service availability of real radiobeacons, both individual stations and complete systems.

Chapter 7

Modelling availability

7.1 Introduction

Chapter 6 reviewed methods of modelling availability, from which it was determined that a fault tree analysis would be the most suitable. In this chapter, the fault tree analysis is incorporated into the software model with its new architecture. The model is then used to determine the availability of individual beacons and networks of beacons.

7.2 Availability requirements

There are international and national standards for availability, as for other DGNSS service parameters. In Chapter 4.2 the *factors* included within service availability were considered. Now, using the same set of sources, the *quantitative standards* will be identified. The following documents were reviewed: the relevant current resolutions of the IMO, Resolution 860, *"IMO (860)"* [15]; documents from the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA), *"IALA (Guide), IALA (draft guide)"* [16,83] including changes IALA have proposed to IMO resolution A.815, *"IALA (815)",* [84]; the 1999 US Federal Radionavigation Plan (FRP), *"FRP"* [24] and United States Coast Guard (USCG) documentation, *"USCG"* [58] (both only strictly applicable within the US); and recent proposals for changes to the IMO documentation from the European Maritime Radionavigation Forum (EMRF), *"EMRF(App)"* [13]. Table 7.1 summarises the requirements set out in these documents; as with the standards for time-to-alarm, they vary considerably!

IMO, USCG and EMRF each set a single availability figure, applicable everywhere and at all times. IALA, in contrast, set a 99.8% requirement for high-risk areas, and a lower, 99.5%, requirement for areas of single beacon coverage, and lower risk. In the candidate's judgement, it is appropriate to employ these 99.8% and 99.5% IALA values; they are world values, rather than US national ones, and they are a later development of the IMO requirements specified in resolution A.815. The US national requirement is different: 99.9% availability is required in high risk areas, and 99.7% elsewhere. These figures would be used should the availabilities of US beacons be considered.

Document	Availability Requirement
IMO (860)	99.8% Everywhere
IALA (815)	99.8% Critical areas 99.5% All other areas
IALA (Guide)	None Specified
IALA (Draft Guide)	99.8% Critical areas 99.5% All other areas
FRP	99.9% Critical areas 99.7% All other areas
USCG	99.9% Everywhere
EMRF (App)	99.8% Everywhere

Table 7.1: Signal availability specifications

After this decision on the availability standard to be employed in this research had been made, the IMO released a new recommendation. Happily, this specifies the same requirements selected by the candidate [98].

Calculating availability in an environment in which a number of factors are stochastic is clearly a probabilistic process. So, the new software model will now be developed to predict availability values in accordance with our earlier decision to take both the beacon and environmental factors into account, and the later decision to employ availability specifications of 99.8% and 99.5%.

7.3 Development of availability prediction

The new model will be developed in three stages. The first is to return to the simple approach of using edge-of-coverage conditions.

7.3.1 Edge-of-coverage method

As in Chapter 6.5, the first and simplest assumption when working with the FTA is to apply edge-of-coverage conditions at all locations. Table 7.2 lists the various factors whose individual effects are combined when determining the overall service availability. These figures result from our adopting values for own-skywave fading, atmospheric noise, and skywave interference that are either "not exceeded" or "exceeded" (as appropriate) 95% of the time" [14]. Thus, the non-availability is 5% (ie a factor of 0.05) everywhere.

Event	Probability of each event's causing signal non-availability
Beacon	0.005
Own skywave fading	0.05
Atmospheric noise	0.05
Skywave interference	0.05

Table 7.2: Factors that can cause non-availability of the signal.

The first stochastic factor in the table is the availability of the beacon itself. IALA recommend calculating a "broadcast availability" from records of the station's *mean-time-between-failures* (MTBF) and *mean-time-to-repair* (MTTR) [84]. This broadcast availability is the percentage of time the beacon broadcasts a healthy signal. The method assumes that an "unhealthy" signal would be detected by the beacon's associated integrity monitor, which would then switch off the transmission. IALA suggest working to a beacon availability of greater than 99.5%. This is a target figure, one that IALA recommends, but is not a strict limit. Two beacons with overlapping coverage, each offering an availability of 95%, are normally sufficient to meet this 99.5% standard [99].

The first environmental factor, the strength of the beacon's signal, is not stochastic by day, but rather a fixed, deterministic, value since the signal then reaches the receiver by groundwave propagation alone. At night, the skywave component intervenes; its signal strength varies stochastically in a known fashion. The two components interact, giving a total signal the strength of which also varies (that is, the night-time signal fades) in a statistically-predictable fashion.

Poppe has shown that the probability distribution of skywave field strengths is close to Gaussian [14] and her model is employed here to predict the field strength exceeded 95% of the time at each array point.

This 95% value at night, or the groundwave field strength by day, is then compared with the minimum field strength value specified by ITU [61]. By day, if the field strength at an array point falls short of the minimum, availability there is always zero. At night, the model computes the probability of the field strength's failing to meet the ITU criterion. If this happens less than 95% of the time, availability there is again deemed to be zero.

The third factor listed in Table 7.2 is atmospheric noise. This varies stochastically in the short term around a mean value that depends on the time of day, season of the year, location, and frequency. It is calculated at each point in the array as the atmospheric noise level at 300kHz not exceeded 95% of the time throughout the year. Using this noise value, and either the daytime or the night-time beacon field strength as appropriate, the signal-to-atmospheric noise ratio at that location can be computed. Finally, the probability of the SNR's failing to meet the minimum value of 7dB, and so causing the signal to become unavailable, can be estimated.

The remaining factor affecting availability is interference causing the signal-to-interference ratio (SIR) to fall below the appropriate protection ratio, resulting in non-availability. By day, interference is received via groundwave propagation only and its value is deterministic. The software estimates the field strengths, at the array point, of all potential groundwave interferers. Taking their individual frequencies into account, it determines whether any of them causes the SIR limit to be breached. If so, availability at that array point is always zero. This happens in only a few, very small, areas surrounding interfering stations. More commonly, strong interference is received at night via skywave propagation.

The strength of each potential interferer is estimated at each location, the value computed being that not exceeded 95% of the time. Using this interference level and the night-time (ie 95%-faded) beacon field strength, the SIR is calculated.

Finally, the probability of the SIR's failing to meet the appropriate protection ratio, and so causing the signal to be unavailable, is estimated.

The four stochastic factors listed in Table 7.2 have now been dealt with, leaving us free to calculate availability at each array point from these four factors. Consider the values in the right-hand column of Table 7.2. These are the individual probabilities discussed above (and, of course, the limiting values at any point for it to be deemed to lie within coverage). Each of them represents the probability that the corresponding event will occur; for example, the probability of the atmospheric SNR's falling below 7dB is 0.05%. If any of these events does occur, that will result in non-availability of the signal.

Equation 7.1 is now used to calculate the overall availability given these four component values. The result is an availability of 0.85, or 85%. This is a very low value; clearly, it falls well below the 99.5%, let alone the 99.8%, standard. But the result is not surprising given that each of the individual 5%-probability factors can cause loss of availability.

$$\textit{Single station availability} = \prod_{i=1}^{N}(1-U_i) \tag{7.1}$$

A higher service availability can be expected if, instead of using a single beacon, one can employ the best of several overlapping signals. Let us assign to each beacon the single-beacon availability of 85%. Then, the number of signals which can be received at each location is considered. Taking the British Isles beacons, the service availability at each location is computed, resulting in the availability plot shown in Fig. 7.1. The red area shows where the availability exceeds 99.5% at night.

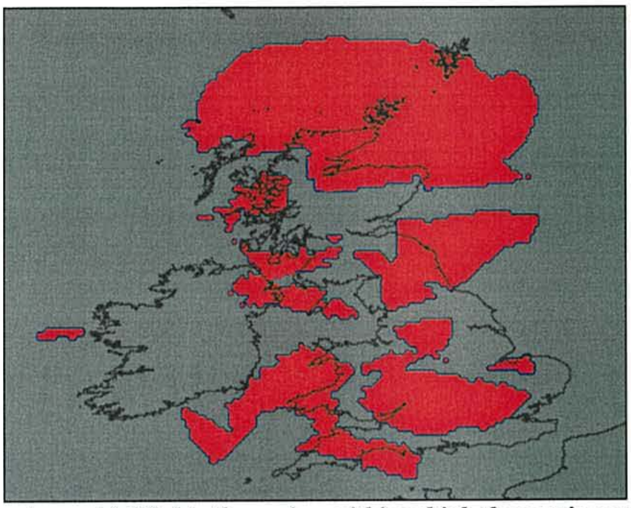

Figure 7.1: The red area highlights the region within which the service availability exceeds 99.5% by night, using the edge-of-coverage method.

Equ. 7.2 tells us that, to provide the overall target availability of 99.5%, requires simultaneous coverage from three beacons.

$$Availability = 1 - \prod_{i=1}^{N} (1 - Q_i) \tag{7.2}$$

The implications of this result can be seen in Fig. 7.2. This figure shows, point-by-point, the number of beacons simultaneously available. The green and blue areas are those in which three or more beacons are providing coverage. Together, as would be expected, they match the red areas in Fig. 7.1.

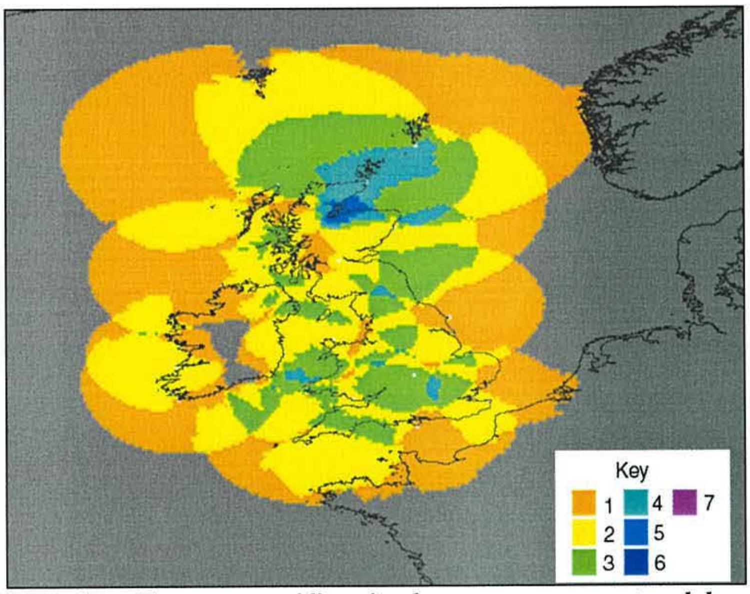

Figure 7.2: The number of beacons providing simultaneous coverage at each location (at night), using the 16 beacons of the United Kingdom and Ireland.

7.3.2 Edge-of-coverage method reviewed

The 85% availability of the single station has been calculated using 95% values for three of the four individual factors that combine to give service availability. These 95% figures are, of course, minimum values. One would expect to encounter them only at, or close to, the boundaries of a beacon's coverage. But here they have been used everywhere throughout the coverage area, even close to the station where common sense tells us that failure to meet the minimum standards is highly improbable! The result of using this "*edge-of-coverage*" strategy is a very low service availability figure.

Further, the edge of coverage may well be where the groundwave field strength has fallen as low as 20dBμV/m, and this very low field strength value will have been used in calculating the propagation components of availability. Many administrations, however, limit coverage to the nominal range of the beacon, at which range the field strength over seawater is much higher, either 34 or 37.5dBμV/m. At this much shorter range the availability would, of course, be expected to be much greater. But despite these higher field strengths, the set of 95% probabilities has been employed.

In summary, this method assumes that every location within the coverage region suffers edge-of-coverage conditions. In practice, this is not the case. Closer to the beacon SNR and SIR values be much higher and so will availability. So, while this method was a valuable first stage in the development process, one concludes that it underestimates availability over much of the coverage area.

7.3.3 Localised availability

Let us now attempt to employ more realistic estimates at each location of the probabilities that the stochastic values will meet their minimum requirements there. Happily, the new software architecture provides the data required at each location to compute these probabilities.

This second analysis method, the "*localised availability*" method, makes a simplifying assumption that the signal from the beacon is deterministic at all times. This strictly isn't true, but is needed to develop this method of working (Section 7.3.5 deals with the stochastic wanted signal). By day the groundwave value is used. At night, it is assumed that the signal everywhere is the lowest value that can be guaranteed 95% of the time. Now, the nearer the receiver is to the beacon, the greater the signal strength, while the atmospheric noise will remain much the same. Thus, the SNR will be greater and the probability of its not meeting the 7dB minimum will fall progressively from the edge-of-coverage value of 5%. The probability of failing to meet the signal-to-interference limit will fall in the same way as one gets closer to the station.

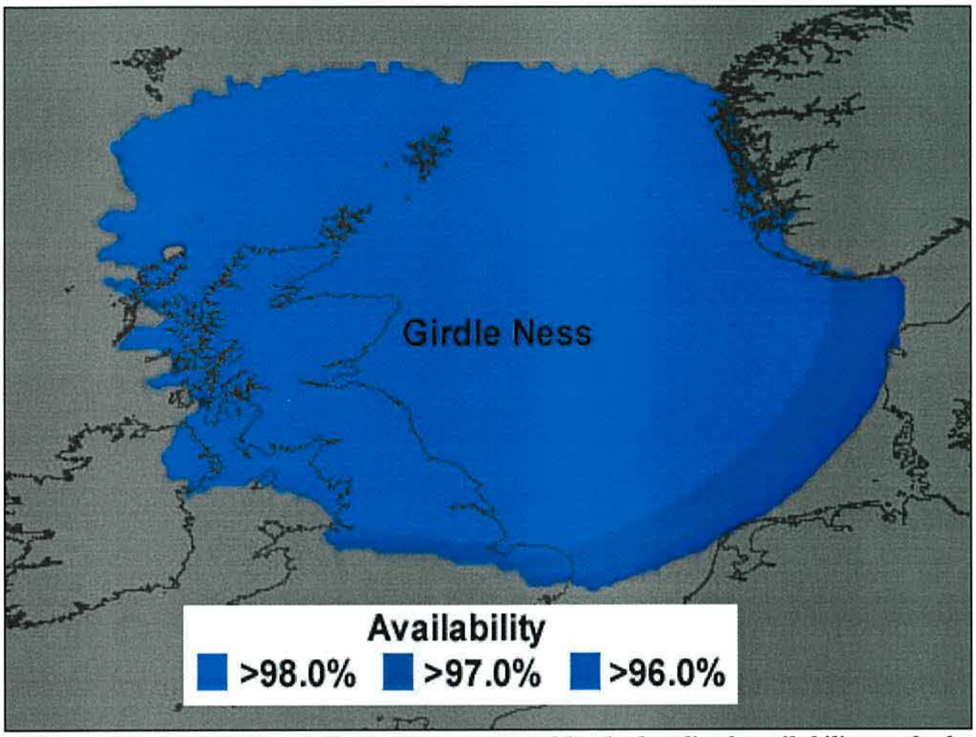

Figure 7.3: Availability of Girdle Ness computed by the localised availability method. The contours represent the service availability at each location.

Again equations 6.12 and 6.13 are used, but this time we employ the local probability values at each location. The results are shown in Fig. 7.3 in the form of an availability plot for the radiobeacon at Girdle Ness on the north-east coast of Scotland. The outer contour again represents the 95% availability, as with the *edge-of-coverage* method. But now there are inner contours that represent the increased availability nearer the station.

However, although the probabilities of the propagation factors continue to rise the nearer one travels to the beacon, the limit to service availability is now the 99.5% availability of the beacon itself. Fig. 7.3 was produced using Matlab during the development of the availability computation method. Unfortunately, the way it was generated does not differentiate between availability values higher than 98%.

This method was also used to estimate availabilities across the entire EMA, under both daytime (Fig. 7.4) and night-time conditions (Fig. 7.5). Fig. 7.4 shows that, by day, the 99.8% critical area requirement are been met everywhere.

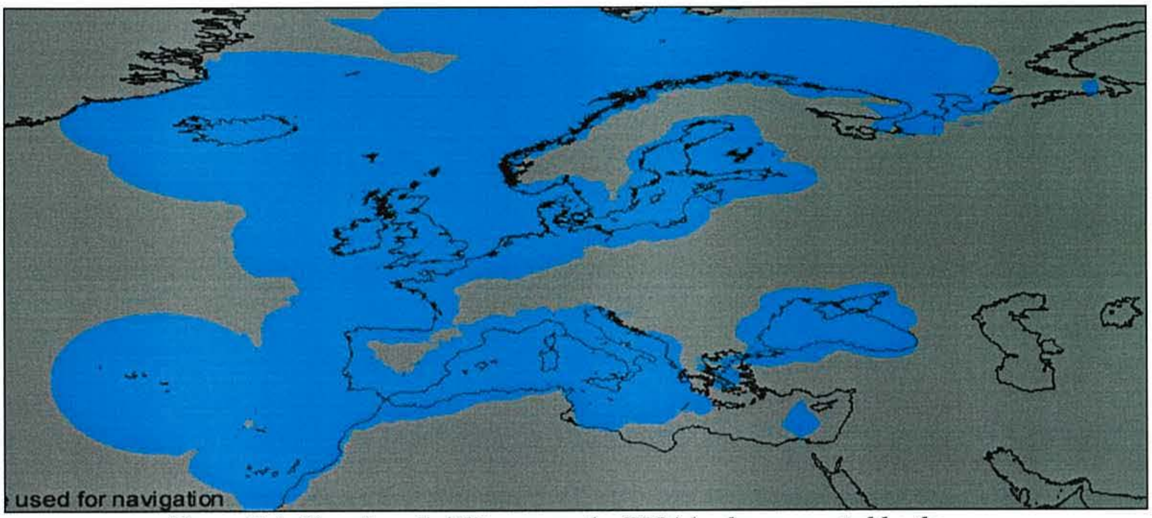

Figure 7.4: Signal availability across the EMA by day computed by the* localised availability *method. Beacon availability is 99.5%.
Light blue areas = 99.8% (ie critical areas requirement met).

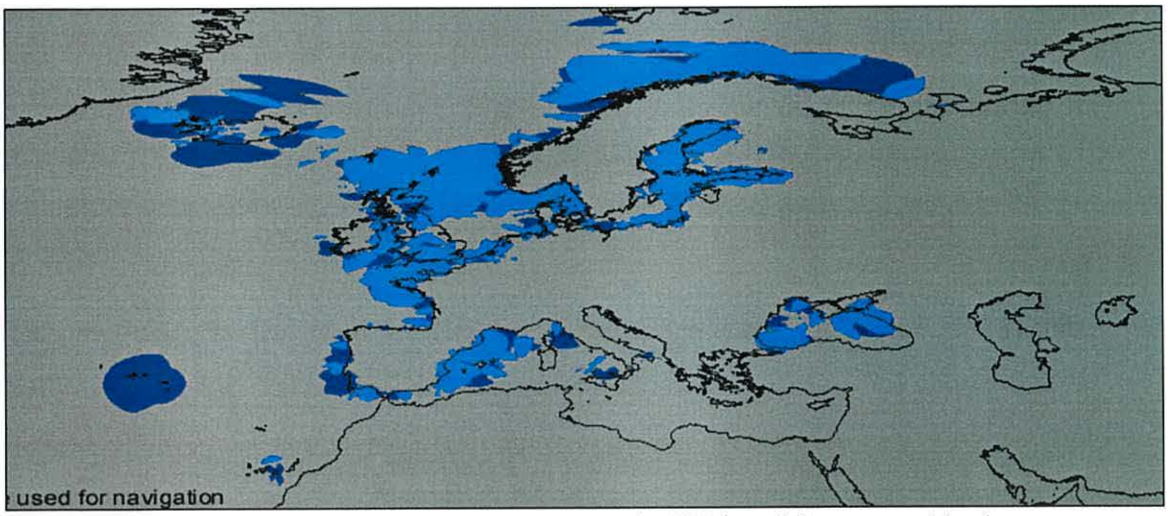

Figure 7.5: Signal availability provided across the EMA at night computed by the localised availability method. Beacon availability is 99.5%.
Light blue = 99.8% (critical areas requirement met).
Dark blue = 99.5% (other areas requirement met).

Fig. 7.5 shows that at night there is a marked reduction in the regions achieving the higher requirement (light blue), although in many areas the lower 99.5% requirement (dark blue) has been met. The availability is, of course, considerably worse by night than by day because of increased skywave interference and the reduction of the beacon's signal by self-fading.

It is important to note that the beacon availability used so far has been the IALA example value of 99.5. This figure is the same as the service availability requirement for non-critical areas. Thus, when the reduction of availability due to signal-in-space factors is added to the marginal availability of the beacon itself, it is clear that a single beacon could never meet the service availability requirement. However, a small increase in the beacon's availability would lead to a dramatic improvement in service availability, allowing a single beacon to meet the non-critical area requirement over substantial regions. Let us therefore examine this critical parameter: the beacon availability.

7.3.3.1. Beacon availability

In this analysis, a single value of beacon availability - the IALA example value of 99.5% - has been employed. In the candidate's view, the use of the same value by day and night is unrealistic. The reason is a practical one. When one examines beacon records, it becomes clear that the major components of beacon downtime are outages due to failures, and scheduled maintenance. Unscheduled outages due to failures are equally probable by day or night. But almost all scheduled maintenance is carried out by day only. Thus the probability of a beacon's being off the air is much less at night than by day. The availability of a beacon that meets the overall 99.5% figure will invariably be higher than this figure by night, and lower by day. This higher beacon availability at night partly compensates for the additional night-time propagation factors that reduce service availability. Taking a beacon off the air for scheduled maintenance during the day generally has relatively little impact on the service, since so many alternate beacons are available then.

Let us assume that a beacon meets the IALA 99.5% example availability overall [84]. In the IALA example, 24 hours are lost annually to scheduled maintenance, and 63 hours to unscheduled outages. Let us assume that the scheduled maintenance occurs by day only. We calculate (see Section 7.4) that for 57.6% of the year night-time radio conditions apply, and for the remaining 42.4%, daytime conditions. Thus we enjoy a night-time beacon availability of 99.6%. The availability by day, when all scheduled and some unscheduled outages occur, falls to 99.3%.

The *localised availability* method is now used to re-compute the night-time availability using the increased beacon availability figure of 99.6%. The result is shown in Fig. 7.6. Although the beacon availability has risen by just 0.1%, the effect on night-time service availability is dramatic, as is clear from comparing this figure with Fig. 7.5. Since single stations can now provide signal availabilities above 99.5% at night, the areas in which neither standard is met are greatly reduced. The areas of 99.8% availability are also substantially increased. This demonstrates the critical sensitivity of the service availability to the value of beacon availability and the resulting importance of using appropriate values of this parameter.

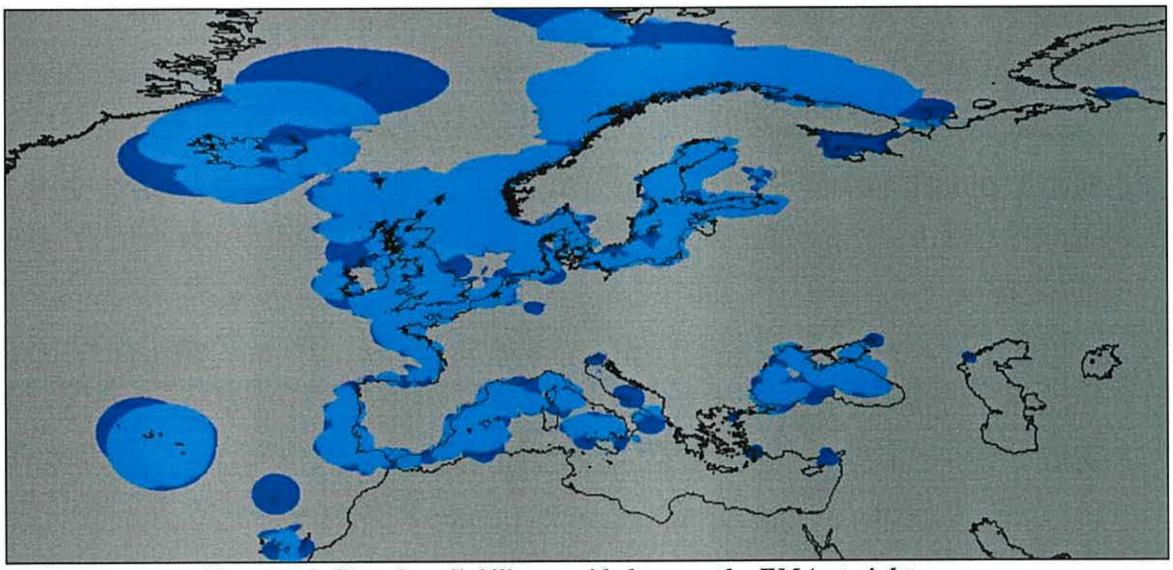

Figure 7.6: Signal availability provided across the EMA at night.
Beacon availability is now 99.6%. Light blue = 99.8% (critical areas requirement), Dark blue = 99.5% (other areas requirement).

7.3.4 Localised availability reviewed

This *localised availability* method has for the first time introduced the concept of calculating the service availability from the conditions at each location, as opposed to assuming edge-of-coverage conditions, everywhere. This is a great improvement on the previous model. However, one can go further by removing the simplifying assumption that the night-time field strength is deterministic.

7.3.5 Statistical availability

Let us now develop our third method, the *statistical availability* method. First, the stochastic nature of night-time field strength is taken into account. This is not trivial! The *localised availability* method calculated the probabilities of exceeding the SNR and SIR minima by comparing the stochastic atmospheric noise, or interference signal, to the deterministic field strength of the wanted beacon. But at night we must now regard the wanted signal as also being stochastic.

In this new method, all stochastic events at each location are taken into account when calculating the availability. In this approach one starts by calculating the probability of the SNR and SIR being exceeded, from which one can calculate the probability of failure. Clearly, we require a statistical approach to the modelling of the effects of multiple stochastic elements. Poppe [14] has shown that the skywave field strength at night has a Gaussian probability distribution. She has provided data from which one can calculate the mean and standard deviation values of own-beacon skywave, and skywave interference.

Likewise, the mean and standard deviation of the atmospheric noise can be obtained from the ITU noise data [78]. Atmospheric noise, however, has a two-sided distribution to which Poppe has shown that both sides are close to Gaussian, but their standard deviations are different (10.9 for upper and 8.9 for lower) [14]. Poppe shows that a single Gaussian distribution can be applied as a good approximation and the upper standard deviation is used as this will provide the greater accuracy in the upper decile.

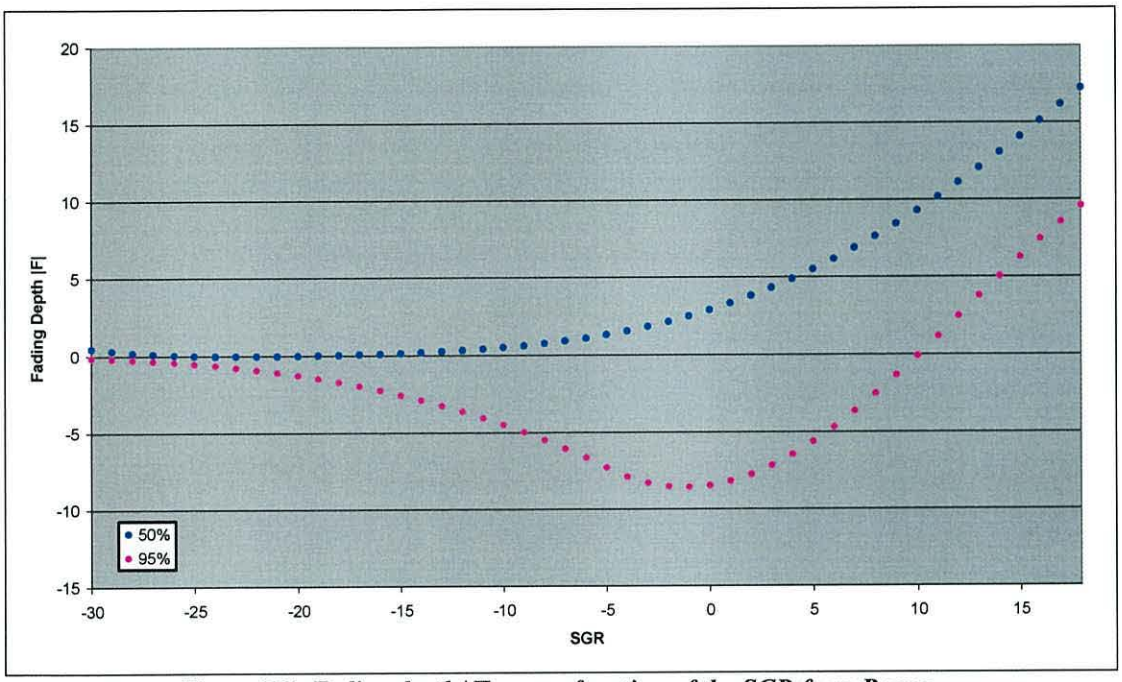

Figure 7.7: Fading depth $|F|_{dB}$ as a function of the SGR from Poppe, for both the 50%-ile and 95%-ile.

The statistical distributions for the groundwave and skywave signals are known from Poppe's work. Poppe does not calculate the standard deviation of the self-faded signal. However, her work can be used to calculate this unknown; Poppe developed a method of calculating the field strength of a self-fading signal. She treated self-fading as an additional attenuation factor, called the fading depth, and showed how it depended on the skywave-to-groundwave ratio (SGR). Self-fading is a function of a deterministic and a stochastic event and so is itself stochastic. Poppe used the 95%-ile values in estimating coverage. However, she also calculated the fading depths for various other fixed percentage probabilities. By using her data and by subtracting the 50%-ile fading depth from the 95%-ile (Fig. 7.7) to calculate *Δfade,* it is possible to calculate the standard deviation for each value of SGR using:

$$\sigma = \frac{\Delta fade}{1.65}, \tag{7.3}$$

where σ is the standard deviation and *1.65* is the multiplication factor to calculate the 95%-ile once the mean is known.

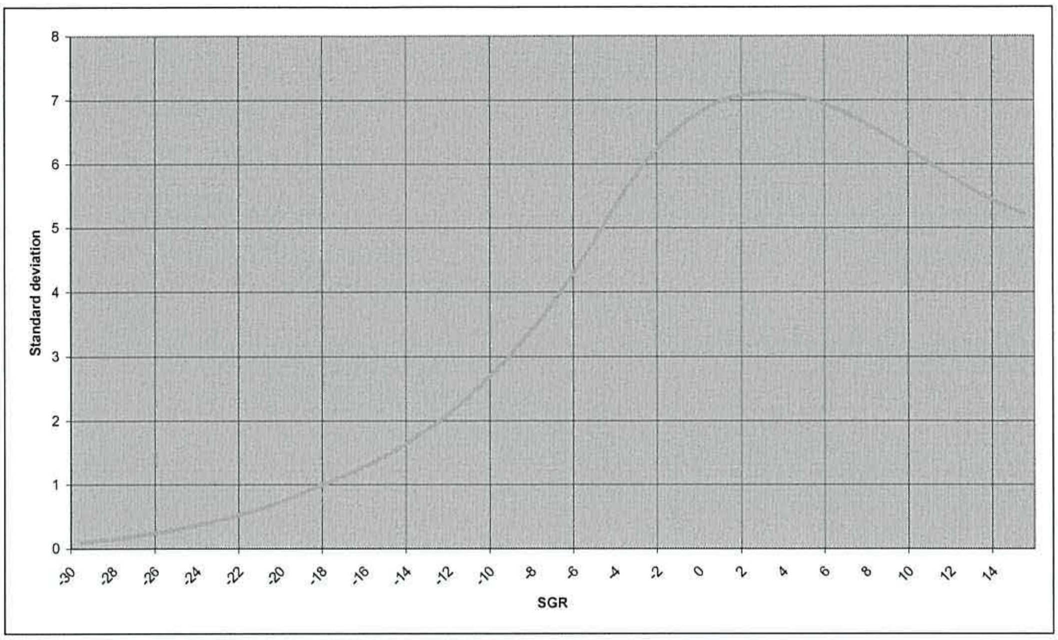

Figure 7.8: Standard deviation of skywave self-fading, in dB, as a function of skywave-to-groundwave ratio.

In order to model the standard deviation (sd) of this interaction, the standard deviation is calculated as shown in Fig. 7.8. This curve is implemented in the model by applying the following polynomial.

$$\text{sd} = (a + b * SGR + c * SGR^2 + d * SGR^3 = e * SGR^4 + f * SGR^5)\,, \qquad (7.4)$$

where

	SGR <= 0	SGR > 0
a	6.9432	6.9671
b	1.6943 x10^{-1}	2.9084 x10^{-2}
c	-6.8366 x10^{-2}	1.5909 x10^{-2}
d	-6.3333 x10^{-3}	-5.4639 x10^{-3}
e	-2.1399 x10^{-4}	3.2760 x10^{-4}
f	-2.5581 x10^{-6}	-5.2379 x10^{-6}

By using the mean and standard deviation values of own-skywave and atmospheric noise, the probability of exceeding the 7dB atmospheric SNR floor can now be calculated as a function of SGR. By using the mean and standard deviation of own-skywave and of the strongest skywave interferer, the probability of the SIR's exceeding the appropriate protection ratio, can be calculated in the same way. From these one can calculate the probability of failure, which then replace the edge-of-coverage factors of 0.05%.

When calculating the probability of exceeding the signal-to-noise ratio, the statistical distribution information for both the wanted signal and atmospheric noise are combined to make a new distribution, labelled "*new*". The probability of this new distribution exceeding the SNR floor (labelled "*floor*") is [100]:

$$Pr(new \geq floor) = 1 - \Phi_d\left(\frac{floor - (\mu_s - \mu_n)}{\sqrt{\sigma_s^2 + \sigma_n^2}}\right) \tag{7.5}$$

where μ_s is the mean of the beacon's signal, μ_n is the mean of the noise signal (atmospheric noise or interference), σ_s is the standard deviation of the beacon's signal, σ_n is the standard deviation of the noise signal (atmospheric noise or interference) and $\Phi_d(z)$ is the standard normal cumulative distribution function. This function is given by [100]:

$$\Phi_d(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{\frac{-t^2}{2}} dt \tag{7.6}$$

By using Gaussian distributions for all three elements, the wanted signal, atmospheric noise and skywave self-fading, we know that they are all statistically independent and that Equ 7.5 is applicable.

Under night-time conditions, this process results in three probabilities: the probability of the beacon's signal being available, the probability of the SNR floor being exceeded, and the probability of the SIR floor being exceeded. In each case, self-fading is taken into account by Equ. 7.5. By day, when the beacon's signal propagates via a deterministic groundwave path only, the same equation is employed, but the standard deviation of the signal is set to zero to represent its deterministic nature.

Once the probabilities have been calculated, the availability of each station and its signal-in-space which provide coverage are calculated using the same methods as previous (Equ 7.1). Then these are factored together using Equation 7.2 to calculate the final availability for each location.

Figures 7.9 and 7.10 show the resulting day and night availability plots for the United Kingdom and Ireland, using the 16 beacons listed in the latest band plan (more details in Appendix B). The day and night beacon availabilities are as calculated in Section 7.3.3.1 above.

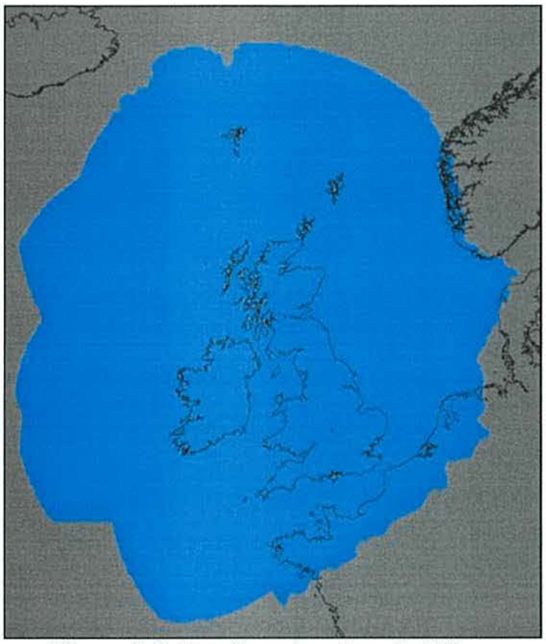

Figure 7.9: Daytime signal availability provided by the 16 beacons of the United Kingdom and Ireland

Figure 7.10: Night time signal availability provided by the 16 beacons of the United Kingdom and Ireland

Light blue = 99.8% (critical areas requirement met), Dark blue = 99.5% (other areas requirement met).

As before, at every location served by at least two beacons, the higher 99.8% availability standard is achieved by day. At night, the service availability achieves this standard in a greater number of locations than previously. In most other coastal regions the lower 99.5% requirement is met, with neither standard achieved in only a few locations. However, these figures exclude beacons outside the British Isles. When these are included, it is only along the southern coast of Ireland that neither standard is achieved.

While it appears that the availability has significantly improved, in reality it has not changed. The improvement has been in the accuracy with which we model the stochastic interaction between the wanted signal and the noise. This is now done intelligently, where previously we used the simple 95% figure.

This new method of computing availability also takes into account those occasions where the stochastic events compensate for each other: for example, when the noise increases but the wanted signal also increases due to skywave effects, with the result that the availability criteria are still met.

Figures 7.11 and 7.12 show the corresponding day and night availability plots, respectively, for the entire EMA, taking all 462 beacons into account. Again availability by day is not of concern: the 99.8% requirement is achieved everywhere. By comparing figures 7.12 and 7.6, the substantial improvement in the level of availability achieved across the EMA due to our more accurate estimating of the strengths of beacons is shown.

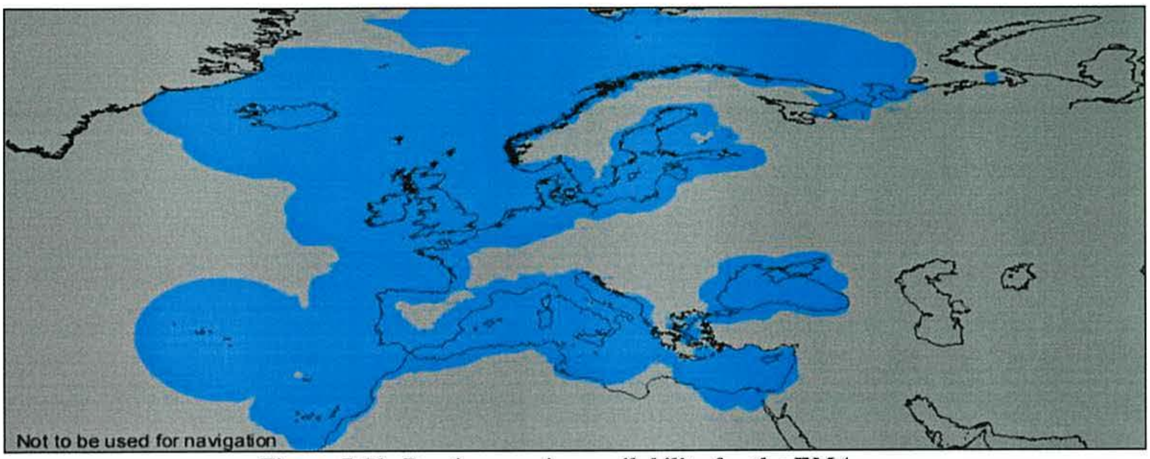

Figure 7.11: Daytime service availability for the EMA.
Light blue = 99.8% (critical areas requirement met)

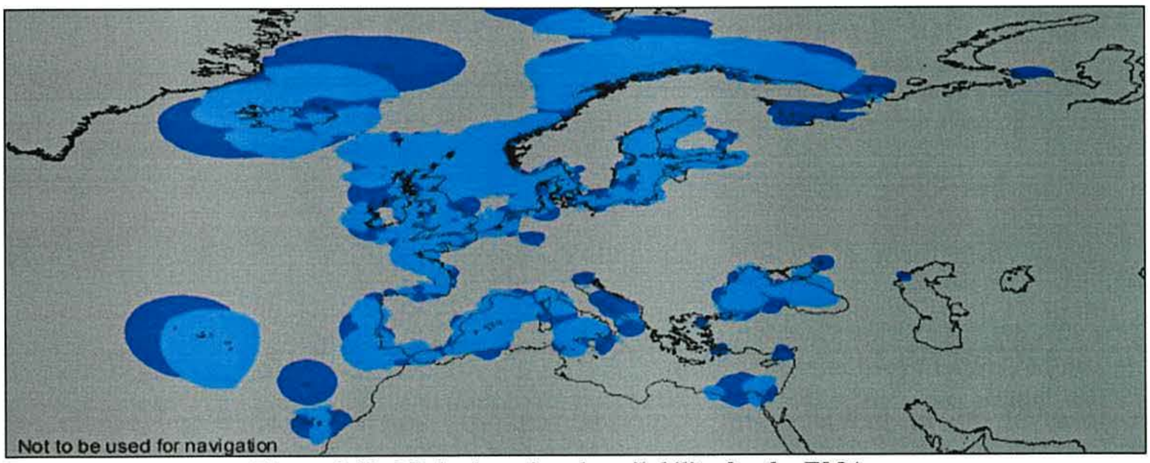

Figure 7.12: Night time signal availability for the EMA.
Light blue = 99.8% (critical areas requirement met),
Dark blue = 99.5% (other areas requirement met).

7.3.6 Review of statistical availability method

The new statistical approach to calculating availability combines two statistical distributions to calculate the probability of achieving a usable signal at each location. The statistical distributions for atmospheric noise, skywave fading, and skywave propagation are used to model reality, using the best information available. The results from this new statistical calculation show an increase in the availability of the EMA DGNSS beacons; however, the actual availability has not altered, rather the change is due to the improvements in the model.

7.4 Day and night considerations

The period over which the availability standards discussed in Section 7.2 are specified has recently been changed [101]. They are now to be calculated over a two-year period, where previously they were calculated over 30 days. This change has been introduced in order to provide a more realistic time-scale for maintenance to be conducted, as a single beacon could not meet the old standards over 30 days [102]. In areas such as Australia, where beacons are on very remote sites, calculating availability over 30 days simply did not give a sufficient time in which to repair faults [82,99]. Extending the calculation period to two years allowed a longer repair time.

However, the software models availability separately under day or night conditions. In calculating a *two-year probability*, it is thus necessary to take into account the different availabilities to be expected by day and by night. These should then be weighted in accordance with the proportion of the two years that is day and that is night, respectively. Our computation model incorporates the different day and night values of beacon availability (Section 7.3.3.1 above). It allows for the use of the groundwave signal by day and the fading signal at night.

In calculating the day and night availabilities, the annual average noise figure experienced by day and by night are used (Tables 7.3 and 7.4 respectively). Interference is already separated into groundwave-only by day and groundwave-plus-skywave by night.

	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
80	-4	-4	-5	-5	-5	-4	-4	-4	-4	-4	-4	-5	-7	-9
70	-4	-5	-6	-6	-6	-4	-2	1	3	3	2	0	-3	-7
60	-6	-7	-7	-6	-4	-1	3	6	7	6	5	4	0	-4
50	-3	-3	-3	-1	1	4	8	9	8	6	6	4	4	1
40	0	-1	0	2	5	7	7	7	5	4	4	3	6	9
30	6	6	6	6	7	9	10	8	6	6	6	8	15	21
20	14	9	8	9	12	15	17	15	12	10	11	15	23	28

Table 7.3: Annual daytime average noise

	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80
80	-2	-1	-3	-3	-3	-3	-2	-2	-1	-1	-2	-2	-4	-6
70	1	-2	-2	-1	0	2	5	8	8	8	6	5	1	-2
60	4	4	5	7	9	12	15	16	15	13	12	9	4	1
50	9	9	9	10	13	16	18	18	16	14	13	12	11	7
40	13	12	12	14	16	19	19	19	18	16	15	14	15	17
30	18	17	16	17	18	19	19	18	16	16	17	18	24	26
20	22	19	18	19	21	24	24	23	21	21	23	25	31	32

Table 7.4: Annual night-time average noise.

It is now necessary to establish the percentages of the two years during which daytime and night-time skywave propagation conditions obtain. These are, of course, the same percentages as in a single year. A way to estimate them is to use Decca Navigator "time and season factor" diagrams. Decca was a navigation system that was decommissioned in the 1990s [103]. It operated in the frequency range, 70-130kHz, in which propagation is basically similar to that at 300kHz. Because the repeatable accuracy of Decca position fixes was critically dependent on skywave propagation factors, Decca investigated diurnal variations of propagation in great detail. They produced diagrams, such as Fig. 7.13, for each of their chains of stations. These split the 24 hours of the day into various periods of different skywave intensity and did so throughout the year.

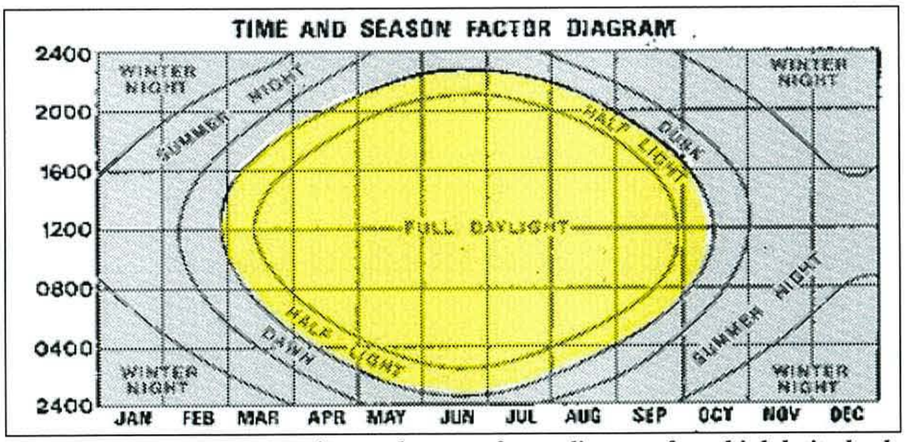

Figure 7.13: Decca Navigator time and season factor diagram for a high latitude chain. The yellow region is deemed to represent 'daytime'.

Decca classified skywave propagation intensity into 5 different levels, whereas in this analysis only two are required. Let us make an approximation: we will assume that daytime conditions (ie no skywave propagation) apply throughout Decca's *Full Daylight* and *Half Light* periods (yellow in Fig. 7.13), since they are periods of negligible skywave propagation. During the other three Decca periods, *Dawn/Dusk*, *Summer Night* and *Winter Night* (grey in Fig. 7.13) we will assume that skywave propagation and self-fading are at the levels built into the availability model. Once this division had been made, the proportions of these two states can be calculated, by measuring the proportions of Fig. 7.13 that are yellow and grey, respectively. They turn out to be: 42.4% daytime, and 57.6% night.

Fig. 7.13 actually represents the Finnmark Decca chain, centred at latitude 70°N, the highest latitude Decca chain [103]. The lowest latitude chain was the Dampier chain, centred at 20°S [104]. Fig. 7.14 shows its time and season factor diagram. The annual pattern of daytime and night-time is quite different between these two figures. However, the proportions are not: the low-latitude chain has 43.2% of daytime and 56.8% of night.

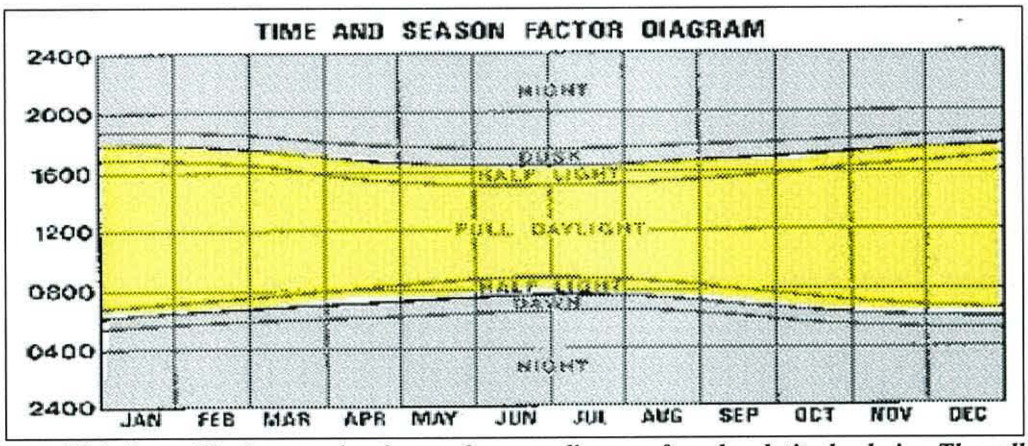

Figure 7.14: Decca Navigator solar time and season diagram for a low latitude chain. The yellow region is deemed to represent 'daytime'.

By averaging the two sets of results, so as to take in a wide range of latitudes, we conclude that 42.8% of the time is daytime, and 57.2% night. These percentages were then used in the availability model to weight the day and night availability values at each array point, so producing an annualised result. The two-year availability is, of course, the same.

Fig. 7.15 shows the results of this process. It combines the results from Figs. 7.11 (day) and 7.12 (night) in this weighted fashion to produce two-year availability estimates for the EMA.

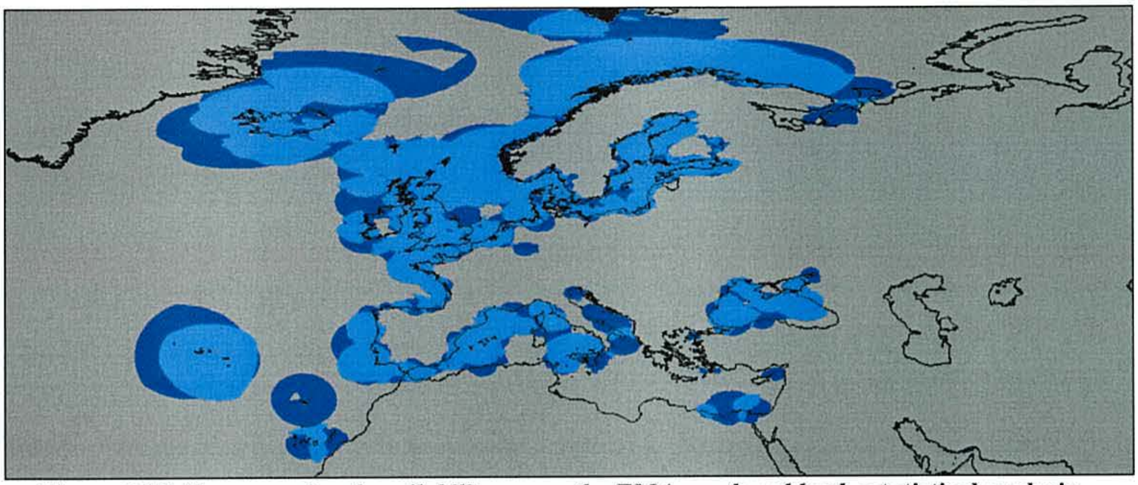

***Figure 7.15:** Two-year signal availability across the EMA, produced by the* **statistical analysis** ***method.** Light blue = 99.8% (critical areas requirement met), Dark blue = 99.5% (other areas requirement met).*

7.5 Verification

Signal availability, as modelled by the new software, cannot be measured directly. The model does not take into account any factors for the receiver, which would be required to measure signal availability.

At the start, the methodology of using a fault tree analysis was verified against the commercial software package. As explained in Chapter 6, the software matches closely the results given by the commercial package. This verifies that the software processes the fault tree analysis correctly.

The availability section of the software model has been verified by a number of tests. The first was to examine conditions at the edge of coverage, by forcing the new statistical approach to repeat the method used within the *localised availability* method. That is, at all times the wanted beacon was deemed to be deterministic. The *localised availability* method then calculated the probability of exceeding the SNR and SIR. The results obtained at the edge of coverage, using the new statistical model matched those as calculated previously, that is, they matched the expected 95% figures. The statistical equations were also repeated using pen-and-paper and again agreement was obtained.

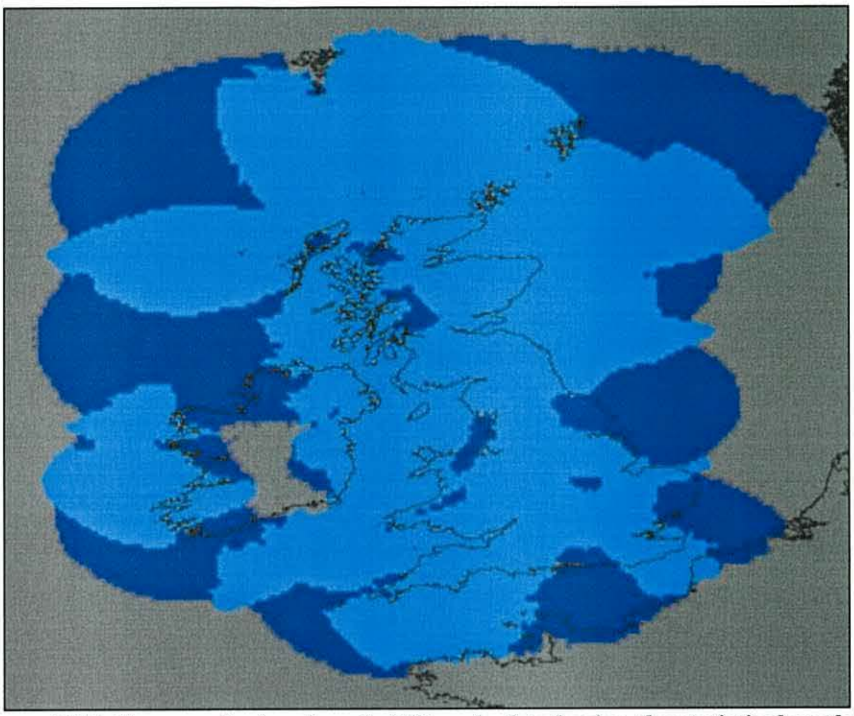

***Figure 7.16: Two-yearly signal availability calculated using the* statistical method.**
Light blue = 99.8% (critical areas requirement met),
Dark blue = 99.5% (other areas requirement met).

Further verification of the availability results and technique included discussion with representatives of the General Lighthouse Authorities (GLA's) of the United Kingdom and Ireland at regular intervals [82,99,105]. During several meetings, the signal availability results were discussed and the values at various were locations investigated. An example is the south coast of Ireland: Dr Ruttle, Engineer-in-Chief of the Commissioners of Irish Lights, was curious as to the reason why the availability along a stretch of that coast fails to meet either requirement at night (Fig. 7.16) [105], (See Appendix D). In response to this query (as with others), the software was used in an investigative mode to identify the reason.

It confirmed that there is a hole in coverage in this region, hence the lack of availability. Then, each beacon that could potentially provide coverage to this location was investigated individually. The results are shown in Table 7.5. Two beacons that formally provided coverage were shown to suffer skywave interference due to the introduction of additional stations after the band-plan was optimised. The others suffered self-fading or groundwave attenuation. Each beacon's signal fell just short of the minimum standard in some respect. The result is that this confirmed the correctness of the model's prediction.

Potential beacon	Reason for lack of coverage
Lizard	Skywave Interference from Molunat.MB
Nash Point	Skywave Interference from Cap_Blanc.MB
Mizen Head	Fails to provide coverage due to self-fading, or groundwave attenuation
Loop Head	Fails to provide coverage due to self-fading, or groundwave attenuation
Point Lynas	Fails to provide coverage due to self-fading, or groundwave attenuation

Table 7.5: The potential beacons which may provide coverage to the South coast of Ireland and the reasons why they don't.

Throughout the development of this model, regular meetings' with the GLA's representatives raised a succession of such queries which were investigated in every case. Further, the GLA representatives examined the methods employed at every stage in the progress of the research.

7.6 Conclusions

This chapter has presented the development of a model for predicting availability based on the FTA approach and appropriate equations. The availability standards of various authorities have been reviewed and compared, with the IALA standards being employed as the most appropriate.

The first attempt at plotting availability, using the *edge-of-coverage* technique and applying the FTA directly, was successful. But the results were shown to underestimate availability since the model ignored its spatial variations. The *localised availability* method was then developed which introduced the concept of estimating availability at each location. Then the decision was made to use different values of beacon availability by day and night, to reflect maintenance practice.

Finally, the analysis started to take into account the stochastic nature of the beacon's signal strength at night. The resulting new *statistical method* combines stochastic distributions of events to calculate availability at each location. Its operation was demonstrated across both the United Kingdom and Ireland and the European Maritime Area. Individual plots of day and night availability were then factored together, weighted according to proportions of day and night obtained from Decca Navigator data, to create the two-year availability figures now required by IALA.

The result is a model capable of estimating the availability of a single network, or a system of several hundred beacons, that provides results in a format which allows administrations to ensure that they are meeting international standards.

Chapter 8

Continuity

8.1 Introduction

Continuity is defined by the IMO as *the ability of a system to function within specified performance limits without interruption during a specified period* [15]. It is the probability of the service's remaining available for a short period of time. Continuity is the current name for what many people call *reliability*.

As with any criterion, the standards must be clearly identified so that the requirements are known.

8.2 Continuity standards

As with coverage and availability, continuity is defined by standards set by governing authorities. The same set of sources have been explored as for availability: the relevant current resolution of the IMO, Resolution A.860 [15]; documents from the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA) [16,83], including the changes IALA have proposed to IMO resolution A.815 [84]; standards of the US Federal Radionavigation Plan (FRP) [24] and United States Coast Guard (USCG) documentation [58] (both only strictly applicable within the US); and recent proposals for changes to the IMO documentation from the European Maritime Radionavigation Forum (EMRF) [85]. Table 8.1 summarises the continuity requirements set out in these documents; as with the standards for time-to-alarm and availability, they vary considerably!

IMO set a single continuity figure, applicable everywhere and at all times. IALA and EMRF set a 99.97% requirement for high-risk areas, but a lower 99.85% requirement for areas of lower risk and single beacon coverage.

An exception to this is the IALA proposal for revision of IMO resolution A.815, which uses the same standard as does that IMO resolution. The FRP standard for continuity (or *reliability* as they still refer to it) is that the *number of outages per site will be less than 500 in one million hours of operation* [24]. As a continuity requirement this is vague, since there is no indication as what duration constitutes an outage! Similarly, the USCG specify the reliability of the system in terms of a number of vessel manoeuvres of different durations, and the corresponding numbers of outages allowed per million hours. But, again, no indication is given as to what constitutes an outage.

<table>
<tr><th>Document</th><th colspan="2">Continuity Requirement</th><th>Calculation Period</th></tr>
<tr><td>IMO (860)</td><td colspan="2">≤ 99.97% Everywhere</td><td>1 year</td></tr>
<tr><td>IMO (815)</td><td colspan="2">≤ 99.97% Everywhere</td><td>1 year</td></tr>
<tr><td>IALA (815)</td><td colspan="2">≤ 99.97% High risk areas
≤ 99.85% All other areas</td><td>3 hours</td></tr>
<tr><td>IALA (Guide)</td><td colspan="2">≤ 99.97% Everywhere</td><td>1 year</td></tr>
<tr><td>IALA (Draft Guide)</td><td colspan="2">≤ 99.97% High risk areas
≤ 99.85% All other areas</td><td>3 hours</td></tr>
<tr><td>EMRF (App)</td><td colspan="2">≤ 99.97% Port areas
≤ 99.85% Coastal areas</td><td>3 hours</td></tr>
<tr><td>EMRF (815)</td><td colspan="2">≤ 99.97% High risk areas
≤ 99.85% All other areas</td><td>3 hours</td></tr>
<tr><td>FRP (1999)</td><td colspan="3">The number of outages per site will be less than 500 in one million hours of operation</td></tr>
<tr><td rowspan="4">USCG</td><td>Manoeuvre Category (seconds)</td><td colspan="2">Reliability (Outages/Mhr)</td></tr>
<tr><td><140</td><td colspan="2">2000</td></tr>
<tr><td>140 to 280</td><td colspan="2">1000</td></tr>
<tr><td>280 to 560</td><td colspan="2">50</td></tr>
</table>

Table 8.1: Continuity specifications and periods

In the candidate's judgement it is appropriate to employ the 99.97% and 99.85% IALA values: they are world values, rather than US national ones, and they are a later development of the IMO requirements. IALA also make it clear that they calculate continuity over three hours, as opposed to "1 year" or "1 million hours". Since continuity is concerned with providing guidance for the whole of a manoeuvre such as port entry and docking, the 3 hour definition appears appropriate given that such manoeuvres typically take three hours or less [102]. Also, the two values appear realistic figures according to [84].

After this choice of working standard had been made, the IMO released a new recommendation which happily specifies the same requirements as selected by the candidate [17].

8.3 Continuity of the service

Of all the components that combine to make up the DGNSS service, only the stochastic ones affect continuity. As with availability, the deterministic events that affect the beacon's signal-in-space have already been taken into account when predicting the coverage area. Since they are deterministic, they can have no effect on the continuity of the service. As with availability, the stochastic factors are the beacon's own signal and the three stochastic events: atmospheric noise, skywave interference and own-skywave fading. These four factors will now be examined in detail in respect of their possible effects on continuity.

8.3.1 Beacon continuity

The beacon's continuity can be calculated in accordance with the method given in the IALA guidelines [16]. The continuity is calculated over two years using:

$$continuity = 1 - \left(\frac{CTI}{MTBF} \right) \tag{8.1}$$

where *CTI* is the continuity time interval (three hours in this case) and *MTBF* is the mean time between failures, in hours. When calculating beacon continuity, in contrast to availability, it is assumed that there are no scheduled outages during the duration of the manoeuvre. This assumption is based on the fact that scheduled outages are announced in advance. Thus, no manoeuvre that depends critically on the system should be commenced if the system is forecast to be unavailable for any part of the duration of the manoeuvre. Continuity failure occurs where a manoeuvre has been commenced and then cannot be completed because the system fails.

Using the example from IALA's revision of IMO resolution A.815(19) [84] and assuming the lowest beacon availability of 99.5%, the corresponding MTBF calculated would be approximately 1947 hrs. This number would be the same under both day and night conditions. From this one can calculate:

$$continuity = 1 - \left(\frac{3}{1946.68} \right) = 99.85\% \tag{8.2}$$

This is the basis of the IALA continuity figure of 99.85% in areas served by a single beacon.

Taking only the beacon's continuity into account, Figs. 8.1 and 8.2 show the first results. These are the continuity values provided by the 16 beacons of the United Kingdom and Ireland. Fig. 8.1 is for daytime, and Fig. 8.2 for night-time, conditions. The light blue regions show where the 99.97% continuity requirement is met, while the dark blue corresponds to the 99.85% requirement. These plots use the coverage boundaries of each individual beacon and calculate the continuity at each location as the continuity of any signal being provided by any of the several beacons that give simultaneous coverage. So, where more than one beacon provides coverage, the continuity of service is greater than with a single beacon. This assumes an instantaneous transfer from one beacon to the next, should the first fail. The effect on continuity of the various propagation factors is not included.

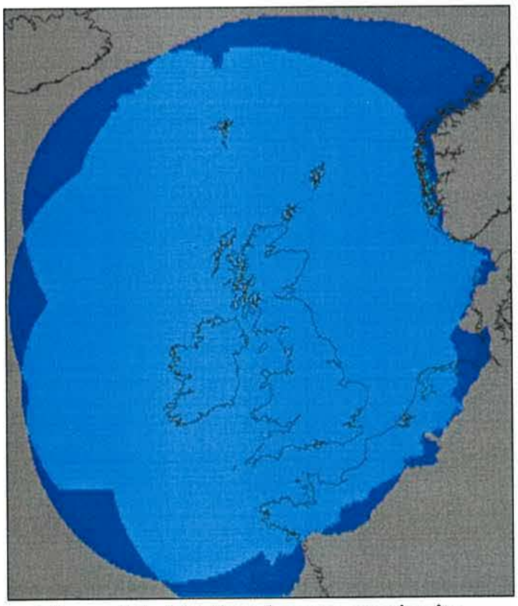

Figure 8.1: Daytime beacon continuity for the United Kingdom and Ireland.

Figure 8.2: Night-time beacon continuity for the United Kingdom and Ireland.

Light blue = 99.97% standard is met Dark blue = 99.85% standard is met

As with availability, the probability of a failure due to a rise in atmospheric noise, self-fading or skywave interference, will decrease the closer the receiver is to the beacon. Thus, close to the beacon, continuity is dominated by that of the beacon itself, that is, as in Figs. 8.1 and 8.2. Now let us include the stochastic events that affect the signal-in-space, which will increasingly modify the results the further one goes from the beacon.

8.3.2 Atmospheric noise

Calculating the effect of atmospheric noise on the continuity of a beacon's signal is considerably more difficult than calculating the continuity of the beacon itself. Since atmospheric noise is stochastic and difficult to predict, even knowing its standard deviation and mean value does not suffice. They tell us the percentage of the time that atmospheric noise will cause non-availability, but they give us no information as to the *distribution in time* of those failures, and so no knowledge of the MTBF. Thus they cannot directly be used to compute the effect of atmospheric noise on continuity. As it is not possible to calculate the continuity using the MTBF, a different approach was required, which started with examining atmospheric noise.

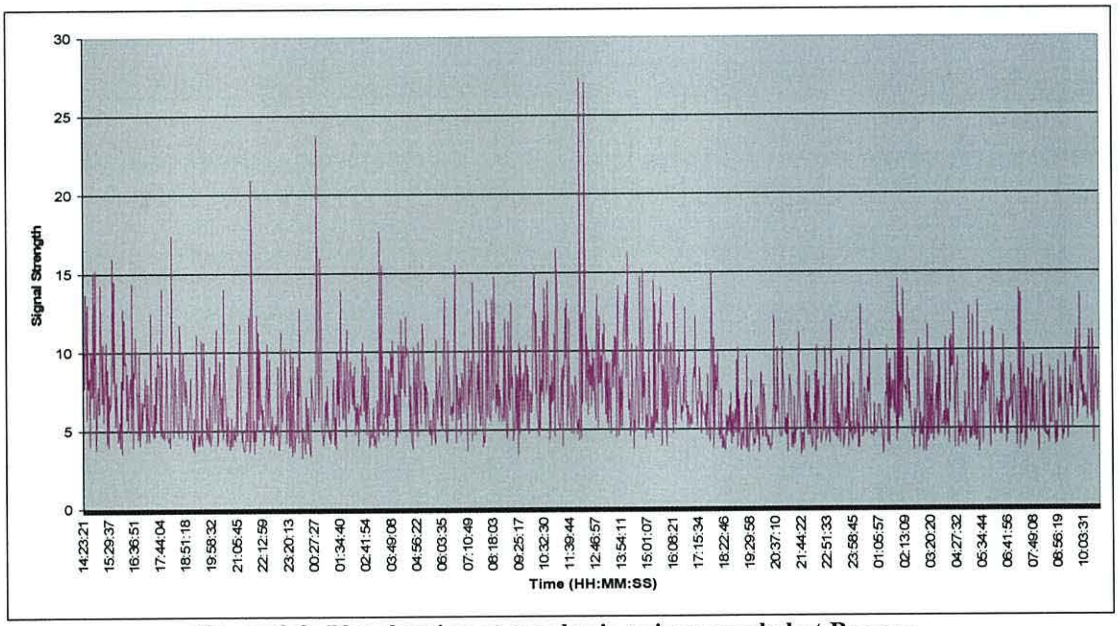

Figure 8.3: Plot showing atmospheric noise recorded at Bangor.

Fig. 8.3 shows atmospheric noise recorded at Bangor. The noise appears to consist of the two parts that characterise atmospheric noise: random spikes of relatively high intensity, and a continuous background noise of lower intensity.

The high-intensity random spikes are what predominately disrupt the service. To calculate their effect on continuity, one needs a measure of the mean time between these spikes and thus of the relationship between the SNR of the received signal and the MTBF of the message. To measure these factors with a high level of confidence would require a far longer period of monitoring than that shown here. No such set of data appears ever to have been recorded. The MTBF is required to calculate the continuity, which is the probability of the messages remaining available over a short period of time. However, an alternative approach is to seek this probability directly, from which one can gather some indirect evidence from Poppe's research [14]. Poppe studied atmospheric noise extensively and recorded the variation of word error rate (WER) with SNR, as shown in Fig. 8.4.

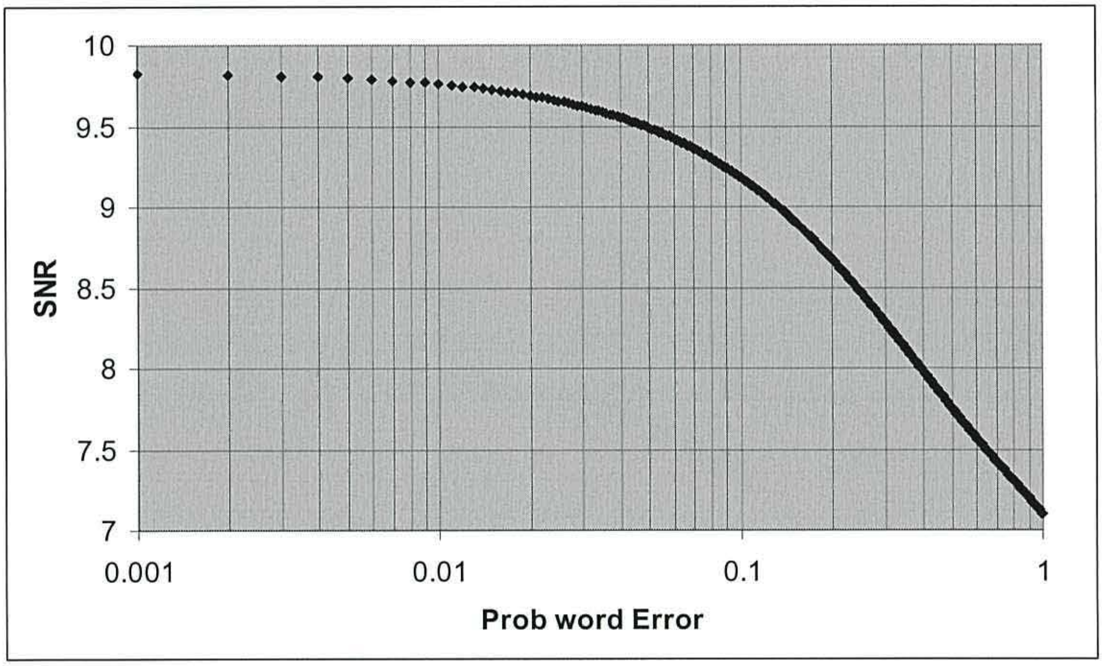

Figure 8.4: Probability of a received word error against SNR, from Poppe [14].

Poppe recorded this data in a quiet location using an off-air transmission, with negligible propagation effects, and a conventional differential beacon receiver. Noise was off-air atmospheric noise. Poppe's results appear reasonable: her measurements show that an SNR of 7dB, the ITU threshold, corresponded to a fairly high probability of word error. However, increasing the SNR slightly, to just 9dB, caused errors to become rare. So her "threshold" agreed with the ITU's to a dB or so. Thus, Poppe's results appear accurate enough to provide us with a good estimate of the effects of atmospheric noise on continuity.

Poppe's word error rate (WER) results may be used to calculate the probability of the service's becoming unavailable due to noise. This can be done knowing the number of words in each message. The probability of a message being successfully received is given by:

$$\Pr(message\ success) = \left[1 - \Pr(word\ error)\right]^{W}, \tag{8.3}$$

where W is the number of words (7 in the case of a Type 9-3 message), and Pr means probability. Fig. 8.5 plots this probability of message success against the signal-to-noise ratio.

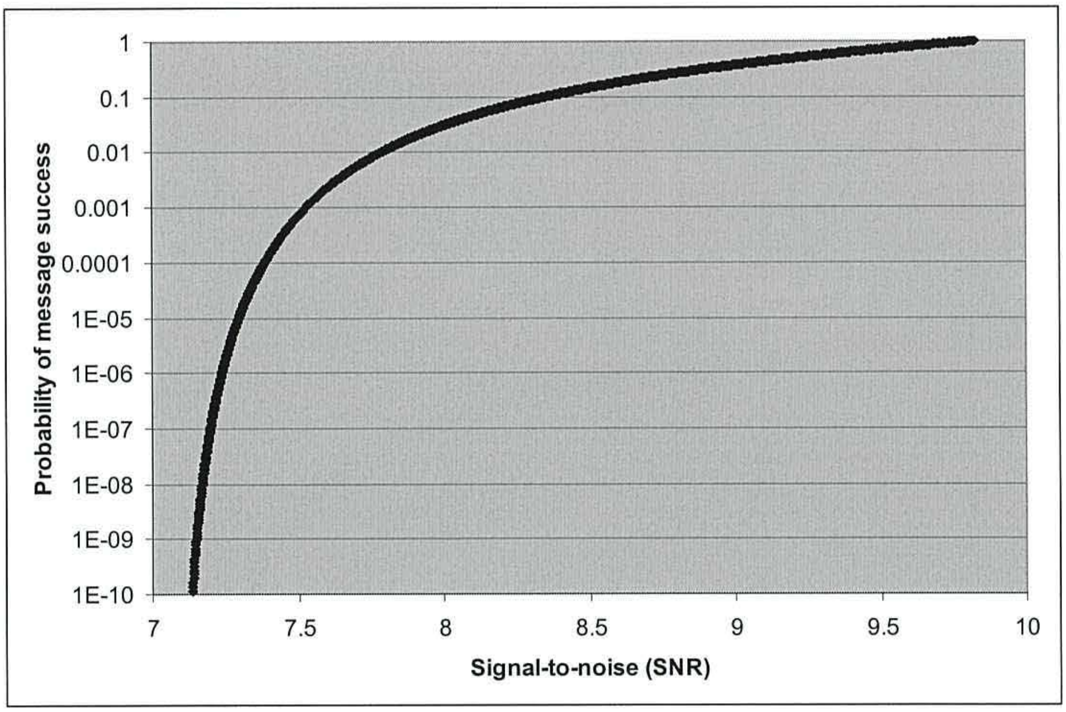

Figure 8.5: Probability of a Type 9-3 message being received successfully, plotted against SNR.

In Chapter 5.5, in considering the post-SA beacon selection strategy, the time-to-alarm requirement of 10s defined the maximum gap between successive messages. Since each Type 9-3 message takes 2.1s to transmit, it would be necessary to miss at least four consecutive messages for there to be a failure of the service. The probability of four successive messages failing can be calculated using the results from Fig. 8.5 and the following equation:

$$\Pr(failure) = (1 - \Pr(success))^{4} \tag{8.4}$$

Fig. 8.6 plots, against signal-to-noise ratio, the probability of failing successfully to receive any one of four consecutive messages. Clearly, this graph shows that in areas where the SNR is greater than 9dB, the probability of service failure is extremely small.

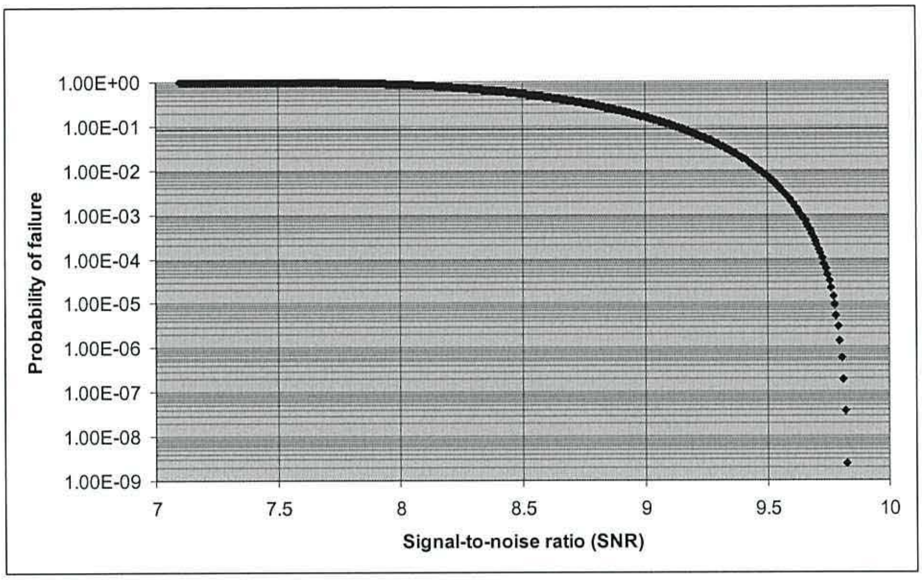

Figure 8.6: Probability of service failure against SNR

This method lets us calculate the probability of a short-term unavailability of the service due to a rise in atmospheric noise. This probability is used directly in the calculation of continuity to represent the probability of atmospheric noise disrupting the service.

8.3.3 Skywave interference

Like atmospheric noise, skywave interference is stochastic and can affect the continuity of the signal. Again, simple measures of statistical distribution are meaningless in this new context of continuity, since again it is the time between failures we need. As with atmospheric noise, no long-term data records are available from which one can compute an MTBF or its dependence on SNR. Such measurements would in practice be difficult to make in the radiobeacon band since it would be essential to separate the skywave interfering signal from all other unwanted skywave signals and from atmospheric noise.

The approach taken here is to assume that, for a given SNR, the probability of an error is the same for skywave interference as for when the noise is atmospheric noise of the same SNR. Then the same continuity/SNR relationship as for atmospheric noise (Fig. 8.7) can be used. Again, since there is a rapid change of error rate over just a small number of dB of SNR, this approximation is unlikely to result in significant errors.

In the case of SIR, however, the lowest value that should ever be encountered within the coverage area is 15dB, the edge-of-coverage limit. Thus, while there will undoubtedly be a finite probability of message failure due to skywave interference, it will be extremely small, and insignificant in comparison with the other two factors studied. The result of our analysis, therefore, has been to demonstrate that one need not take skywave interference into account in computing continuity.

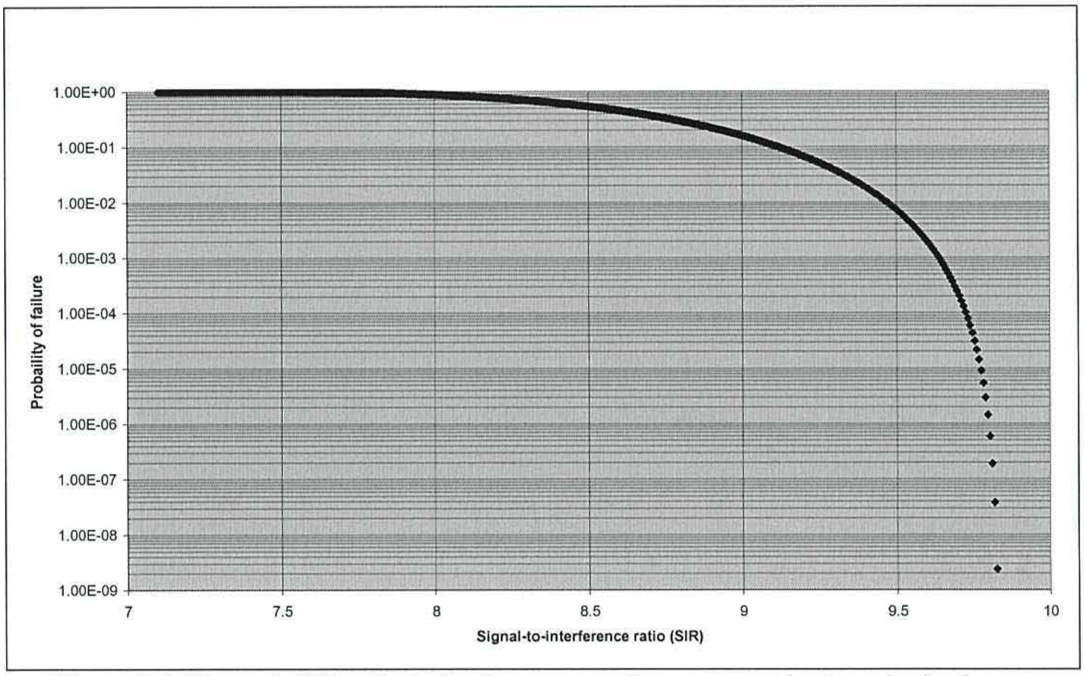

Figure 8.7: The probability of missing four consecutive messages due to a rise in skywave interference.

8.3.4 Self-fading

Self-fading, due to the interaction between the deterministic groundwave signal and the stochastic skywave signal, gives a stochastic result. Again, the mean time between events in which it disrupts the service is needed and again, the necessary large volume of experimental data to establish the relationship accurately is not available.

The following method of taking into account the effect of signal fading on continuity has been adopted. When calculating the night-time SNR and SIR values used to determine the continuity figure, a reduced beacon field strength due to self-fading is used. The value employed at each point is the strength exceeded 95% of the time [14]. This 95%-ile figure is, of course, the same one as was used to establish the outer edge of the beacon's coverage. While it is appreciated that self-fading is stochastic and alters with time, in the absence of any statistics, the field strength exceeded 95% of the time is used as a lower bound. It means that the stochastic effect of self-fading is set at a conservative level, as the actual field strength will be greater most of the time.

8.4 Continuity results

As explained in Section 8.3, several assumptions have been made in order to allow continuity to be estimated. These assumptions are that: Poppe's measurements reflect annual conditions; the effects of skywave interference on continuity closely resemble those of atmospheric noise for the same SNR; and that the effect of self-fading may be taken into account with sufficient accuracy by using the 95%-ile field strength figure at night. With these assumptions built into the model, the 3-hour service continuity figures can be calculated [106].

Figures 8.8 and 8.9 show the results for the 16 beacons of the United Kingdom and Ireland, for daytime and night-time respectively. The conventions are the same as in Figs. 8.1 and 8.2 above: light blue shows where the beacons provide the higher level of service continuity (99.97%) and dark blue the lower requirement (99.85%). Meeting the higher standard requires more than one beacon to provide coverage simultaneously. Just a single beacon is sufficient to meet the lower standard.

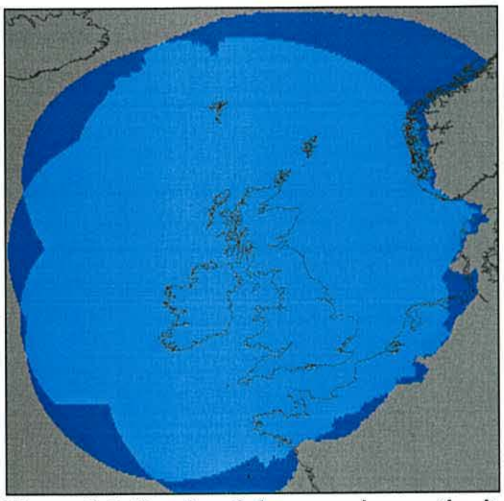

Figure 8.8: Daytime 3-hour service continuity for the 16 beacons of the UK and Ireland.

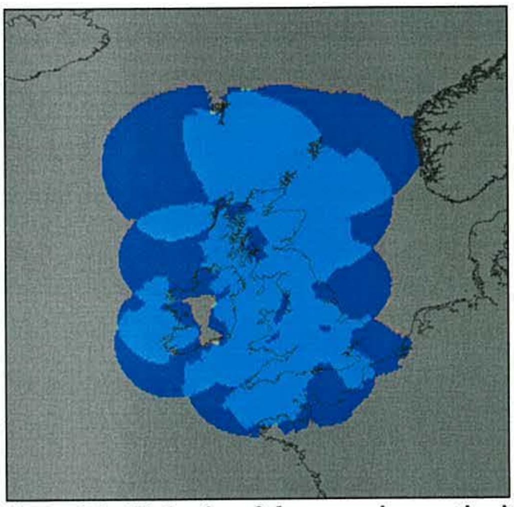

Figure 8.9: Night-time 3-hour service continuity for the 16 beacons of the UK and Ireland.

Light blue = 99.97% (critical areas requirement met),
Dark blue = 99.85% (other areas requirement met).

Fig. 8.8 shows that, as with availability, meeting the higher continuity requirement by day is not a problem. In all coastal and inland locations, sufficient multiple beacons provide coverage simultaneously to allow the 99.97% requirement to be met easily.

By night, in contrast, with the reduction of beacons' coverage areas due to self-fading and the rise in skywave interference and atmospheric noise, substantial reductions in the areas in which either standard is met are clearly seen. Fewer coastal areas now receive a service that meets the 99.97% continuity standard. But in all other coastal regions the lower 99.85% is achieved, with the exception of the southern Irish coast.

Figure 8.10: Daytime 3-hour service continuity provided by the DGNSS beacons of the EMA.
Light blue = 99.97% (critical areas requirement met),
Dark blue = 99.85% (other areas requirement met).

Figs. 8.10 and 8.11 show the daytime and night-time continuity results, respectively, for the whole EMA.

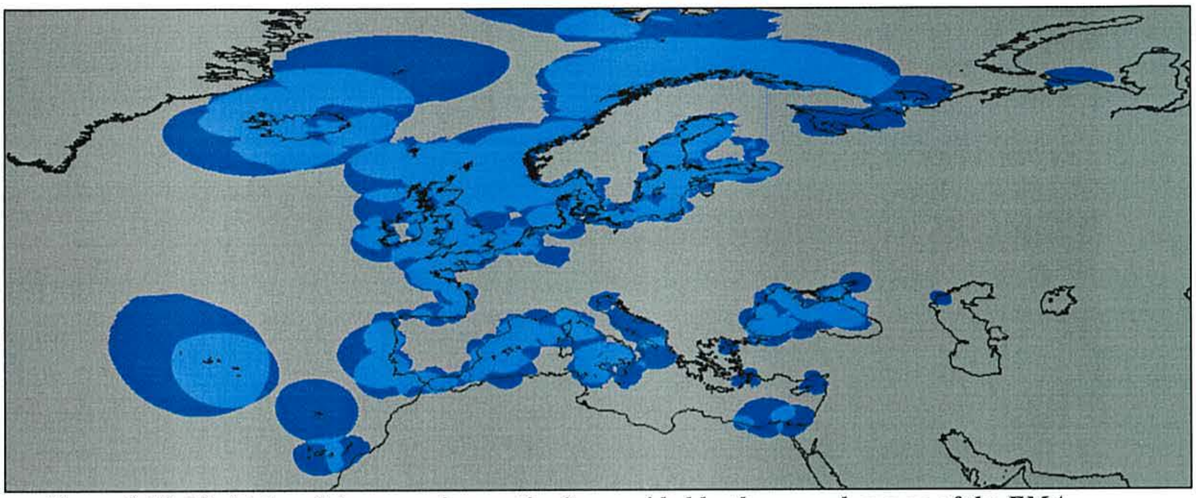

Figure 8.11: Night-time 3-hour service continuity provided by the many beacons of the EMA. Light blue = 99.97% (critical areas requirement met), Dark blue = 99.85% (other areas requirement met).

Again, by day (Fig. 8.10), all coastal regions meet the higher 99.97% continuity requirement. Fig. 8.11 shows the now familiar night-time reduction. Nevertheless, in most coastal regions the 99.97% standard is achieved, with the other areas getting the lower-standard service.

8.5 Set of service standards

The set of service standards that have been calculated at each location includes the coverage criteria, the availability standards and the continuity standards. For a service to be satisfactory, all must be met.

Taking the 16 beacons of the United Kingdom and Ireland, let us first compare the new continuity results (Fig. 8.12) with the availability results computed earlier (Fig. 8.13). It is clear that the service meets the continuity requirements in areas where it fails to meet the availability requirements. In such areas the service is available for 3-hour periods of time, but is not available 99.5% of the time over two years. So one concludes that the availability criterion is the more stringent one.

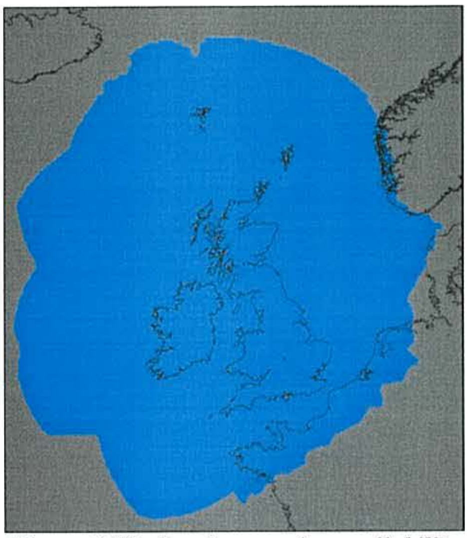

Figure 8.12: Daytime service availability.
Light blue = 99.8%
(critical areas requirement met),
Dark blue = 99.5%
(other areas requirement met).

Figure 8.13: Daytime 3-hour service continuity.
Light blue = 99.97%
(critical areas requirement met),
Dark blue = 99.85%
(other areas requirement met).

The new software has been extended to let us examine all service criteria and plot the regions in which the service meets all three standards: coverage, availability and continuity. Fig. 8.14 shows the results by day for the 16 beacons of the United Kingdom and Ireland and Fig. 8.15 shows the equivalent night-time results.

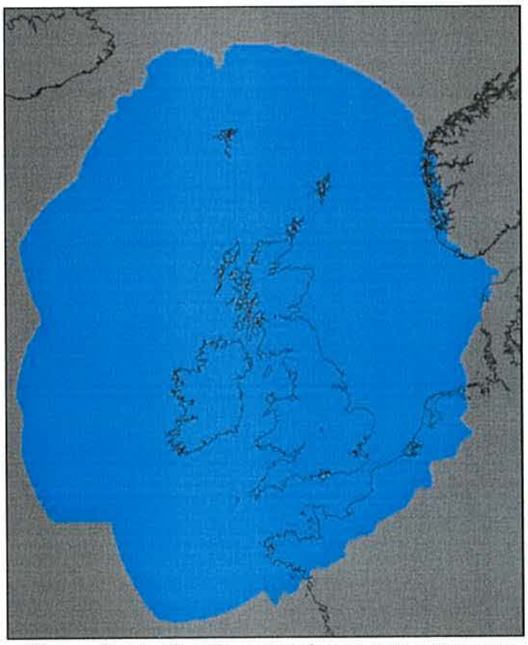

Figure 8.14: Daytime service meets coverage, availability and continuity requirements.

Figure 8.15: Night-time service meets coverage, availability and continuity requirements.

Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%.
Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

Because the availability requirements are more stringent than the continuity ones, Figs. 8.14 and 8.15 are identical to the corresponding day and night availability plots. Figs. 8.16 and 8.17 show the equivalent plots for all the DGNSS beacons of the EMA.

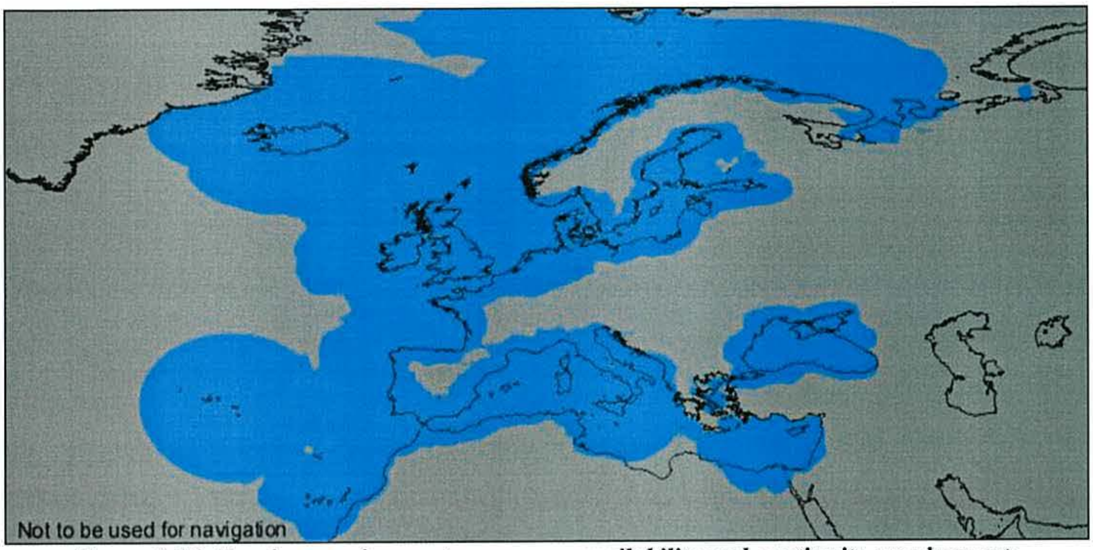

Figure 8.16: Daytime service meets coverage, availability and continuity requirements. Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%. Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

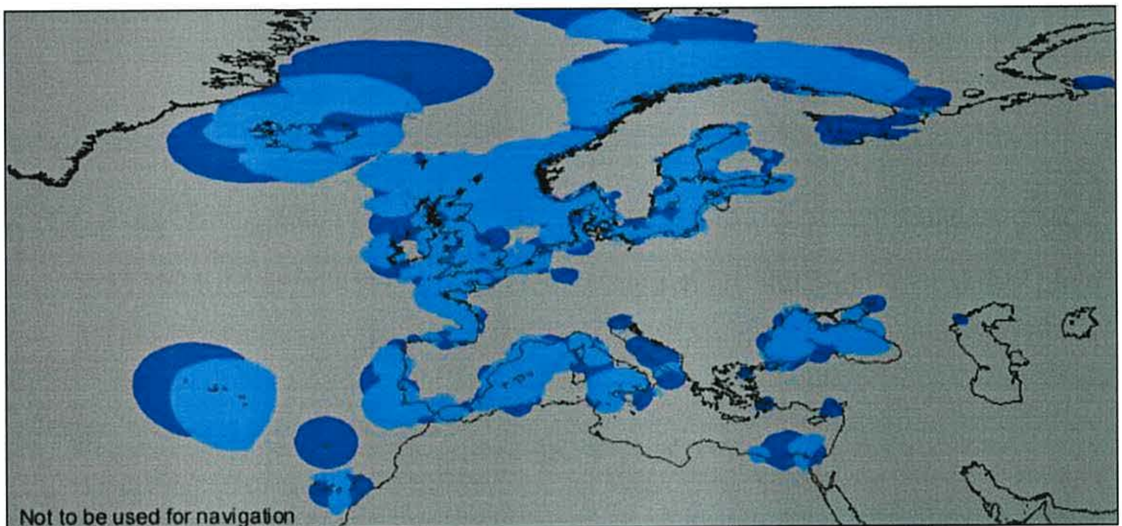

Figure 8.17: Night-time service meets coverage, availability and continuity requirements. Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%. Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

Fig. 8.16 shows that with the figures used, which include the IALA's example values in the case of the beacon, by day all of coastal regions of the EMA are provided with a service which meets the higher standards for coverage, availability and continuity.

By night (Fig. 8.17), when coverage areas are reduced, the majority of the coastal regions are still provided with a service that meets the more stringent requirements. In those regions where these conditions are not met, the service nevertheless meets the requirements for areas of low-risk and single beacon coverage.

8.6 Verification

As we have seen in this chapter, continuity is an extremely complex factor to calculate. It is also a difficult one to measure, for two reasons. Firstly, even to use a receiver introduces a component into the system that is not included in the model and so can affect the result. Secondly, it would be very difficult to distinguish between self-fading, atmospheric noise and skywave interference, as the source of any given disruption. For these reasons, the candidate has not attempted to make measurements to verify the continuity results.

However, the examination of the factors that determine coverage above has been valuable in that it has further justified the minimum SNR values employed to establish the coverage limits. The assumptions made have been clearly stated, and justified.

8.7 Conclusions

In this chapter, for the first time, continuity has been examined. The same events that set availability are shown to determine continuity. Each of these events has been examined. Without knowing, or being able to calculate, an MTBF for each signal-to-noise ratio, it is impossible to calculate precisely their effects on continuity. But an alternative approach has been pioneered, based on the work of Poppe. Her research has shown the dependence of word error rate (WER) on signal-to-noise ratio. This has allowed us at least to estimate the probability of missing a message, given knowledge of the SNR. A failure of the service is then defined as a failure to receive four consecutive messages and so experiencing a message break in excess of the time-to-alarm. Using this method, the probability of such a failure can be calculated as a function of SNR, and hence the effect of that failure on continuity.

This is done first for atmospheric noise. The process is then repeated for skywave interference, the assumption being made that the receiver behaves similarly. However, it becomes clear that interference is most unlikely to reach levels that affect continuity within the coverage of a beacon. Finally, the effect of self-fading is taken into account by calculating an appropriate field strength for use when determining the SNR and SIR ratios to be used in continuity calculations at night. In this way, continuity values are estimated and the results compared with the international standards.

We have developed separately the abilities to plot coverage, availability, and continuity. Now, for the first time, we bring the results together. This lets us show just where administrations, service providers, and other bodies, simultaneously meet all these individual standards. In other words, the final results show where the beacons should provide a safe and reliable service.

Chapter 9

Conclusions

The primary objective of this research has been to develop techniques for predicting the signal availability and continuity of marine radiobeacon DGNSS systems that are as precise and comprehensive as the state of present understanding allows. However, it has accomplished a good deal more.

Prior to this research, service providers were left to devise their own methods of calculating availability and continuity and, as shown in this research, the standards they were to follow were far from clear. They were also left to establish the availability of the service they provided by laborious analysis of recordings of the outages of the multiple beacons, identifying those outages of beacons with overlapping coverage that could mean a failure of the service to meet the required standards.

This research fills two voids. The software model developed as part of this research incorporates the standards. The values to be built in have been selected using a common-sense approach, and happily the IMO has subsequently chosen to employ the same values in respect of availability and continuity [17]. In addition, several methods of calculating availability have been examined and the use of Fault Tree Analysis has been chosen as the most appropriate and built into the software.

The engine that powers all these analyses in the new software model developed for this research, draws on the Bangor Coverage Prediction Model, developed in the mid-1990's for predicting the coverage of marine radiobeacons. This earlier software was examined, and while its functionality was found still to be sound for predicting a beacon's coverage area, its structure was shown to limit greatly the amount of information it stored.

It was shown that the old software would be quite inadequate for the demands of an availability and continuity model. A new software architecture was developed for this purpose which allows detailed information relating to many beacons to be accessed simultaneously. Whilst developing the new software, the functionality of the previous Bangor model was maintained; indeed, the results of the old model were used to verify those from the new one.

The new software model was designed to let administrations predict the coverage, availability and continuity of their beacons, or networks of beacons. But its development also opened the door to the analysis of another issue, that of beacon selection. The two beacon selection methods employed by existing receivers were identified and investigated. Using the software model, they were then shown to select different beacons across many regions, some of considerable significance. Then the beacon selection problem was considered afresh. It was realised that neither existing selection strategy actually chose the beacon that would give the highest-accuracy fixes. So a new strategy was devised, modelled, and the results published. Then, with the ending of SA, it was realised that the rules of the game had changed fundamentally: in many instances, what had been the "Best Beacon" was no longer so. A new method was required. The situation was re-analysed in the light of the setting-to-zero of SA, and the most promising approach was shown to be the use of the nearest beacon (ie the one with least spatial dilution of precision) that met the time-to-alarm requirement. This realisation led to a detailed study of the complex and often conflicting standards for time-to-alarm in the international documentation and, in turn, to the modelling of the new strategy. Finally, "Best Beacon" and "Best Alternate" results were generated for the whole of the European Maritime Area, and published for use by the radiobeacon DGNSS community.

In essence, this research has answered many questions, on how to calculate availability and continuity and also helped identify which standards should be employed. It goes beyond this by plotting where a single beacon, or a network of beacons, meets the standards for coverage, availability and continuity. It predicts where the best service is provided and then, drawing on the beacon selection work, informs the mariner which beacon he should be using, while informing the administration about the number and identities of the beacons that serve any area.

9.1 Review of thesis

Chapter 2 gave an introduction to Global Navigation Satellite Systems, explaining how they work and discussing the three main systems: GPS, GLONASS and Galileo. GPS was chosen to be treated in much greater detail than the others, since it is the principal system currently used in marine radiobeacon DGNSS. The need for DGNSS was then introduced, with a particular discussion of its importance in enhancing integrity.

An analysis of the performance of DGNSS radiobeacons was presented in Chapter 3. The Bangor Coverage Prediction Model (BCPM) was introduced and its operation explained. Radiobeacon signal propagation modes, and the interaction between skywave and groundwave signals, were discussed. Other factors that affect the coverage of a radiobeacon, such as interference and atmospheric noise, are also introduced. The atmospheric noise database used in this research was introduced and the candidate's work on extending it to cover areas outside the EMA boundaries, so that full coverage of beacons could be plotted, was set out. The coverage factors discussed in this early chapter play important parts throughout this research. Previous relevant work on optimising the radiobeacon band plan so as to minimise interference was also introduced and explained. The candidate's contribution to the verification of the optimisation process, something he undertook having found a weakness in the earlier work, is also presented in this chapter. He concluded that, while the optimisation had been successful, a recent trend of ever-increasing station power levels in the limited frequency band had resulted in some long-range skywave interference being neglected. The candidate demonstrated clearly that the band had become saturated and that interference from powerful beacons is now an unavoidable problem.

Chapter 4 is about the development of the new software architecture. The BCPM having been reviewed in Chapter 3 and shown to be inadequate for predicting availability and continuity, a new software architecture was proposed. This chapter describes how it was developed, refined, and its results verified.

The novel approach allows data on many beacons to be accessed simultaneously, which the BCPM could not do. The operation of the new architecture was verified against the BCPM and ITU curves, to ensure that the coverage software functionality remained correct.

The development of the new software architecture paved the way for an additional question to be answered, that of beacon selection, which is the subject of Chapter 5. For the first time, existing beacon selection methods were examined and the candidate showed that there are significant differences between the beacons they selected. The task of beacon selection was reviewed and a novel selection algorithm was developed, one that selected the beacon offering the highest quality. Then, with the removal of selective availability (which happened whilst this work was under way), the constraints on beacon selection changed. A new method was developed, one that selects the nearest beacon that meets the time-to-alarm requirements, so providing the greatest accuracy and integrity. Along with identifying the "Best beacon" the candidate has also identified the "Best alternate" beacon to be used if the best is not available.

The candidate also developed formats for presenting the results of this work designed to make them convenient for users of various kinds of receivers. Manual receiver users could employ charts that showed them where to swap from one beacon to the next, while at the same time indicating the coverage of the service by day and night. In parallel, a text-based list format was developed so that designers of automatically-tuning receivers could ensure that they too always selected the best beacon. Finally, the new software allowed the number of beacons that simultaneously provided an acceptable service to each location to be counted; this information is needed by system planners and administrations as they attempt to provide adequate, but not excessive, redundancy.

Current approaches to studying the service availability of radio systems were introduced in Chapter 6. Three such approaches were analysed, with a Fault Tree Analysis being selected as the most appropriate for further development within the new model.

The other two techniques were deemed either too complicated or inappropriate for the service to be modelled. A commercial Fault Tree Analysis software package was installed and operated, but then replaced by functions written by the candidate and incorporated in to the new model.

Nevertheless, it served to verify the results of those functions. For the first time, the events that are capable of affecting availability were examined. They were shown to fall into two distinct groups: deterministic and stochastic. The candidate showed that all relevant deterministic events had already been taken into account in determining the coverage of each beacon and that they could not affect its availability; however, the stochastic events certainly could. These events were identified as: failures at the beacon itself, and increases in atmospheric noise, skywave interference, and skywave self-fading. For the first time in the radiobeacon context, algorithms were developed to calculate first the availability of a single beacon and its signal-in-space. Then they were extended to the more common, but more demanding case of the availability of the service provided by multiple beacons with overlapping coverage. This final step required the degree of correlation of failure mechanisms, as between beacons, to be investigated, and this was done by means of a programme of experimental measurements and analysis of the results. The degree of correlation was shown to be negligible in respect of all three stochastic events.

Chapter 7 introduces the development of the availability model. The first stage was to identify the service availability requirements to be employed in this research. Standards from many authoritative sources were examined, and the requirements set by IALA were selected, this decision being carefully justified. Availability was then modelled using first the approach of applying the edge-of-coverage conditions everywhere, the various failure mechanisms being combined by means of the FTA. This work resulted in the first plot of availability. It was novel, but could clearly be improved. A novel, and more accurate, approach of calculating the availability based on the conditions at each location was then devised and implemented. This method gave a much more realistic result and showed the way ahead.

The final approach employed a novel technique in which the statistical distributions of the stochastic events were incorporated and their effects combined to give the availability of the service. In order to use this method the candidate developed a means of calculating the standard deviation of stochastic skywave self-fading.

This method resulted in a procedure that, in the candidate's opinion, best models reality. For the first time, daytime and night-time availability plots were produced for both the British Isles and the European Maritime Area.

Since availability results are required to be calculated over two years, it was necessary to devise a means to combine the separate daytime and night-time results produced by the model into annualised data. This required the percentage of the two-year period in which 'night-time' conditions applied (or day-time) to be calculated. The basis on which this was done was an analysis by the candidate of Decca Navigator skywave data, something not previously attempted in the radiobeacon context. Finally, two-year availability plots could be produced for the British Isles and the EMA. These have been published in international conferences.

Continuity is the subject of Chapter 8. The first stage was to select the continuity requirements. Again, many authoritative sources were reviewed, with the IALA recommendations being selected as the most appropriate. Calculating the continuity of the beacon was shown to be a straightforward task; however, the continuity of the other stochastic signal-in-space events was shown to be more complicated. Without knowing, or being able to calculate, the failure rate for each stochastic event, an alternative approach was chosen. Measurements recorded by Poppe were analysed, and a method developed to calculate the probability of a short-term failure due to atmospheric noise for a given signal-to-noise ratio. This novel approach was then also assumed to give a reasonable representation of failures due to skywave interference. However, the analysis proved that any effect skywave interference has on continuity will be extremely small, and may be regarded as negligible. When calculating the continuity effects of self-fading, the following conservative approach was chosen. The signal strength employed at night to determine SNR is to be that at the edge of coverage, that is, 95%-ile faded signal.

The stochastic nature of self-fading means that this may slightly underestimate the strength of the wanted signal at night. However, the exact statistics are not known so the candidate preferred to produce conservative results.

The individual continuity probabilities were then combined in the software model to produce results showing where the service meets the continuity standards. Results were produced and published showing the 3-hour continuity, by day and night, across the British Isles and the EMA.

Finally, plots were produced and published showing where all three standards: coverage, availability and continuity, are all met, and a reliable and safe service provided. This is the first time this has been done, and the results have proved of great interest to the GLAs of Great Britain and Ireland

9.2 The Bangor radiobeacon analysis model (BARAM)

The principal achievement of this research has been to develop a software model that predicts the coverage, availability, and continuity of radiobeacon systems and identifies at every point the best beacon to use. The *Bangor Radiobeacon Analysis Model* that has resulted is a self-contained application. The candidate is responsible for the architecture of the new software, plus the beacon selection strategies and the availability and continuity prediction functionality of this model. The candidate is also responsible for the implementation, testing, and verification of its output.

During its development, the model has been used extensively to assist in the planning and trouble-shooting of radiobeacon systems. A guide to operating the software resulting from this research is presented in Appendix E. The GLAs have reviewed the work and results at four-monthly intervals throughout. In addition, coverage diagrams have been produced using the new software for the administrations of Norway, Germany, the UK and Ireland. In a specific example of its use, the Commissioners of Irish Lights were concerned at the lack of coverage provided by the 16 beacons of the United Kingdom and Ireland along the Southern Irish coast. The software was employed on a fact-finding mission, to identify the reason for this 'hole'.

The results showed that beacons added to the band since the band was optimised were causing skywave interference to the two beacons that should have covered this coast. A report on this work is presented in Appendix D.

9.3 Suggestions for further work

As mentioned in Chapter 8, the most promising line of future work is extending the quantitative understanding of the stochastic events that determine continuity. This would require a series of extensive, and careful, measurements to record their behaviour. It would be necessary to record a considerable volume of data, from which it should be possible to obtain an MTBF value that could then be used to refine the accuracy of the continuity calculations.

At the present time, global navigation is a promising and developing area. The removal of selective availability has raised many questions, such as: Can the beacon data rate be changed? Can the beacon service be used to transmit other data including, for example, carrier-phase corrections?

The rate, message type, and information transmitted currently by radiobeacons were originally chosen to combat the quickly-changing SA errors. Now that this error source has been removed, there is scope for changes in the RTCM messages, the information they carry, and the rate at which they are transmitted. Future work would be to develop software that took these changes into account, for use in investigating and planning such potential changes.

Concurrent work at Bangor in which the candidate is playing an important part, involves a first investigation into the simultaneous use of corrections from multiple beacons, employing a regional-area augmentation strategy (RAAS) (See Section 2.7) [63]. Should this study show that there is a benefit in the RAAS technique, a future project would be to modify the candidate's model to show where users are likely to benefit from this innovation, plus which set of beacons should be used at any location, and what effects the new mode would have on availability and continuity.

9.4 Conclusions

This research has introduced, analysed, and implemented a more precise and comprehensive method of calculating signal availability and continuity within the coverage region of a DGNSS radiobeacon, or a series of radiobeacons. The model brings together existing coverage prediction techniques and then adapts them within a new architecture that, while maintaining their functionality, enables much more information to be handled. The model brings together both the deterministic and stochastic events that affect coverage, availability, and continuity.

Within a beacon's coverage area, only the stochastic events can affect the availability and continuity of the service and they are identified and employed accordingly. The software calculates the availability and continuity of a single beacon or network of beacons and shows both where they meet the most stringent requirements and which beacon should be selected point-by-point.

It is hoped this software which is able, and has been used, to predict coverage, availability and continuity, as well as to highlight the best beacon to use, will be widely employed in the future for analysing problem areas and designing new beacon systems.

References

[1] P. Misra and P. Enge. *"Global Positioning System - Signals, Measurements, and Performance"*, Ganga-Jamuna Press, 2001.

[2] US Department of Defense, *"Global Positioning System Standard Positioning Service Performance Standard"*, 2001.

[3] GLONASS website, *http://www.rssi.ru/SFCSIC/english.html*.

[4] Galileo website, *"http://www.esa.int/export/esaSA/GGGMX650NDC_navigation_0.html"*.

[5] Admiralty list of radio signals.

[6] IALA, *"Draft Recommendation on the Performance and Monitoring of DGNSS Services in the Frequency Band 283.5 - 325 kHz"*, IALA Recommendation R-121, 2002.

[7] General Lighthouse Authorities of the United Kingdom and the Republic of Ireland, *"Marine Differential GPS Service"*, Information Leaflet, 2002.

[8] P. Enge, M. Ruane and D. Langlais, *"Coverage of a Radio Beacon-Based Differential GPS Network"*, Journal of The Institute of Navigation, Vol. 34, No. 4, 1988.

[9] I Korn, *"Simple Expression for Interchannel an Intersymbol Interface Degradation in MSK systems with Application to Systems with Gaussian Filters"*, IEEE Transactions on Communications. pp.1968-1972, 1982.

[10] F. Howard et al, *"A Comparison of Data Transmission Methods for Realtime DGPS"*, ION Satellite Division's Technical Meeting. 1991.

[11] IALA, *"List of Radionavigation Services - DGNSS Reference and Transmitting Stations in the Maritime Radionavigation (Radiobeacons) Band"*, 1999.

[12] International Maritime Organization, *"Word-Wide Radionavigation System"*, Resolution A.815(19), 1995.

[13] European Maritime Radionavigation Forum, *"Draft revised Applications and User Requirements report"*, EMRF 6/9/1, 2001.

[14] D. C. Poppe, *"Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions"*, Ph.D. Thesis, University of Wales, Bangor. 1995.

[15] International Maritime Organization, *"Maritime Policy For A Future Global Navigation Satellite System (GNSS)"*, Resolution A.860(20), 1997.

[16] IALA, *"Guidelines for the Performance and Monitoring of a DGNSS Service in the Band 283.5 - 325 kHz"*, 1999.

[17] International Maritime Organization, *"Revised version of "World-wide Radionavigation System", A.815(19)"*, Resolution A.XXX (A.815(19)), 2001.

[18] T. Moore, C. Hill and L. Monteiro, *"The Portuguese DGPS Network"*, Proc. 5th European Symposium on Global Navigation Satellite Systems (GNSS '01, Sevillia - Spain). 2001.

[19] C. Specht, A. Felski and F. Grabski, *" Availability of the DGPS radiobeacon signals - analytical method"*, Proc. 3rd European Symposium on Global Navigation Satellite Systems (GNSS 1999 - Genoa, Italy). 1999.

[20] P. Creamer, D. Cho, P. Morris and J. Pisano, *"Differential GPS Mission Needs Analysis: Harbor Entry and Approach"*, TASC, Nov 1997.

[21] US Department of Defense and Department of Transportation, *"Federal Radionavigation Plan 2001"* FRP 2001, http://www.navcen.uscg.gov./. 2001

[22] P.H. Dana, *" Global Positioning System Overview - The Geographer's Craft Project"* 1999

[23] United States Coast Guard, " Presentation *on Precise Positioning Service - 30th CGSIC Meeting"* http://www.navcen.uscg.gov./cgsic/meetings/ summaryrpts/30thmeeting/aii/tsld004.htm. 1997

[24] US Department of Defense and Department of Transportation, *"Federal Radionavigation Plan 1999"*, FRP1999, http://www.navcen.uscg.gov./. 1999

[25] B. E. Turhan, *"Optimisation of MF DGNSS, Maritime and Aeronautical Radiobeacon coverage by frequency re-assignment"*, Ph.D. Thesis, University of Wales, Bangor. 1999

[26] US Presidential Statement, *"Statement By The President Regarding The United States' Decision To Stop Degrading Global Positioning System Accuracy"*, 2000.

[27] B. W. Parkinson and J. J. Spilker Jr, *"Global Positioning System: Theory and Applications (Volume 1)"*, American Institute of Aeronautics and Astronautics, Inc. 1996.

[28] A. J. Van Dierendonck, *"Understanding GPS Receiver Technology: A Tutorial"*, GPS World, Vol.6, pp.34-44. 1995.

[29] P. Mattos, *"GPS 2: Receiver Architecture"*, Electronic World and Wireless World, pp19-32. 1993.

[30] R. B. Langley, *"The GPS Observables"*, GPS World, Vol. 4, pp.52-59. 1993.

[31] B. Forssell, *"Radionavigation Systems"*, Prentice Hall. 1991.

[32] L. Wanninger, *"Effects of Equatorial Ionosphere on GPS"*, GPS World, Vol.4, pp.48-54. 1993.

[33] W. A. Fees and S. G. Stephans, *"Evaluation of GPS Ionospheric Time Delay Algorithm for Single-Frequency Users"*, IEEE PLANS Symposium, pp.206-213. 1986.

[34] R. L. Greenspan et al, *"The Effects of Ionospheric Errors on Single-Frequency GPS users"*, ION Satellite Division's Technical Meeting. 1991.

[35] P. S. Jorgensen, *"An Assessment of Ionospheric Effects on the GPS User"*, Navigation, Vol.36, pp.195-204. 1989.

[36] C. Cohen, B. Pervan and B. Parkinson, "*Estimation of Absolute Ionospheric Delay Exclusively Through Single Frequency GPS Measurements*", Proceedings of ION. 1992.

[37] F. K. Brunner and W. M. Welsch, "*Effect of the Troposhere on GPS Measurements*", GPS World, Vol.4, pp.42-51. 1993.

[38] E. C. Ifeachor and B. W. Jervis, "*Digital Signal Processing - A practical approach*", Addison-Wesley, 1999.

[39] H. Z. Abidin, "*Multi-Monitor Station "On the Fly" Ambiguity Resolution: The Impacts of Satellite Geometry and Monitor Station Geometry*", IEEE PLANS Symposium, pp.412-418. 1992.

[40] B. Hofmann-Wellenhof, H. Lichtenegger and J. Collins, "*GPS Theory and Practice (3rd Edition, Revised)*", Springer-Verlag Wien New York. 1994.

[41] L. C. Larijani, "*GPS For Everyone*", American Interface Corporation. 1998.

[42] The German GPS information and observation group (GIBS), "*Information on the Russian GLObal NAvigation Satellite System (GLONASS)*", http://gibs.leipzig.ifag.de/cgi-bin/Info_glo.cgi?en.

[43] GPS World Online, "*Global View - January 2002*", http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=8263. 2002

[44] European Space Agency, "*Galileo - The European Programme for Global Navigation Services*" Galileo Brochure, http://europa.eu.int/comm/dgs/ energy_transport/galileo/doc/galileo_brochure_may2002.pdf. 2002.

[45] European Commission and European Space Agency, " *GALILEO Definition Studies Summary (Summary of Galileo Definition Phase, from Summer 1999 to the end of 2000)*".

[46] European Space Agency, "*Galileo Applications Website*", http://europa.eu.int/ comm/dgs/energy_transport/galileo/applications/maritime_en.htm.

[47] G. W. Hein et al, "*The GALILEO Frequency Structure and Signal Design*", ION Satellite Division's 14th International Technical Meeting (ION GPS 2001). 2001.

[48] US Institute of Navigation, "*Plenary session of the ION's Satellite Division's International Technical Meeting 2002*", Portland, Oregon. 2002.

[49] R. Johannesen, "*International Future Navigation Needs: Options and Concerns*", Navigation, Vol.34, pp.279-289. 1987.

[50] N. H. Keeler, "*Maritime Future Navigation Needs and Plans*" Navigation, Vol.34, pp.290-296. 1987.

[51] G. Gibbons et al, "*Automatic Vehicle Location: GPS meets IVHS*" GPS World, Vol.3, pp.22-34. 1993.

[52] R. M. Kalafus, "*GPS Integrity Channel RTCA Working Group Recommendations*", Navigation, Vol.36, pp.25-44. 1989

[53] A. J. Grant, D. Last and N. Ward, "*Quality criteria for the Maritime DGNSS system in a world without SA*", Proc. 5th European Symposium on Global Navigation Satellite Systems (GNSS '01, Sevillia - Spain). 2001.

[54] Radio Technical Commission for Maritime Services, "*RTCM Recommended Standards for Differential NAVSTAR GPS Reference Stations and Integrity Monitors (RSIM)*", Version 1.0, 1996.

[55] Radio Technical Commission for Maritime Services, "*RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service*", Version 2.2, 1998.

[56] N. Ward, "*The Future Development of Maritime Differential GNSS*", ION Satellite Division's National Technical Meeting (ION NTM) - San Diego, California. 2002.

[57] Radio Technical Commission for Maritime Services, "*RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service*", Version 2.3, 2002.

[58] US Department of Transportation and United States Coast Guard, "*Broadcast Standard for the USCG DGPS Navigation Service*", COMDTINST M16577.1, 1993.

[59] F. Forbes, S. Ryan and S. Wee, "*The CCG DGPS Project*", ION Satellite Division's Technical Meeting, pp.1451-1460. 1994.

[60] IALA, "*The provision of maritime radionavigation services in the frequency band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3*", IALA Recommendation R-115, 1999.

[61] International Telecommunications Union, "*Technical Characteristics of Differential Transmissions for Global Navigation Satellite Systems from Maritime Radio Beacons in the Frequency Band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3*", Recommendation ITU-R M.823-2, 1997.

[62] International Telecommunication Union, "*Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radiobeacons) in the European Maritime Area*", Geneva. 1985

[63] SATLOC, "*Introduction to e-Dif*", http://www.satloc.com/site_News4_02_01_22.htm.

[64] Canada NewsWire, "*CSI Wireless Awarded U.S. Patent for Revolutionary "e-Dif" Software*", http://micro.newswire.ca/releases/June2002/19/c7795.html, 2002.

[65] D. Last, A. Grant, A. Williams and N. Ward, "*Enhanced accuracy by regional operation of Europe's new radiobeacon differential system*", ION Satellite Division's International Technical Meeting (ION GPS 2002) - Portland, Oregon. 2002.

[66] ICAO, "*ICAO Frequency Assignment for NDBs*",1990.

[67] CT Systems, *www.ctsystems.org/Europe.gif.*

[68] International Electrotechnical Commission, "*Shipborne DGPS and DGLONASS Maritime Radio Beacon receiver Equipment*", IEC 61108-4:2001, 2000.

[69] International Telecommunication Union, "*Ground-wave Propagation Curves for Frequencies Between 10 kHz and 30 MHz*", Recommendation 368-7, 1992.

[70] G. Millington, "*Ground-Wave Propagation over an Inhomogeneous Smooth Earth*", Proceedings of the Institution of Electrical Engineers, Vol. 96, Part III, pp. 44-53. 1949.

[71] J. D. Last, M. D. Searle and R. G. Farnworth, "*The Northwest European Loran-C System: Coverage and Performance Predictions*", Navigation, Journal of The Institute of Navigation, Vol. 40, No.3, pp. 209-226. 1993.

[72] International Telecommunication Union, "*World Atlas of Ground Conductivities*", Recommendation ITU-R P.832-2, 1999.

[73] International Telecommunication Union, "*Prediction of Sky-Wave Field Strength at Frequencies between about 150 and 1700 kHz*", Recommendation ITU-R P.1147-1, 1999.

[74] J. D. Last, R. G. Farnworth and M. D. Searle, "*Effect of skywave interference on the coverage of Loran-C*", IEE Proceedings-F, Vol. 139, No.4. 1992.

[75] CCIR (International Radio Consultative Committee), "*Prediction of Skywave Field Strength Between 150 and 1600 kHz*", Recommendation 435-6, 1990.

[76] J. D. Last and D. C. Poppe, "*Effect of Skywave Interference on Coverage of Radio Beacon DGPS Stations*", IEE Proceedings on Radar, Sonar and Navigation, Vol. 144, No. 3, pp. 163-168. 1997.

[77] CCIR (International Radio Consultative Committee), "*Characteristics and Applications of Atmospheric Noise Data*", Report 322-3, ITU, Geneva. 1988.

[78] International Telecommunication Union, "*Radio Noise*", Recommendation ITU-R P.372-7, 2001.

[79] J. D. Last and B. E. Turhan, "*DGNSS Radiobeacons - The European Frequency Problem*", ION Satellite Division's International Technical Meeting (ION GPS) - Nashville. 1998.

[80] J. D. Last and B. E. Turhan, "*Maximising Radiobeacon Coverage in the EMA by Optimising the Band Plan*", Frequency Planning Conference for the European Maritime Area of ITU Region 1, International Association of Lighthouse Authorities, Paris. 1998.

[81] J. D. Last, B. E. Turhan and N. Ward, "*Replanning the European Radiobeacon DGNSS band*", International Loran Association and Royal Institute of Navigation ILA28/NAV99 Convention and Technical Symposium, London. 1999.

[82] DARP, "*Minutes of a meeting with representative of the General Lighthouse Authorities of the United Kingdom and the Republic of Ireland*", DARP 5, Dun Laoghaire, Ireland. 2001.

[83] IALA, "*Draft IALA Guidelines for the Performance and Monitoring of a DGNSS Service in the Band 283.5-325 kHz*", RNAV11/11/10, 1999.

[84] IALA, "*Draft revision of IMO resolution A.815(19)*", RNAV 15/5/1r1, 2001.

[85] European Maritime Radionavigation Forum, "*Review of IMO Resolution A.815(19)*", EMRF 6/7/1, 2001.

[86] G. Roberts, A. Grant and D. Last, "*Radiobeacon DGNSS Coverage Planning - a National Case Study*", Proc. MTS/IEEE Oceans 2001, Honolulu, HI, pp1800-1807. 2001.

[87] D. Last, A. Grant and N. Ward, "*Radiobeacon DGNSS station selection strategies - can we do better?*", ION Satellite Division's National Technical Meeting - (ION NTM), Longbeach, California. 2001.

[88] A. Grant and D. Last, "*Understanding Radiobeacon DGNSS Standards, Post-SA*", NAV01 Location and Navigation Conference, Royal Institute of Navigation, London. 2001.

[89] D. Last and A. Grant, "*Optimum Choice of Beacon in Maritime DGNSS Systems*", Journal of the Royal Institute of Navigation, 55, pp.249-262. 2002.

[90] P. Enge, D. Young, L. Sheymblatt and B. Westfall, "*DGPS/Radiobeacon Field Trials Comparing Type 1 and Type 9 Messaging*", Navigation: Journal of The Institute of Navigation. Vol.40, No.4. 1993-1994.

[91] P. B. Morris and D. P. McGaffigan, "*Differential GPS Harbor Entrance and Approach Requirements Analysis*", TASC, March 1999.

[92] U.S. Coast Guard Research and Development Center, "*Model Basis for the Navigation Aid Analysis Tool*", 1999,

[93] J. Bechta Dugan, S. J. Bavuso and M. A. Boyd, "*Fault Trees and Sequence Dependencies*", Proceedings of Annual Reliability and Maintainability Symposium. 1990.

[94] S. Zacks, "*Introduction to Reliability Analysis - Probability Models and Statistical Methods*", Springer-Verlag. 1992.

[95] W. A. Gardner, "*Introduction to Random Processes with Applications to Signals and Systems*", McGraw-Hill. 1990.

[96] ISOGRAPH Limited, "*Fault Tree+ Software*", Version 9.0,

[97] ISOGRAPH Limited, "*Fault Tree+ User Manual*", Version 9.0, 1999.

[98] International Maritime Organization, "*Revised maritime policy and requirements for a future global navigation satellite system (GNSS)*", Resolution A.915(22), 2001.

[99] DARP, "*Minutes of a meeting with representative of the General Lighthouse Authorities of the United Kingdom and the Republic of Ireland*", DARP 6, East Cowes, Isle of Wight. 2001.

[100] M Abramowitz and I. A. Stegun, "*Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables*", Dover Publications, Inc. 1965.

[101] IALA, "*DGPS Failure Definition*", RNAV 16/2/8 Radionavigation Committee, 16th Session, 2001.

[102] IALA, "*DRAFT note to the IALA Council on Availability and Reliability for Modification of IMO Resolution A.815(19)*", RNAV 14/5/7 Radionavigation Committee (14th Session), 2000.

[103] Decca Navigator, "*Operating Instructions and Marine Data sheets – Volume 1: North West Europe*", Amendment No.6, 1980.

[104] Decca Navigator, "*Operating Instructions and Marine Data sheets - Volume 2 - The World*", Amendment No.6, 1980

[105] DARP, "*Minutes of a meeting with representative of the General Lighthouse Authorities of the United Kingdom and the Republic of Ireland*", DARP 7, Bangor. 2002.

[106] A. Grant, D. Last and N. Ward, "*Marine Radiobeacon DGNSS Service - Predicting Availability and Continuity*", ION Satellite Division's International Technical Meeting (ION GPS) - Portland, Oregon. 2002.

Appendices

Appendix A

Millington's Method

Millington's method is used to calculate the attenuation of groundwave signals over a mixture of ground conductivity types. It works on the assumption that the direction of propagation is irrelevant the total attenuation, so the process is repeated for both directions and the average taken.

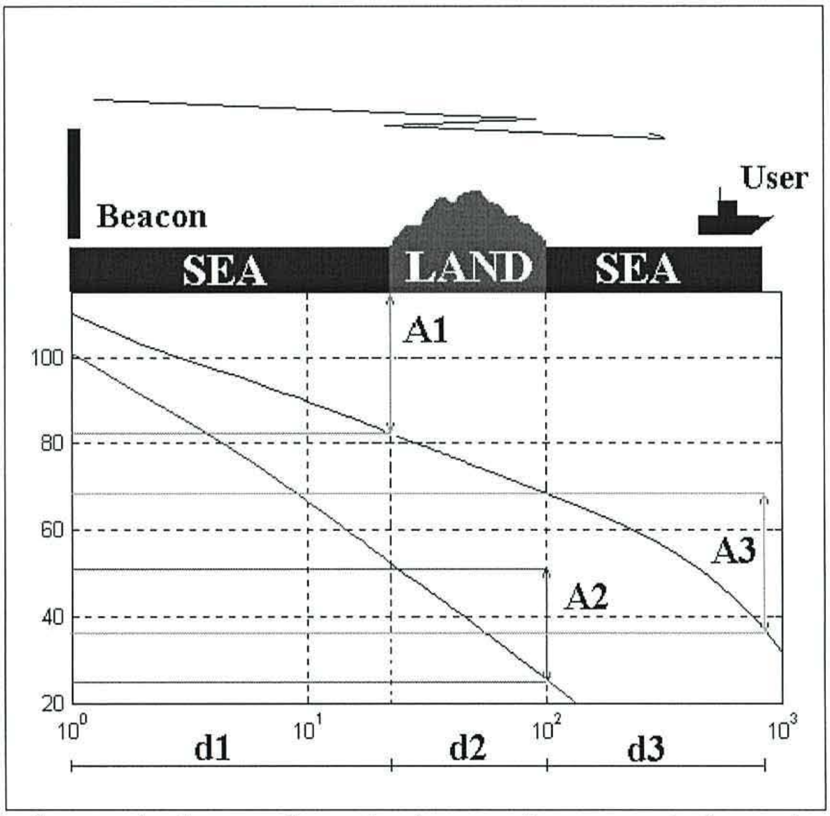

Figure A.1: An example of a groundwave signal propagating over a mixed ground conductivity.

Fig A.1 gives an example of Millington's method. The groundwave signal propagates over three ground conductivity areas, propagating across seawater, land and seawater once more. The attenuation experienced between the beacon and the edge of land results in the attenuation *A1,* shown in green. Then across the land, the signal is further attenuated by the amount *A2,* shown in red. Then, when it propagates over seawater once again, it is attenuated by *A3*, (shown in orange), until it reaches the receiver.

The total attenuation on the signal across the full propagation path is the sum of all three, A1+A2+A3. This is then repeated from the other direction and the two attenuation figures averaged, resulting in the total attenuation.

Appendix B

Current band-plan

The IALA frequency plan used in this research is shown below.

Frequency Plan for the European Maritime Area in the Band 283.5 - 315 kHz,
By frequency Fplan 45/46 (key to abbreviations at the end)

Channel	Freq	Name	Type	Lat	Long	Country	Range km	Range n.m.
-1	283.0	GRACIOSA	NDB	39N05	28W01	Port	185	100
-1	283.0	VRLIKA	NDB	43N56	16E26	Cro	90	49
0	283.5	ASTRAHANSKY	DGP	45N41	47E35	Rus	200	110
0	283.5	BRESSY	NDB	50N41	04E17	Belg	48	26
0	283.5	C_MAYOR	MB	43N29	03W47	Sp	90	49
0	283.5	C_TRAFALGAR	MB	36N11	06W02	Sp	90	49
0	283.5	DGEDGINSKY	DGP	65N12	36E49	Rus	320	170
0	283.5	DZIWNOW	DGP	54N01	14E44	Pol	150	81
0	283.5	KHERSONESSKIY	DGP	44N35	33E23	Ukr	200	110
0	283.5	LA_ENTALLADA	MB	28N13	13W56	Sp	205	111
0	283.5	MUGLA	DGP	37N02	28E10	Turk	300	162
1	284.0	ALEXANDRIA	DGP	31N09	29E51	Egy	277	150
1	284.0	ALMERIA_1	NDB	36N53	02W15	Sp	24	13
1	284.0	FASSBERG	NDB	52N55	10E11	Germ	90	49
1	284.0	GORNA_2	NDB	43N10	25E36	Bulg	10	5
1	284.0	LA_ENTALLADA	DGP	28N13	13W56	Sp	205	111
1	284.0	MIZEN_HEAD_LSTN	DGP	51N27	09W49	Ire	277	150
1	284.0	NINIAN_CENTRAL	NDB	60N51	01E27	UK	37	20
1	284.0	NINIAN_NORTH	NDB	60N54	01E25	UK	37	20
1	284.0	TORSVAAG	DGP	70N15	19E30	Nor	300	162
2	284.5	C_MACHICHACO	MB	43N27	02W45	Sp	180	97
2	284.5	DUESSELDORF	NDB	51N14	06E39	Germ	18	10
2	284.5	KANINSKY	DGP	68N39	43E18	Rus	240	130
2	284.5	LEIRVIKA	NDB	64N26	11E17	Nor	300	162
2	284.5	MYS_AYTODORSKIY	DGP	44N26	34E08	Ukr	200	110
2	284.5	P_ROSCA	MB	28N01	16W33	Sp	205	111
2	284.5	TRIESTE	DGP	45N41	13E46	It	277	150
3	285.0	C_MACHICHACO	DGP	43N27	02W45	Sp	180	97
3	285.0	GRANADA	NDB	37N11	03W50	Sp	25	14
3	285.0	KARISTOS	NDB	38N01	24E25	Gre	90	49
3	285.0	MADRID	NDB	40N22	03W46	Sp	45	24
3	285.0	P_ROSCA	DGP	28N01	16W33	Sp	205	111
3	285.0	PADOVA	NDB	45N21	11E49	It	45	24
3	285.0	RAS_TENES	MB	36N33	1E20	Alg	55	30
3	285.0	ROME	NDB	41N57	12E29	It	55	30
3	285.0	SOLLEFTEAA	NDB	63N09	17E01	Swe	31	17
3	285.0	SZCZECIN	NDB	53N34	14E56	Pol	90	49
3	285.0	TEMIRYUKSKIY_1	DGP	45N20	37E14	Rus	200	110
4	285.5	CASTELLON	MB	39N58	00E01	Sp	180	97
4	285.5	STIRLING	DGP	56N04	04W04	UK	370	200

4	285.5	TORRE_DE_HERCULES	MB	43N23	08W24	Sp	90	49
5	286.0	CASTELLON	DGP	39N58	00E01	Sp	180	97
5	286.0	HOHENFELS	NDB	49N13	011E51	Germ	45	24
5	286.0	MEHMETCIK	DGP	40N02	26E10	Turk	100	54
5	286.0	ROKISKIS	NDB	55N58	25E36	Lith	45	24
5	286.0	SAVONLINNA	DGP	61N55	28E45	Fin	70	38
5	286.0	TAGANROGSKY	DGP	47N12	38E57	Rus	200	110
6	286.5	BALTIYSK	DGP	54N38	19E54	Rus	200	110
6	286.5	DUNCANSBY_HEAD	DGP	58N39	03W01	UK	370	200
6	286.5	KEREMPE	DGP	42N01	33E20	Turk	300	162
6	286.5	PORQUEROLLES_PHARE	DGP	42N59	06E12	Fr	360	195
6	286.5	SKOMVAER	DGP	67N24	11E52	Nor	300	162
6	286.5	VILLACOUBLAY_1	NDB	48N46	02E06	Fr	45	24
7	287.0	HASSELT	DGP	50N56	05E20	Belg	200	108
7	287.0	KEFKEN	DGP	41N13	30E17	Turk	300	162
7	287.0	KLAMILA	DGP	60N30	27E30	Fin	250	135
7	287.0	LLANES	MB	43N25	04W45	Sp	90	49
7	287.0	RAS_CAXINE	DGP	36N49	2E57	Alg	370	200
7	287.0	SAMARRA	NDB	53N30	53E08	Rus	45	24
7	287.0	SKARDSFJARA	DGP	63N31	17W59	Ice	350	189
8	287.5	HAIFA	NDB	32N50	34E58	Is	148	80
8	287.5	MANTYLUOTO	DGP	61N36	21E28	Fin	250	135
8	287.5	P_PENNA	MB	42N10	14E43	It	277	150
8	287.5	PORTO_SANTO	DGP	33N04	16W21	Port	370	200
8	287.5	THORSHAVN	DGP	62N01	06W50	Dk	370	200
9	288.0	ANDA	NDB	61N50	06E07	Nor	300	162
9	288.0	CEUTA	MB	35N54	05W18	Sp	90	49
9	288.0	ESSARURIA	NDB	31N30	09W46	Mor	10	5
9	288.0	MERSIN	DGP	36N47	34E37	Turk	300	162
9	288.0	MONOR	NDB	47N20	019E24	Hung	105	57
9	288.0	PNT_LLOBREGAT	MB	41N19	02E39	Sp	180	97
9	288.0	SZYMANY	NDB	53N26	20E55	Pol	150	81
9	288.0	TRABLUS	NDB	32N54	13E12	Lib	37	20
9	288.0	YENIKALSKIY	DGP	45N23	36E39	Ukr	200	110
10	288.5	AVORD_GRON	NDB	47N07	02E48	Fr	90	49
10	288.5	GORKOVSKY	DGP	59N50	30E10	Rus	100	54
10	288.5	NJURUNDA	DGP	62N17	17E23	Swe	240	130
10	288.5	PNT_LLOBREGAT	DGP	41N19	02E39	Sp	180	97
10	288.5	SLETTNES	DGP	71N05	28E13	Nor	300	162
10	288.5	TORY_ISLAND_LSTN	DGP	55N16	08W15	Ire	370	200
11	289.0	EKOFISK	DGP	56N35	03E12	Nor	185	100
11	289.0	HERICOURT	NDB	47N34	06E44	Fr	60	32
11	289.0	JARNAS	DGP	63N29	19E39	Swe	240	130
11	289.0	MANSBACH	NDB	50N46	09E54	Germ	75	41
11	289.0	PUNTA_SILLA	DGP	43N24	04W25	Sp	180	97
11	289.0	RIJEKA	NDB	45N08	14E39	Cro	45	24
11	289.0	RUMELI	DGP	41N13	29E06	Turk	100	54
11	289.0	SKAGATA	DGP	66N07	20W06	Ice	200	108
11	289.0	TORTOLI	NDB	39N55	09E41	It	45	24
12	289.5	HAMMERODDE	DGP	55N18	14E46	Dk	330	178
12	289.5	KODOSHSKIY_1	DGP	44N06	39E02	Rus	200	110
12	289.5	LAMPEDUSA	MB	35N29	12E36	It	370	200
12	289.5	PUNTA_SILLA	MB	43N24	04W25	Sp	180	97
12	289.5	RAUFARHOEFN	DGP	66N27	015W57	Ice	400	216
13	290.0	BLAAVANDSHUK	DGP	55N34	08E05	Dk	277	150
13	290.0	GRAZ_WUNDSCHUH	NDB	46N56	015E28	Aust	75	41
13	290.0	LECA	DGP	41N12	08W42	Port	185	100
13	290.0	LIEGE_BIERSET	NDB	50N42	05E33	Belg	45	24
13	290.0	MOSCOW	NDB	55N35	37E21	Rus	10	5
13	290.0	MOVAR	MB	43N31	15E58	Cro	185	100

13	290.0	OULU_2	NDB	64N53	025E32	Fin	10	5
13	290.0	PORT_SAID	DGP	31N16	32E18	Egy	234	126
13	290.0	PUUMALA	DGP	61N24	28E14	Fin	70	38
13	290.0	TIRANA	NDB	41N28	19E43	Alb	10	5
14	290.5	C_SALOU	MB	41N03	01E10	Sp	180	97
14	290.5	FLAMBOROUGH_HEAD	DGP	54N06	00W04	UK	277	150
14	290.5	KOKKOLA	DGP	63N50	23E10	Fin	250	135
15	291.0	ARBANCON	NDB	40N57	03W07	Sp	75	41
15	291.0	C_SALOU	DGP	41N03	01E10	Sp	180	97
15	291.0	DJUPIVOGUR	DGP	64N39	014W16	Ice	250	135
15	291.0	GRENOBLE_PAJAY	NDB	45N22	05E09	Fr	13	7
15	291.0	HELSINKI	NDB	60N20	24E58	Fin	10	5
15	291.0	KOZANI	NDB	40N17	21E51	Gre	90	49
15	291.0	WORMLEIGHTON	DGP	52N12	01W22	UK	277	150
16	291.5	ABRAMOVSKY	MB	66N25	43E16	Rus	60	30
16	291.5	CHESHSKY	MB	67N54	48E36	Rus	70	40
16	291.5	CONSTANTA	MB	44N10	28E38	Rom	185	100
16	291.5	DAUGAVGRIVA	MB	57N04	24E02	Lat	148	80
16	291.5	GENOVA	MB	44N24	08E54	It	277	150
16	291.5	GULYAEVSKAYA_KOSHKA3	MB	68N54	55E32	Rus	30	15
16	291.5	KHODOVARYKHA	MB	68N56	53E46	Rus	280	150
16	291.5	KILDINSKY_SEVERNIY	MB	69N23	34E09	Rus	70	40
16	291.5	MASLEN_NOS	MB	42N19	27E48	Bulg	185	100
16	291.5	MATVEEV	MB	69N28	58E30	Rus	70	40
16	291.5	MERSRAGS	MB	57N22	23E07	Lat	28	15
16	291.5	NOS_EMINE	MB	42N42	27E54	Bulg	185	100
16	291.5	NOS_KALIAKRA	MB	43N22	28E28	Bulg	185	100
16	291.5	RAS_MATIFOU	MB	36N49	3E15	Alg	50	27
16	291.5	RUSSKY	MB	69N05	36E21	Rus	370	200
16	291.5	SFANTU_GHEORGHE	MB	44N54	20E37	Rom	185	100
16	291.5	SUMBURGH_HEAD	DGP	59N51	01W16	UK	370	200
17	292.0	BARCIAL_BARCO	NDB	41N56	05W40	Sp	37	20
17	292.0	HOLMSJO	DGP	56N26	15E39	Swe	240	130
17	292.0	MELILLA	NDB	35N16	02W56	Sp	90	49
17	292.0	MILAN	NDB	45N25	08E48	It	45	24
17	292.0	NECKAR	NDB	49N20	008E44	Germ	90	49
17	292.0	NOVOROSSIYKAY_1	DGP	44N36	37E58	Rus	200	110
17	292.0	OSIJEK	NDB	45N25	18E58	Cro	90	49
17	292.0	S_MARIA_D_LEUCA	DGP	39N47	18E22	It	277	150
18	292.5	ESTACA_DE_BARES	MB	43N47	07W41	Sp	180	97
18	292.5	PORVOO	DGP	60N12	25E50	Fin	250	135
18	292.5	VIESTE	DGP	41N53	16E11	It	277	150
19	293.0	BRUXELLES_2	NDB	50N56	004E35	Belg	47	25
19	293.0	ERRACHIDIA	NDB	31N56	04W22	Mor	10	5
19	293.0	ESTACA_DE_BARES	DGP	43N47	07W41	Sp	180	97
19	293.0	KULLEN	DGP	56N18	12E27	Swe	240	130
19	293.0	LOOP_HEAD_LSTN	DGP	52N34	09W56	Ire	277	150
19	293.0	MAHON	DGP	39N52	04E18	Sp	180	97
19	293.0	OSTROV_ZMEINY	MB	45N15	30E12	Ukr	185	100
19	293.0	WIEN_WILHELM	NDB	48N13	16E15	Aust	74	40
20	293.5	MAHON	MB	39N52	04E18	Sp	180	97
20	293.5	PORKKALA	DGP	59N58	24E23	Fin	250	135
20	293.5	REYKJANES	DGP	63N49	022W43	Ice	350	189
21	294.0	ATHENS	NDB	37N52	23E45	Gre	45	24
21	294.0	CALA_FIGUERA	MB	39N27	02E31	Sp	180	97
21	294.0	VAASA	DGP	63N13	21E10	Fin	250	135
21	294.0	VLIELAND_PHARE	DGP	53N18	05E04	Neth	220	119
21	294.0	VRSAC	NDB	45N05	21E18	Serb	45	24
22	294.5	CALA_FIGUERA	DGP	39N27	02E31	Sp	180	97
22	294.5	DGEDGINSKY	MB	65N12	36E49	Rus	200	110

22	294.5	KASHKARANSKY	MB	66N20	36E01	Rus	200	100
22	294.5	KAYBOLOVO	MB	59N44	28E02	Rus	110	60
22	294.5	MUDYUGSKY	MB	64N55	40E14	Rus	190	100
22	294.5	NIKODIMSKY	MB	66N06	39E06	Rus	190	100
22	294.5	OSTROV_ZMEINY	DGP	45N15	30E12	Ukr	200	110
22	294.5	YUZHNY_GOGLANDSKY	MB	60N00	27E00	Rus	90	50
23	295.0	C_PENAS	DGP	43N39	05W51	Sp	180	97
23	295.0	JAROSLAWIEC	DGP	54N33	16E33	Pol	90	49
23	295.0	KUOPIO	DGP	63N00	27E30	Fin	70	38
23	295.0	LUDVIKA	NDB	60N09	15E07	Swe	25	14
23	295.0	MESSINA	DGP	38N12	15E36	It	277	150
23	295.0	NUERNBERG	NDB	49N31	010E58	Germ	25	14
23	295.0	SKOPJE	NDB	41N55	21E38	Mace	45	24
23	295.0	SLIAC	NDB	48N37	19E08	SloR	45	24
24	295.5	BUTT_OF_LEWIS	DGP	58N31	06W16	UK	370	200
24	295.5	C_PENAS	MB	43N39	05W51	Sp	180	97
24	295.5	CIVITAVECCHIA	MB	42N06	11E49	It	277	150
24	295.5	ETAMPES	NDB	48N25	002E05	Fr	45	24
24	295.5	MYS_TARKHANKUTSKIY	DGP	45N21	32E30	Ukr	200	110
24	295.5	NARVA	DGP	59N28	28E02	Est	185	100
25	296.0	C_FINISTERRE	DGP	42N53	09W16	Sp	180	97
25	296.0	JYVA_ESKYLAE_2	NDB	62N21	25E48	Fin	45	24
25	296.0	LJUBLJANA	NDB	46N10	14E33	Slva	45	24
25	296.0	MIELEC	NDB	50N19	21E32	Pol	90	49
25	296.0	P_CARENA	MB	40N32	14E12	It	277	150
25	296.0	SKAGEN	DGP	57N44	10E35	Dk	185	100
26	296.5	C_FINISTERRE	MB	42N53	09W16	Sp	180	97
26	296.5	CAP_BON	DGP	37N04	11E03	Tun	370	200
26	296.5	GOTEBORG	DGP	57N37	11E59	Swe	240	130
26	296.5	RAS_AIGUILLE	MB	35N53	00W29	Alg	185	100
27	297.0	C_DE_LA_NAO	MB	38N44	00E14	Sp	180	97
27	297.0	FRANKFURT_MAIN	NDB	50N04	008E42	Germ	25	14
27	297.0	GAP_CLARET	NDB	44N22	05E57	Fr	10	5
27	297.0	GIRDLE_NESS	DGP	57N08	02W03	UK	277	150
27	297.0	ODESSKIY	DGP	46N23	30E45	Ukr	200	110
27	297.0	PRILEP	NDB	41N20	21E27	Mace	145	78
28	297.5	BATUMSKIY	MB	41N39	41E39	Geo	277	150
28	297.5	C_DE_LA_NAO	DGP	38N44	00E14	Sp	180	97
28	297.5	HOBURG	DGP	56N55	18E09	Swe	240	130
28	297.5	MIKULKIN	MB	67N48	46E41	Rus	90	50
28	297.5	PITSUNDSKIY	MB	43N09	40E20	Rus	280	150
28	297.5	PNT_LYNAS_LSTN	DGP	53N24	04W17	UK	277	150
28	297.5	POTIYSKIY	MB	42N08	41E40	Geo	277	150
28	297.5	SAMBALUDA	MB	65N38	35E14	Rus	90	50
28	297.5	SOCHINSKIY	MB	43N35	39E43	Rus	280	150
28	297.5	SUKHUMSKIY	MB	42N59	40E58	Geo	277	150
28	297.5	UNSKY	MB	64N50	38E22	Rus	40	22
28	297.5	VIEVNAVOLOK	MB	69N27	33E04	Rus	30	15
29	298.0	C_FERRO	DGP	41N09	09E31	It	277	150
29	298.0	NYNASHAMN	DGP	58N56	17E57	Swe	240	130
29	298.0	TALAVERA_BADAJ	NDB	38N50	06W41	Sp	74	40
30	298.5	C_DE_GATA	DGP	36N43	02W11	Sp	180	97
30	298.5	EL_ATTAIA	MB	34N45	11E19	Tun	185	100
30	298.5	HELGOLAND	DGP	54N11	07E53	Germ	285	154
30	298.5	P_MAESTRA	MB	44N58	12E32	It	277	150
30	298.5	SHEPELEVSKY_1	DGP	59N59	29E08	Rus	200	110
31	299.0	C_DE_GATA	MB	36N43	02W11	Sp	180	97
31	299.0	GATTEVILLE_PHARE	DGP	49N42	01W16	Fr	180	97
31	299.0	KAMENJAK	MB	44N47	13E55	Cro	185	100
31	299.0	KHIOS	NDB	38N20	26E08	Gre	145	78

31	299.0	STETTIENNE	NDB	45N31	04E18	Fr	10	5
31	299.0	TORUNGEN	DGP	58N23	08E47	Nor	300	162
32	299.5	MALAGA	DGP	36N43	04W25	Sp	180	97
32	299.5	NO_FORELAND_LSTN	DGP	51N22	01E26	UK	185	100
32	299.5	OERSKAER	DGP	60N31	18E22	Swe	240	130
32	299.5	SKROVA	MB	68N09	14E39	Nor	300	162
33	300.0	BJARGTANGAR	DGP	65N30	024W32	Ice	150	81
33	300.0	CASTELLON	NDB	39N58	00E01	Sp	25	14
33	300.0	CAVARNA	DGP	43N25	28E22	Bulg	185	100
33	300.0	ES_SIDER	NDB	30N37	18E21	Lib	25	14
33	300.0	KUOPIO_N	NDB	63N00	27E31	Fin	70	38
33	300.0	LA_ISLETA	MB	28N10	15W25	Sp	205	111
33	300.0	LINKOEPINGSAAB	NDB	58N26	15E33	Swe	25	14
33	300.0	MALAGA	MB	36N43	04W25	Sp	180	97
33	300.0	SKROVA	DGP	68N09	014E39	Nor	300	162
33	300.0	SWINOUJSCIE	MB	53N55	14E17	Pol	90	49
33	300.0	ZAMORA	NDB	41N32	05W39	Sp	90	49
34	300.5	BELOSARAYSKIY	MB	46N53	37E21	Ukr	277	150
34	300.5	BERDYANSKIY	MB	46N38	36E46	Ukr	277	150
34	300.5	C_SANDALO	MB	39N08	08E13	It	277	150
34	300.5	C_VILLANO	MB	43N10	09W13	Sp	180	97
34	300.5	CHESMENSKY	MB	64N43	36E32	Rus	60	30
34	300.5	GENICHESK	MB	46N11	34E49	Ukr	277	150
34	300.5	KANINSKY	MB	68N39	43E18	Rus	560	300
34	300.5	KOELN_BONN	NDB	50N54	07E14	Germ	25	14
34	300.5	SETNAVOLOVSKY	MB	69N24	33E30	Rus	370	200
34	300.5	TERIBERSKY	MB	69N15	35E09	Rus	370	200
34	300.5	TYSP_NAVOLOKSKY	MB	69N44	33E06	Rus	370	200
35	301.0	BJORNAYA	DGP	74N30	19E00	Nor	370	200
35	301.0	COZZO_SPADARO	MB	36N41	15E08	It	277	150
35	301.0	HALTEN	DGP	64N10	09E24	Nor	300	162
35	301.0	IJMUIDEN_PHARE	DGP	52N28	04E35	Neth	90	49
35	301.0	MOSTAGANEM	MB	35N56	00E08	Alg	10	5
35	301.0	P_HANK	MB	33N36	7W39	Mor	185	100
35	301.0	ROMORANTIN	NDB	47N19	001E41	Fr	45	24
35	301.0	ROZEWIE	DGP	54N50	018E20	Pol	150	81
36	301.5	C_DE_PALOS	MB	37N38	00W41	Sp	180	97
36	301.5	CAMPAGNANO	NDB	45N26	8E42	It	90	49
36	301.5	TREVISO	NDB	45N37	12E06	It	45	24
36	301.5	TURKU	DGP	60N26	22E13	Fin	200	108
37	302.0	BELLSUND	MB	77N43	13E57	Nor	300	162
37	302.0	C_DE_PALOS	DGP	37N38	00W41	Sp	180	97
37	302.0	GILZE_RIJEN	DGP	51N37	04E56	Neth	185	100
37	302.0	HJORTENSUDDE	DGP	58N38	12E40	Swe	125	68
37	302.0	NIKSIC	NDB	42N46	18E55	Mont	185	100
37	302.0	QATRANEH	NDB	31N15	36E03	Jor	90	49
37	302.0	RODEZ_BAJAQUET	NDB	44N19	02E36	Fr	45	24
37	302.0	VILLACOUBLAY_2	NDB	48N47	002E23	Fr	10	5
38	302.5	BELLSUND	DGP	77N43	13E57	Nor	300	162
38	302.5	KOBLENZ	DGP	50N22	07E35	Germ	225	122
38	302.5	SVINOEY	DGP	62N19	05E16	Nor	300	162
38	302.5	TARIFA	DGP	36N00	05W36	Sp	180	97
39	303.0	ILE_D_YEU_PHARE	NDB	46N43	02W23	Fr	185	100
39	303.0	KAUPANGER	NDB	61N11	07E13	Nor	300	162
39	303.0	RATTENBERG	NDB	47N26	11E57	Aust	45	24
39	303.0	SENIGALLIA	MB	43N43	13E13	It	277	150
39	303.0	STPETERSBURG	NDB	59N49	30E10	Rus	250	135
39	303.0	TARIFA	MB	36N00	05W36	Sp	180	97
39	303.0	VIENNA	NDB	48N09	16E28	Aust	45	24
40	303.5	ALEXANDRIA	MB	31N09	29E51	Egy	277	150

40	303.5	C_VATICANO	MB	38N37	15E49	It	277	150
40	303.5	KOLGUEV-YUZHNY	MB	68N42	48E40	Rus	70	35
40	303.5	KONUSHINSKY	MB	67N12	43E47	Rus	50	25
40	303.5	ROSETTA	MB	31N27	30E26	Egy	90	49
40	303.5	ROTA	DGP	36N38	06W23	Sp	180	97
40	303.5	SHAQIQ	MB	30N57	25E51	Egy	90	49
40	303.5	SKLINNA	DGP	65N12	10E59	Nor	300	162
40	303.5	TEMIRYUKSKIY_2	DGP	45N20	37E14	Rus	200	110
40	303.5	TONKY	DGP	69N51	61E07	Rus	250	140
40	303.5	VAYDAGUBSKY	MB	69N56	31E56	Rus	280	150
40	303.5	ZEVEN	DGP	53N17	09E15	Germ	285	154
41	304.0	ISFJORD	NDB	78N04	13E36	Nor	300	162
41	304.0	LISTA	DGP	58N06	06E34	Nor	300	162
41	304.0	PIOMBINO	DGP	42N55	10E37	It	277	150
41	304.0	ROTA	MB	36N38	06W23	Sp	180	97
41	304.0	TANDAREI	NDB	44N39	27E39	Rom	185	100
41	304.0	VILA_REAL	NDB	41N13	7W45	Port	45	24
42	304.5	C_BEAR	DGP	42N31	03E08	Fr	180	97
42	304.5	KLEIPADA	DGP	55N43	21E05	Lith	92	50
42	304.5	OUTOKUMPU	DGP	62N41	29E01	Fin	70	38
43	305.0	GORNA_1	NDB	43N09	25E49	Bulg	45	24
43	305.0	KLEIPADA	MB	55N43	21EO5	Lith	185	100
43	305.0	LES_BALEINES_PHARE	DGP	46N15	01W34	Fr	180	97
43	305.0	MARIEHAMN	NDB	60N08	019E55	Fin	10	5
43	305.0	MUNSTER	NDB	52N06	07E34	Germ	37	20
43	305.0	YALOVA	NDB	40N34	29E22	Turk	140	76
44	305.5	C_SAN_VITO	MB	40N25	17E12	It	277	150
44	305.5	DALATANGI	NDB	65N16	13W39	Ice	185	100
44	305.5	HEL	MB	54N36	18E49	Pol	19	10
44	305.5	S_VICENTE	DGP	37N02	09W00	Port	370	200
44	305.5	VARDOE	DGP	70N23	31E09	Nor	300	162
45	306.0	JYVA_ESKYLAE_1	NDB	62N23	24E43	Fin	19	10
45	306.0	LIZARD_LSTN	DGP	49N58	05W12	UK	277	150
45	306.0	MOLUNAT	MB	42N27	18E26	Cro	185	100
45	306.0	PARMA	NDB	44N49	10E18	It	90	49
45	306.0	STUTTGART	NDB	48N43	09E20	Germ	45	24
45	306.0	TAPOISAP	NDB	47N30	19E27	Hung	75	41
46	306.5	AYNOVSKY	MB	69N50	31E34	Rus	50	25
46	306.5	C_SILLEIRO	MB	42N06	08W54	Sp	180	97
46	306.5	KOLGUEVSKY	MB	69N30	49E06	Rus	280	150
46	306.5	KOLKASRAGS	MB	57N45	22E36	Lat	185	100
46	306.5	MORZHOVSKY	MB	66N43	42E28	Rus	110	60
46	306.5	S_VITO-LO-CAPO	DGP	38N11	12E44	It	277	150
46	306.5	SOSNOVETSKY	MB	66N29	40E41	Rus	130	70
46	306.5	TERSKO-ORLOVSKY	MB	67N12	41E20	Rus	140	75
46	306.5	VEPREVSKY	MB	65N37	39E52	Rus	190	100
46	306.5	VORONOVSKY	MB	66N30	42E14	Rus	280	150
46	306.5	WICKLOW_HEAD	DGP	52N58	06W00	Ire	277	150
47	307.0	DIEKIRCH	NDB	49N52	06E08	Lux	90	49
47	307.0	JAN_MAYEN	DGP	70N57	08W40	Nor	300	162
47	307.0	JERICHO	NDB	31N51	35E28	Jor	90	49
47	307.0	LAZAREVSKOYE	NDB	43N55	39E20	Rus	250	135
47	307.0	LES_SABLES_OLONNE	DGP	46N31	001W48	Fr	200	108
47	307.0	MERSA_MATRUH	DGP	31N22	27E15	Egy	277	150
47	307.0	RISTNA	DGP	58N56	22E04	Est	200	108
47	307.0	SANTORINI	NDB	36N24	25E29	Gre	145	78
48	307.5	JAN_MAYEN	MB	70N57	08W40	Nor	300	162
48	307.5	KAPELLSKÄR	DGP	59N43	19E04	Swe	240	130
48	307.5	PALMA_MALLORCA	NDB	39N36	02E49	Sp	25	14
48	307.5	ST_CATHERINES_POINT	DGP	50N34	01W17	UK	277	150

49	308.0	BARAJAS	NDB	40N27	03W33	Sp	25	14
49	308.0	DAGALI	NDB	60N25	08E28	Nor	300	162
49	308.0	GRIMSEY	NDB	66N32	17W59	Ice	185	100
49	308.0	HORTA	DGP	38N32	28W37	Port	545	300
49	308.0	MINSK	NDB	53N53	28E01	Belo	10	5
49	308.0	MOJKOVAC	NDB	45N57	19E35	Serb	185	100
49	308.0	OUKACHA	MB	33N37	7W34	Mor	37	20
49	308.0	VITORIA	NDB	42N48	02W49	Sp	90	49
49	308.0	WUSTROW	DGP	54N20	12E23	Germ	285	154
50	308.5	HELNES	MB	71N04	26E13	Nor	300	162
50	308.5	KODOSHSKIY_2	DGP	44N06	39E02	Rus	200	110
50	308.5	PONT_DE_BUIS	DGP	48N18	004W05	Fr	200	108
50	308.5	VENTSPILS	DGP	57N24	21E32	Lat	74	40
51	309.0	ANTWERP_DEURNE	NDB	51N11	04E29	Belg	45	24
51	309.0	DOLE_CHEMIN	NDB	46N59	05E18	Fr	45	24
51	309.0	ILE_DE_GROIX_PEN_MEN	DGP	47N39	03W31	Fr	180	97
51	309.0	S_BENEDETTO	MB	42N57	13E53	It	185	100
51	309.0	SAATENAES	NDB	58N27	12E43	Swe	25	14
51	309.0	TEL_AVIV	NDB	32N02	34E47	Is	185	100
52	309.5	ALGIERS	MB	36N47	3E05	Alg	37	20
52	309.5	CAP_BLANC	MB	37N20	09E50	Tun	185	100
52	309.5	CHERNY	MB	68N22	38E38	Rus	60	30
52	309.5	DGUDGMUYSKY	MB	64N41	35E34	Rus	40	20
52	309.5	FRUHOLMEN	DGP	71N06	23E59	Nor	300	162
52	309.5	KOLGUEVSKY-VOSTOCHNY	MB	69N05	50E18	Rus	50	25
52	309.5	LYAMCHIN	MB	69N52	59E07	Rus	70	35
52	309.5	MYS_TARKHANKUTSKIY	MB	45N21	32E30	Ukr	277	150
52	309.5	NASH_POINT	DGP	51N24	03W33	UK	277	150
52	309.5	OMA	MB	66N50	46E36	Rus	90	50
52	309.5	SHVEDSKY	MB	68N35	55E49	Rus	60	30
52	309.5	TENDROVSKIY	MB	46N19	31E31	Ukr	277	150
52	309.5	VORONTSOVSKIY	MB	46N30	30E46	Ukr	277	150
53	310.0	ALMERIA_2	NDB	36N50	02W22	Sp	110	59
53	310.0	C_FERRET	DGP	44N39	01W15	Fr	180	97
53	310.0	DUBOVE	NDB	48N52	18E48	SloR	90	49
53	310.0	GALLIVARE	NDB	67N08	20E51	Swe	25	14
53	310.0	KAUHAVA	NDB	63N05	23E04	Fin	10	5
53	310.0	KIEV	NDB	50N20	30E53	Ukr	10	5
53	310.0	LANZAROTE	NDB	28N57	13W36	Sp	90	49
53	310.0	OULU_1	NDB	64N55	25E24	Fin	10	5
53	310.0	SELARDALUR	NDB	65N47	24W00	Ice	45	24
53	310.0	SIVAS	NDB	39N47	36E54	Turk	10	5
53	310.0	VALETTA	MB	35N54	14E32	Mal	37	20
54	310.5	CAP_S_MATHIEU_PHARE	DGP	48N20	04W46	Fr	180	97
54	310.5	DAMIETTA	MB	31N31	31E51	Egy	277	150
54	310.5	EL_BRULLUS	MB	31N36	31E05	Egy	90	49
54	310.5	FAERDER	DGP	59N01	10E31	Nor	300	162
54	310.5	PORT_SAID	MB	31N16	32E18	Egy	50	27
55	311.0	ANDENES	DGP	69N20	16E08	Nor	300	162
55	311.0	CELLE	NDB	52N36	10E07	Germ	45	24
55	311.0	ISOLA_PANTELLERIA	MB	36N49	12E01	It	277	150
55	311.0	KOS	NDB	36N48	27E05	Gre	45	24
55	311.0	NIEDERSTETTEN	NDB	49N23	09E57	Germ	46	25
55	311.0	NO_FORELAND	NDB	51N22	001E26	UK	45	24
55	311.0	SHEPELEVSKY_2	DGP	59N59	29E08	Rus	200	110
56	311.5	BJUROKLUBB	DGP	64N29	21E34	Swe	240	130
56	311.5	CARVOEIRO	DGP	39N22	09W24	Port	370	200
56	311.5	OOSTDYCK	DGP	51N16	2E26	Belg	110	59
57	312.0	BOZHOURISTE	NDB	42N47	23E11	Bulg	12	6
57	312.0	CAP_SPARTEL	MB	35N47	05W55	Mor	370	200

57	312.0	KARLSBORG	NDB	58N29	14E23	Swe	90	49
57	312.0	MURI	NDB	46N57	07E28	Swit	25	14
57	312.0	OESTERSUND	NDB	63N12	14E29	Swe	25	14
57	312.0	OOSTENDE	DGP	51N14	02E55	Belg	220	119
57	312.0	PODGORIC	NDB	42N32	19E08	Mont	90	49
57	312.0	RYAZANSKAYA	NDB	44N58	39E34	Rus	10	5
57	312.0	TARQUINIA	NDB	42N13	19E27	Mont	90	49
58	312.5	AKMENRAGS	MB	56N50	21E04	Lat	185	100
58	312.5	ANAPSKY	MB	44N53	37E18	Rus	280	150
58	312.5	BALTIYSK	MB	54N38	19E54	Rus	220	120
58	312.5	DGELEZNY_ROG	MB	45N07	36E44	Rus	50	25
58	312.5	DOBSKY	MB	44N38	37E55	Rus	280	150
58	312.5	GORODETSKY	MB	67N41	40E58	Rus	370	200
58	312.5	HOEKVANHOLLANDPHARE	DGP	51N59	04E07	Neth	220	119
58	312.5	Il_INSKIY	MB	45N01	35E26	Ukr	277	150
58	312.5	LIEPAJA	MB	56N31	21E00	Lat	222	120
58	312.5	MYS_AYTODORSKIY	MB	44N26	34E08	Ukr	277	150
58	312.5	MYS_KYZ-AUL	MB	45N04	36E23	Ukr	277	150
58	312.5	S_MIGUEL	DGP	37N44	25W39	Port	370	200
58	312.5	SHOYNA	MB	67N53	44E08	Rus	280	150
58	312.5	SVYATONOSSKY	MB	68N09	39E45	Rus	280	150
58	312.5	TARAN	MB	54N58	19E59	Rus	220	120
58	312.5	VENTSPILS	MB	57N24	21E32	Lat	185	100
59	313.0	ABSAM	NDB	47N17	11E30	Aust	45	24
59	313.0	KLAGENFURT_GUT	NDB	46N38	14E23	Aust	45	24
59	313.0	RIJEKA	MB	45N06	14E32	Cro	37	20
59	313.0	SPLIT	MB	43N30	16E28	Cro	37	20
59	313.0	UTSIRA	DGP	59N18	04E52	Nor	300	162
60	313.5	C_SAN_SEBASTIAN	DGP	41N53	03E12	Sp	180	97
61	314.0	BRUXELLES_1	NDB	50N49	004E28	Belg	45	24
61	314.0	C_SAN_SEBASTIAN	MB	41N53	03E12	Sp	180	97
61	314.0	FISKA	NDB	41N06	22E59	Gre	75	41
61	314.0	GIESSEN	NDB	50N38	008E49	Germ	75	41
61	314.0	KARPATHOS	NDB	35N25	27E09	Gre	45	24
61	314.0	UTVAER	DGP	61N02	04E30	Nor	300	162
62	314.5	BEJAIA	MB	36N45	5E06	Alg	18	10
62	314.5	MARJANIEMI	DGP	65N02	24E35	Fin	250	135
62	314.5	STRANDHOEFN	NDB	65N54	014W39	Ice	185	100
63	315.0	BERGE_HUGIN	NDB	57N10	02E14	UK	55	30
63	315.0	FES	NDB	33N56	04W54	Mor	10	5
63	315.0	GUILLENA	NDB	37N31	06W02	Sp	370	200
63	315.0	KAJAANI	NDB	64N17	27E39	Fin	30	16
63	315.0	LVOV	NDB	49N47	24E00	Ukr	10	5
63	315.0	NOVOROSSIYKAY_2	DGP	44N36	37E58	Rus	200	110
63	315.0	SCHWERIN-PARCHIM	NDB	53N24	11E40	Germ	46	25
63	315.0	STADSKANAAL	NDB	53N01	006E54	Neth	45	24
63	315.0	TYSP_NAVOLOKSKY	DGP	69N44	33E06	Rus	200	110
63	315.0	VILLACOUBLAY_3	NDB	48N43	01E49	Fr	25	14
63	315.0	WR_NEUSTADT	NDB	47N50	16E17	Aust	75	41
64	315.5	NIDA	DGP	55N18	21E00	Lith	37	20
64	315.5	SCATSTA	NDB	60N27	001W13	UK	45	24
65	316.0	49_27A	NDB	53N03	02E16	UK	27	15
65	316.0	BARRA	NDB	57N02	07W27	UK	25	15
65	316.0	DUBLIN	NDB	53N26	06W27	Ire	10	5
65	316.0	EINDHOVEN	NDB	51N34	5E31	Neth	25	14
65	316.0	EPSOM	NDB	51N19	00W22	UK	47	25
65	316.0	KOSTAJNICA	NDB	45N14	16E32	Cro	90	49
65	316.0	SHELL_ALPHA	NDB	53N05	02E08	UK	18	10
65	316.0	SHELL_BRAVO	NDB	53N05	02E11	UK	37	20
67	317.0	STOETT	NDB	66N56	13E27	Nor	90	49

70	318.5	Il_ICHEVSK	MB	46N19	30E41	Ukr	46	25

INDEX TO COUNTRIES

Alb	Albania	Lith	Lithuania
Alg	Algeria	Lux	Luxembourg
Aust	Austria	Mal	Malta
Belg	Belgium	Mont	Montenegro
Belo	Belorussia	Mor	Morocco
Bulg	Bulgaria	Neth	Netherlands
Dk	Denmark	Nor	Norway
Est	Estonia	Pol	Poland
Fin	Finland	Port	Portugal
Fr	France	Rom	Romania
Geo	Georgia	Rus	Russia
Germ	Germany	SloR	Slovak Rep
Gre	Greece	Sp	Spain
Hung	Hungary	Swe	Sweden
Ice	Iceland	Syr	Syria
Is	Israel	Tun	Tunisia
It	Italy	Turk	Turkey
Jor	Jordan	UK	United Kingdom
Lat	Latvia	Ukr	Ukraine
Lib	Libya	Swit	Switzerland
Ire	Ireland		
Slva	Slovenia		

Other abbreviations:

Freq = Frequency
NDB = Non-Directional Beacon (aeronautical)
MB = Marine Beacon
DGP = Differential GNSS
Lat = Latitude
Long = Longitude

Remarks The ranges based on the following rules

	Service	Location	Field strength
1	MB, DGP	North from a Latitude of 43°	50 uV/m
2	MB, DGP	South from a Latitude of 43°	75 uV/m
3	MB, DGP	South from a Latitude of 43° of 30°	100 Uv/m
4	NDB		75 uV/m

Appendix C

Verification of coverage prediction

This appendix shows a condensed review of the verification process that was employed to ensure that the new software model processes beacon coverage in the same manner as the previous Bangor Coverage Prediction Model.

The Bangor Coverage Prediction Model has been tried and tested over many years. This appendix shows that the new software model matches its functionality.

Introduction

With any piece of software, verification is a very important stage. The role of verification is to ensure that the correct procedures are being carried out with the correct results obtained. This document records various stages of verification, which have been carried out on the new software.

Verification of the software is broken down into four stages,

- Groundwave Coverage
- Groundwave Coverage – including interference
- Skywave Coverage
- Skywave Coverage – including interference

Throughout the verification, a single beacon is used as the wanted beacon.

Wanted beacon details.

Beacon being examined: Point Lynas

Power: -24dB w.r.t 1KW

Latitude: 53N24 (53.4)

Longitude: 04W17 (04.283)

Point Lynas is 24dBμV/m below 1KW, which gives a power of 3.98W.

The first check is to ensure that the software achieves the same field strength for Point Lynas as that calculated by the manual calculations. Four checkpoints have been decided upon, each with a different conductivity path or distance to enable a through check to be conducted. Details of these check points are shown in Table C.1.

Check Point	Path	Location		Distance Km
		Lat	Lon	
1	Sea	53.5	-4.0	21.8
2	Sea	54.3	-3.5	112.65
3	Land	53.3	-4.4	13.59
4	Land	53.0	-3.0	96.60

Table C.1: Details of the four check-points used for the non-interference.

With the four check points defined, the next stage is to check groundwave propagation without interference. This corresponds with daytime coverage without interference.

Groundwave – NO INTERFERENCE.

The different ground conductivity curves from the ITU were used to calculate the field strengths which were then compared to those calculated by the software. The results of this test are shown in Table C.2.

Check Point	Average Conductivity	Curves dBμV/m	Software dBμV/m	Difference dBμV/m
1	5000 mS/m	58	58	0
2	5000 mS/m	44	43	1
3	3mS/m	61	61	0
4	3mS/m	40	40	1

Table C.2: Results of comparing the software with manual calculations for groundwave propagation.

Conclusion for Groundwave with no interference.

The calculated results shown in Table C.2 show that, at worse, the manual calculations and the software differ by 1dBμV/m. This is a perfectly acceptable level of agreement. With groundwave propagation completed, the next test was for skywave propagation without interference.

Skywave – NO INTERFERENCE

Skywave without interference brings in two new concepts, self-fading and skywave propagation. Both of these concepts are checked to ensure correct operation. Self-fading is calculated using the method developed by D.C. Poppe.

The verification here checked skywave propagation, calculated using the ITU methods, and the effect of skywave self-fading, using the method developed by Poppe. A fifth check point was added, one that includes a change in conductivity. The field strengths were calculated both manually and through the software, comparing the results at each stage. Tables C.3 and C.4 show the results for the manual calculations and the software results respectively. Table C.5 then compares the final field strengths.

Manual Calculations

Check Point	Curves				
	Ground dBμV/m	Sky dBμV/m	SGR	F_term dBμV/m	Total dBμV/m
1	58	10	-48	N/A	58
2	44	26	-18	-1.7351	42
3	61	5	-57	N/A	62
4	40	25	-15	-2.569	37
5	29	27	-2	-8.52	20

Table C.3: Manual calculations for Point Lynas' field strength at the check-points.

Software Calculations

Check Point	Software Calculated				
	Ground dBμV/m	Sky dBμV/m	SGR	F_term dBμV/m	Total dBμV/m
1	58.3	10.8	-47.5	N/A	57.8
2	43.2	25.8	-17.4	-1.88	41.3
3	61.3	3.2	-58.1	N/A	61.3
4	40.4	25.4	-15	-2.569	37.8
5	28.4	26.7	-1.7	-8.56	19.8

Table C.4: Software calculations for Point Lynas' field strength at the check-points.

Comparison

Check Point	Total Field Strength (dBμV/m)			Difference
	Software	Software Rounded	Curves	
1	57.8	58	58	0
2	41.3	41	42	1
3	61.3	61	62	1
4	37.8	38	37	1
5	19.8	20	20	0

Table C.5: Comparison of results for Point Lynas' field strength as calculated by the software and manually

Conclusions for Skywave with no interference.

Table C.5, shows that the manual and software calculations match within 1dB. From these results an agreement of 1dB is acceptable. The next stage was to tackle interference.

Interference

Processing interference meant developing the code further to include:

- Decision on potential interferers
- Protection Ratios
- Handling multiple arrays

These are all examined in this check to ensure that the software is working correctly under both daytime and nigh-time conditions.

Daytime.

The first stage was to ensure that only those beacons which can potentially interfere with the wanted beacon are taken into account. This is done by eliminating those beacons which are physically too far away, or too distant on frequency separation. This was checked and the shown to be working correctly.

To ensure the model deals with groundwave interference correctly, Point Lynas was used as a test beacon and potential interferers were identified. A test location was identified as shown in Fig C.1.

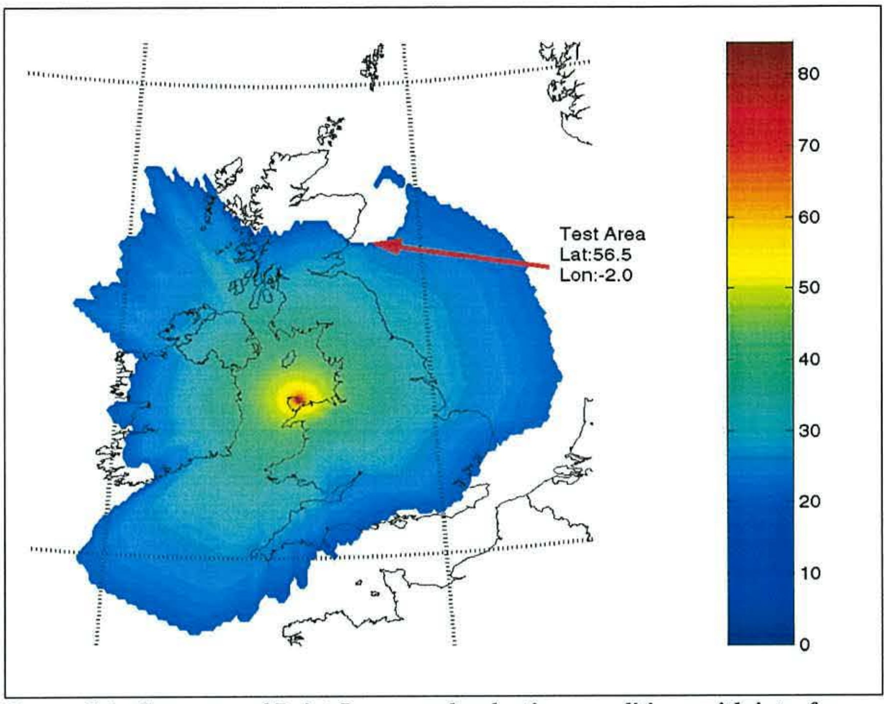

Figure C.1: Coverage of Point Lynas under daytime conditions with interference. Colour indicates field strength in dBμV/m.

Its clear to see that Point Lynas covers a large area and that the check point is referring to a region very near to Girdle Ness, which has a single channel separation.

So at this location one expects Girdle Ness's field strength to be considerably greater than that of Point Lynas, and therefore expect the protection ratio of –22dB to be exceeded.

CHECK POINT 1

Check Point Location - Lat: 56.5 Lon: -2.0
Girdle Ness – Distance to check point = 70Km
Power: -24dB w.r.t 1Kw

Lynas – Distance to check point = 374.7 Km

Transmitter	Conductivity	Field Strength (dBμV/m)		
		Manual	Software	Difference
Point Lynas	Various	28	28	0
Girdle Ness	5 S/m	48	48	0

Table C.6. Groundwave comparison for interference check (check-point 1)

So the SIR would be 28-48 = -20, which at this pairing means that coverage is being provided as the protection ratio is at –22, which means that the interferer's field strength may be 22dB's above the wanted beacon.

In order to check the functionality of the software further, a second check point was investigated.

CHECK POINT 2
Lat: 56.7
Lon: -2.0
Girdle Ness distance = 48 Km
Point Lynas = 395.2 Km

Transmitter	Conductivity	Field Strength (dBμV/m)		
		Manual	Software	Difference
Point Lynas	Various	27	27	0
Girdle Ness	5 S/m	51	51	0

Table C.7. Groundwave comparison for interference check (check-point 2)

From the manual calculation this should give a SIR of 27 – 51 = -24 so coverage should not be provided at this location. The software figures were added to the tables after the manual calculations were complete.

Groundwave Interference Conclusions

These results are impressive and show that the selection algorithm works and the field strengths are calculated to be the same. This proves that this part of the software is working correctly.

Skywave interference.

This section is to ensure that the software is dealing with the skywave interference correctly. Skywave interference can only be a problem on co-channel and can remain a problem over 4000Km away. In order to check this a location was identified where coverage at night is affected by interference. Again Point Lynas was used as the test beacon.

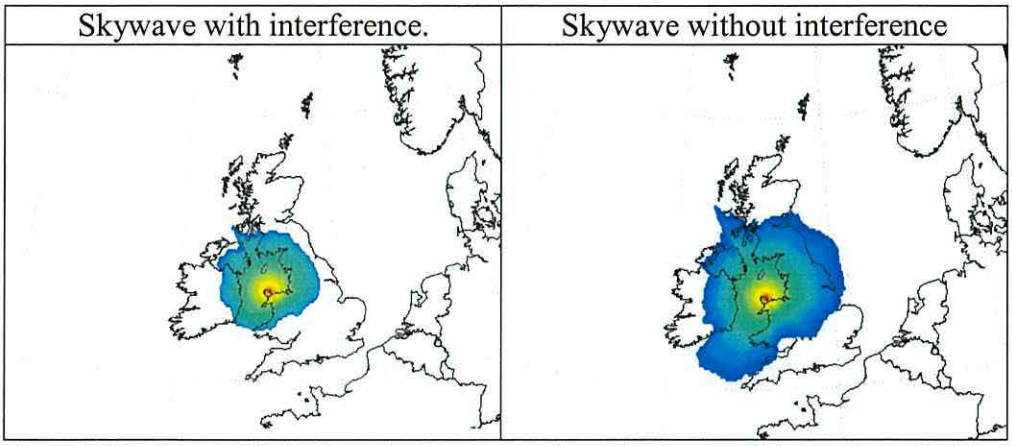

Figure C.2: Images of Point Lynas's coverage under night-time conditions with and without interference.

From these images it was clear that the region of Flamborough on the East coast could receive Lynas under daytime conditions, whereas at night no service is available. So this location was set as a check point, but we initially started looking further inland where coverage appears to be provided.

Check Point – Lat 55.0
Lon –3.0

The first stage is to identify which stations are causing interference. Like groundwave interference, skywave interferers are also subject to both frequency and distance selection criteria.

This check was completed and shown to be successful. 11 beacons were identified as potential interferers. Out of these 11 potential interferers the prime suspects are either, Hoburg or C DE LA NAO, who are the two nearest potential interferers. From this information it was necessary to calculate whether these are the beacons that are causing interference to Point Lynas.

The distance to the check point from each interferer is shown in Table C.8

Transmitter	Type	Distance /Km
Point Lynas	Wanted	196.7
C_DE_LA_NAO	Potential Interferer	1824.9
Hoburg	Potential Interferer	1332.6

Table C.8: Distances from the three transmitters to the check-point.

To calculate the field strengths of the potential interferers, their power with respect to 1KW is required.

C_DE_LA_NAO = 62-37.5 = 24.5dB below 1KW
HOBURG = 60-34 = 26dB below 1KW

The investigation started by calculating Point Lynas's field strength at this location. Both the groundwave and skywave field strengths were calculated as before. Table C.9 shows the resulting field strengths.

Check Point	Curves					Software dBμV/m	Difference dBμV/m
	Ground dBμV/m	Sky dBμV/m	SGR	F_term dBμV/m	Total dBμV/m		
Lynas	36	26	-10	-4.551	31	32	1
C_DE	N/A	12	N/A	N/A	12	11	1
Hoburg	N/A	14	N/A	N/A	14	14	0
*Lynas	36.5	26.6	-9.9	-4.559	31.9		

Table C.9: Results of first checkpoint for skywave with interference.
NOTE: Lynas skywave is median, while C_DE and Hoburg are that not exceeded 95%.
****NOTE – Bottom Line is the results calculated by the software rather than manually.***

With a protection ratio of 15dB, coverage is provided at this location, as the wanted field strength is at least 15dB greater than the strongest interferer. Lets now look a little further away,

Lat: 55N00 (55.0)

Lon: 01W00 (-1.0)

Again the same process is used, so the distances are calculated first.

Transmitter	Type	Distance /Km
Point Lynas	Wanted	278.4
C_DE_LA_NAO	Potential Interferer	1811.1
Hoburg	Potential Interferer	1210.8

Table C.10: Distances for the three transmitters used in the second skywave check.

Then the corresponding field strengths are calculated and compared with the software.

Check Point	Curves					Software dBμV/m	Difference dBμV/m
	Ground dBμV/m	Sky dBμV/m	SGR	F_term dBμV/m	Total dBμV/m		
Lynas	32	25	-6.6	-6.29	26	25	1
C_DE	< -20	12	29	N/A	12	13	1
Hoburg	< -20	16	36	N/A	16	17	1
*Lynas	31.7	25.7	-6	-6.65	25		

Table C.11. Results of the second skywave with interference check.
NOTE: Lynas skywave is median, while C_DE and Hoburg are that not exceeded 95%.
****NOTE: Bottom line corresponds to the software calculations rather than manual calculations.***

At this location coverage is not provided as the wanted beacons field strength is less than 15dB greater than the interferers.

Skywave interference conclusions.

These results show that the maximum discrepancy between manual calculations and the software is 1dB. Which is satisfactory.

General Conclusions.

The software is within a ±1dB error margin when compared to the manual calculations at its worse. This level of discrepancy is perfectly acceptable and the candidate is happy with these results.

Appendix D

Network problem solving example.

Dr Ruttle is Engineer-in-Chief at the Commissioners of Irish Lights. One of his duties is the marine radiobeacon DGNSS service of the United Kingdom and Ireland. As part of this research regular meetings were held, at which Dr Ruttle was present.

During one of these meeting Dr Ruttle expressed concern at the lack of coverage off the Southern coast of Ireland and the lack of dual coverage at several spots about the British Isles. He asked if the software model could be used to investigate the reason for this lack of coverage and the lack of dual coverage in the specific spot. These areas were investigated and the reasons for beacons failing to provide coverage were identified.

The new software model is very applicable for this role as it can provide information on simultaneous beacons at any location, so it is straightforward to review the field strengths of both the wanted beacon and any potential interferers.

The following pages show the five locations under interest and identifies the reason why particular beacons fail to provide coverage.

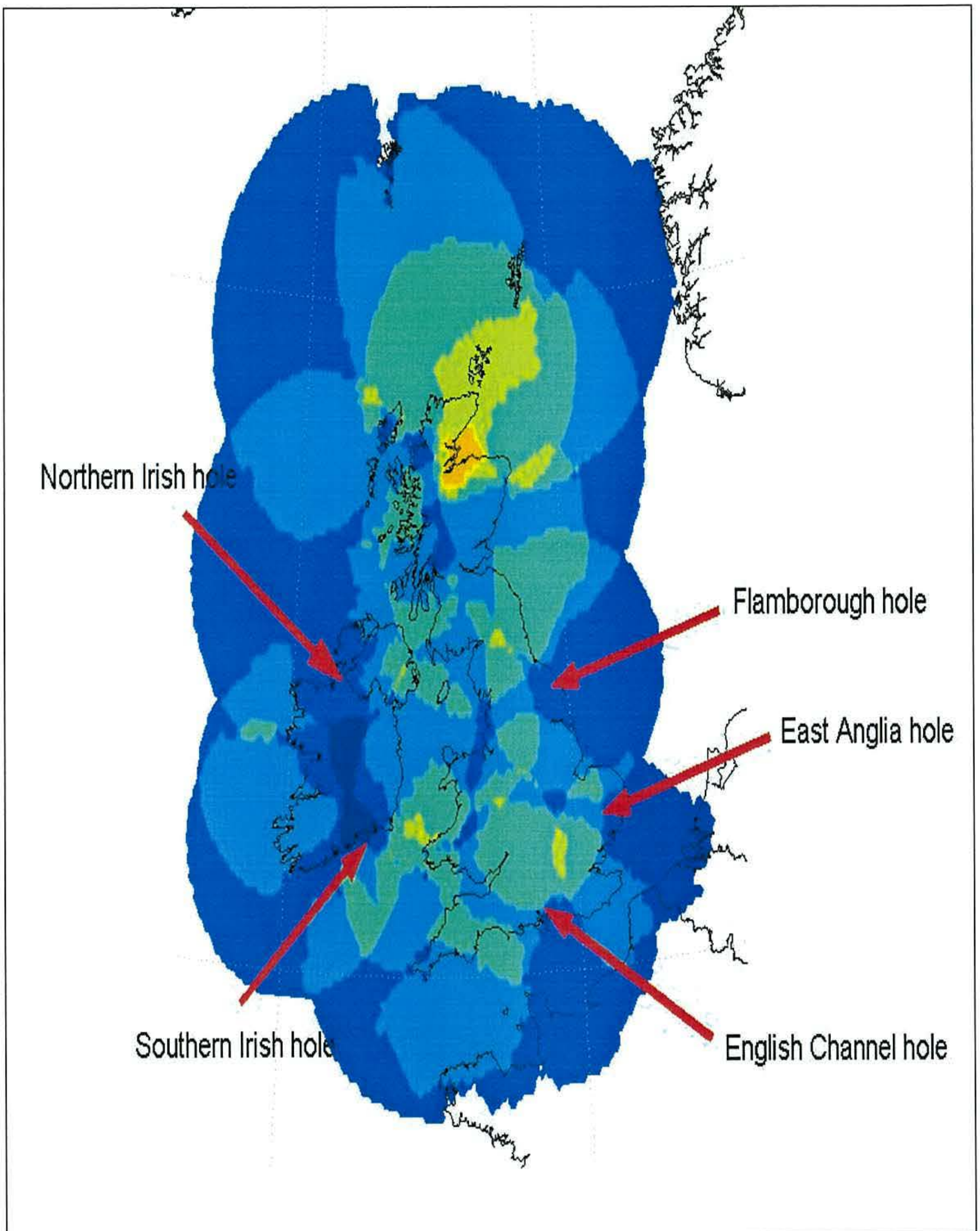

Figure D.1: A plot showing the number of beacons providing simultaneous coverage, using the 16 beacons of the United Kingdom and Ireland, under night-time conditions. The dark blue region in Ireland is a hole in coverage.

Areas of Single beacon coverage

Northern Irish hole

Potential supporting beacon	Reason for lack of coverage
Butt of Lewis	Skywave self fading
Loop Head	Skywave Interference from – Estaca_de_bares.DGP Mahon. DGP Kullen. DGP
Stirling	Skywave self fading

Southern Irish hole

Potential supporting beacon	Reason for lack of coverage
Lizard	Skywave Interference from – Molunat.MB
Nash Point	Skywave Interference from – Cap_Blanc.MB

English Channel hole

Potential supporting beacon	Reason for lack of coverage
Lizard	Skywave Interference from – Stuttgart.NDB Molunat.MB Parma. NDB
Wormleighton	Skywave Interference from – C_Salou.DGP
North Foreland	Skywave Interference from – Malaga.DGP

East Anglia hole

Potential supporting beacon	Reason for lack of coverage
Flamborough Head	Skywave Interference from – C_Salou.MB
Wormleighton	Skywave Interference from – C_Salou.DGP
St. Catherines Point	Skywave Interference from – Kapellskär.DGP

Flamborough hole

Potential supporting beacon	Reason for lack of coverage
Girdle Ness	Skywave Interference from – C_de_la_nao.MB
North Foreland	Skywave Interference from – Malaga.DGP Oerskaer.DGP
Stirling	Skywave Interference from – Castellon.MB

Conclusions

The southern Irish hole didn't exist with the previous edition of the band plan. It has come about with the introduction of the new marine beacon 'Cap_Blanc', which prevents the beacon at Nash Point from providing coverage.

The East Anglia hole and the English Channel hole, both get support from continental beacons.

Appendix E

BARAM user guide

This appendix provides a user guide to the Bangor radiobeacon analysis model. The software is made up of the following applications.

gndarray.exe	– creates the groundwave attenuation arrays for use in the software model.
skyarray.exe	– creates the skywave attenuation arrays for use in the software model.
baram.exe	– evaluates coverage, availability and continuity.
twoyear.exe	– creates the two-year output for availability.

External Applications required:

- Art application which takes the portable pixel format (ppm).
- GEBCO world atlas for the coastline data.

E.1 Introduction

The software runs from a single folder, which by default is set to: *c:\baram* and has the following structure,

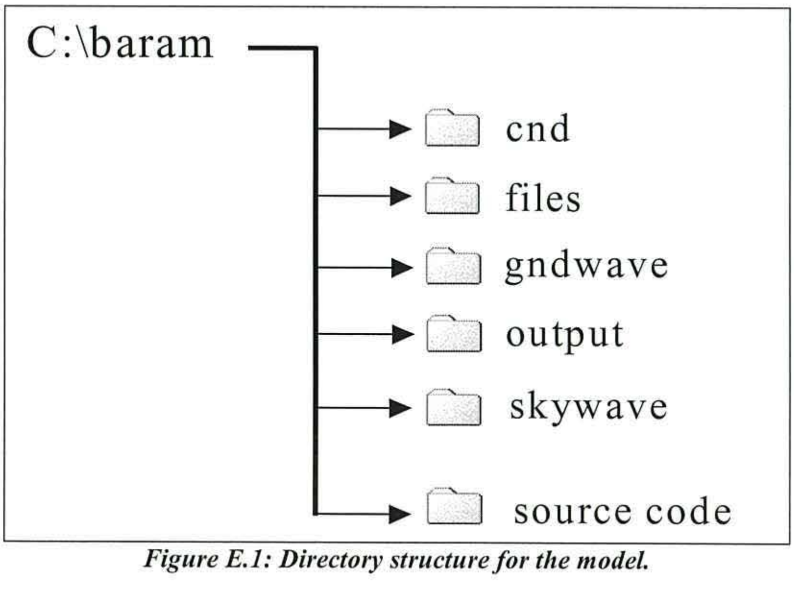

Figure E.1: Directory structure for the model.

The contents of these directories are now explained.

cnd

This directory contains all the ground conductivity files required when creating the attenuation arrays. The filenames are the south-west location of that cell. These files are set and do not require alteration.

files

This directory contains four files; *input.lst, becon.dat, prot_rat_15.dat* and *prot_rat_7.dat.* These files are very important and their use is explained further.

- *input.lst*

This file contains the beacons to be processed and is used when generating the attenuation files and when driving the software. Greater details on the format of this file is shown later in this guide.

- *becon.dat*

This file contains the latest band plan and is read by the software to gather information on each beacon. It's format is important and is explained further in this guide.

- *prot_rat_15.dat and prot_rat_7.dat*

These files contain the protection ratio information. They enable the software to eliminate interferers by range and frequency separation. They contain set data and require no additional amendments.

gndwave

This folder holds the groundwave attenuation arrays for all beacons in the band plan.

output

This folder starts empty, but is used to store any intermediate files created by the software, as well as storing the outputted results.

skywave

This folder holds the skywave attenuation arrays for all beacons in the band plan.

E.2 Creating the arrays

Two applications are used to generate the groundwave and skywave attenuation arrays. *Gndarray.exe* generates the groundwave arrays while the *skyarray.exe* application creates the skywave arrays. These applications are driven in the same manner and produce the arrays in the same format.

To start, the names of the beacons to be generated are listed in the *input.lst* file, in the following format.

```
2
GIRDLE_NESS DGP
MIZEN_HEAD_LSTN DGP
```

Figure E.2: Example input.lst entry for generating arrays

The leading number is the number of beacons to be processed. Then on each line is the beacon's name, (note that spaces are replaced with an underscore) followed by the beacons type. In this example, by running the *gndarray* and *skyarray* applications, the attenuation arrays *GIRDLE_NESS.DGP* and *MIZEN_HEAD_LSTN.DGP* are produced and stored in the appropriate directories.

The dimensions of these arrays are calculated within the creation software and the array limits are stored in the file *mainwin.dat*, which is located within the gndwave and skywave directories. *Mainwin.dat* has the following format,

```
GRACIOSA 21.000000 -52.000000 57.000000 -4.000000
KOBBE 51.000000 -35.000000 80.000000 71.000000
VRLIKA 25.000000 -9.000000 61.000000 41.000000
```

Figure E.3: Format of mainwin.dat file.

The format is the beacon's name followed by the minimum latitude, minimum longitude, maximum latitude and maximum longitude. So for Graciosa, it's groundwave attenuation array covers 21°-57°N by 52°-4°W.

The same is done for the skywave arrays co-ordinates. These co-ordinates are collected and incorporated into the *becon.dat* file. Once the arrays for all the beacons have created, the *beacon.dat* file needs updating before the analysis software can be used.

E.3 Becon.dat

This file is at the heart of the software. Its source is the latest frequency plan obtained from IALA, which contains all of the beacons listed for use in the European Maritime Area, including marine beacons, aeronautical beacons and, of course, DGNSS beacons.

The frequency plan is normally received as a spreadsheet, and the information is extracted (manually) into a text file, to give the following format,

```
-1 283.000000 GRACIOSA NDB 39N05 28W01 185 100 210 -520 570 -40 150 -590 770 220
3 285.000000 GRANADA NDB 37N11 03W50 25 14 190 -270 550 210 150 -520 750 460
```

Figure E.4: Example format of the becon.dat file.

The format of this file is as follows,

						Range		Groundwave array limits				Skywave array limits			
Channel	Frequency	Name	Type	Latitude	Longitude	Km	nm	minlat	minlon	maxlat	maxlon	minlat	minlon	maxlat	maxlon
-1	283	GRACIOSA	NDB	39N05	28W01	185	100	210	-520	570	-40	150	-590	770	220

Figure E.5: Explanation of becon.dat data format.

This file then contains all of the information necessary to run the analysis software.

E.4 Baram

This is the main application at the heart of this research. It can be set to predict coverage, availability, continuity and beacon selection for a single beacon or a series of beacons. The first stage of the process is to list the beacons to be processed in the *input.lst* file. The same format is used as shown in Fig. E.2, except that the beacon type is NOT included.

Once the *input.lst* file has been updated, the *baram.exe* application is executed, which gives the following menu.

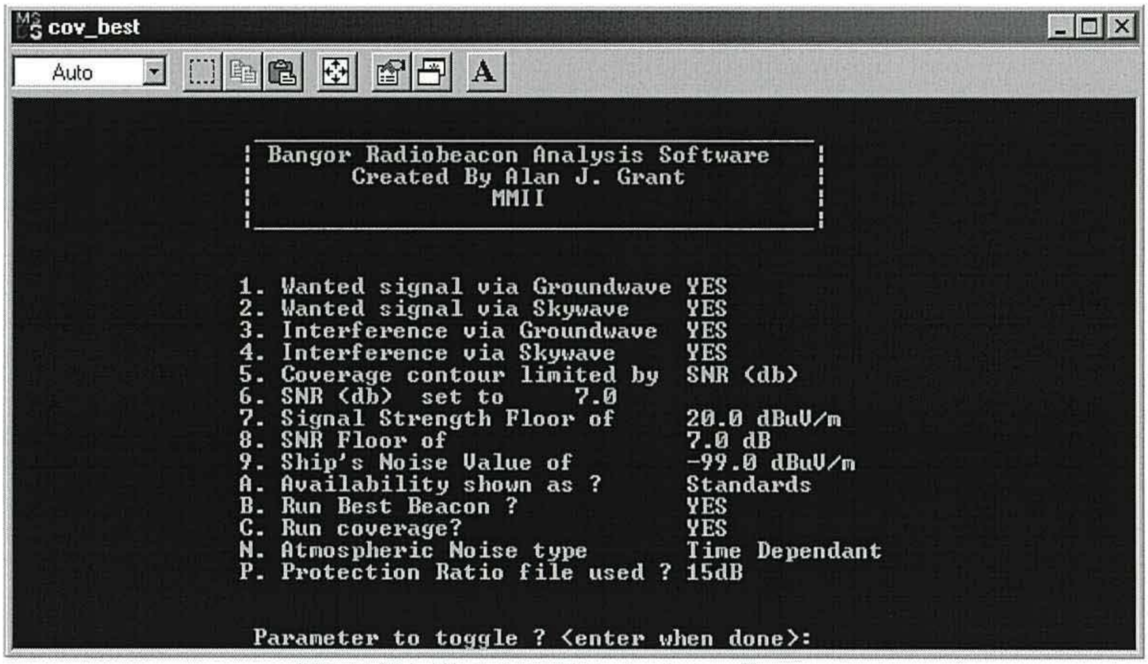

Figure E.6: User menu from analysis software.

This user menu is used to select the various settings of the software. The operator interacts with the menu by pressing the number or character on the left, which then toggles the result. For example, should the user wish to switch interference by goundwave off, they simply press '3' and the menu will alter to show 'NO'.

The menu options are now explained.

1. Wanted signal via groundwave.

   This option enables/disables the wanted beacon's signals via groundwave. It is usually set to YES.

2. Wanted signal via skywave

   This option enables/disable the wanted beacon's signal that travels by skywave path. It is set to NO when calculating daytime conditions and set to YES for night time calculations.

3. Interference via groundwave

   This option enables/disables the processing of interference received via the groundwave propagation paths from all the other beacons in the band. It is switched to NO when calculating interference free coverage.

4. Interference via skywave

   This option enables/disables the processing of interference received via the skywave propagation paths from all the other beacons in the band. It is switched to NO when calculating interference free coverage or coverage with interference by day.

5. Coverage contour limited by...

   The user may select the factor which defines the contour limits. This option toggles between SNR (signal-to-noise ratio), Accuracy and SS (Signal Strength).

6. Value of contour limit set to..

   This selects the limit for SNR, Accuracy or SS as set in option 5.

7. Signal strength floor of....

   This option allows the user to enter the minimum signal strength floor. This option is used when the coverage contour is limited by SNR or Accuracy. It allows the user to determine another coverage limit. However, if the SS contour is used, this option has no effect.

8. SNR floor of...

   This setting is used when the contour is limited by Accuracy. It allows the user to stipulate a minimum SNR setting, below which there is no coverage.

9. Ships Noise

   This option allows the user to set a noisy environment. Mimicking the noise that could be experienced locally. Any value may be inputted and is used when predicting coverage when the contour is limited by SNR or Accuracy. When calculating the SNR the atmospheric noise and ships noise are compared and the largest used.

A. Availability shown as...

This option toggles between 'standards' and 'contours'. The standard setting produces the resulting plot showing where the standards have been met. The contours setting, produces plots showing the availability at each location.

B. Run Best Beacon?

This option toggles between YES and NO. If set to YES then the best beacon analysis is executed once coverage has been completed. This analysis then produces various output plots identifying the best beacon. This needs to be set to YES when calculating availability and continuity.

C. Run Coverage?

This option toggles between YES and NO. If set to YES then the coverage of each beacon is calculated and their arrays are stored. This must be done before any best beacon analysis can be done. It can be set to NO if the analysis needs to be repeated without the conditions being changed.

D. Atmospheric Noise type?

This option toggles between 'Time Dependant' and 'Annual'. With the 'Time Dependant' option set, the model uses either the 95% annual daytime noise, or the 95% annual night-time noise, depending on the settings of options 1 and 2. With the 'Annual' option set, the 95% annual average atmospheric noise is used. The time dependant noise is used when calculating availability over two years.

P. Protection Ratio Used?

This option toggles between '15dB' and '7dB'. The standards state that the skywave co-channel interference ratio should be +15dB. That means the wanted beacon should be 15dB greater than any interferer. By selecting '15', these standards are used and this is the default setting. However, occasionally there is the need to produce plots using a 7dB co-channel interference ratio and this setting will allow for this.

When the selection has been completed, press return and Y to run the software.

The software then proceeds to evaluate the beacons using the settings selected by the user. When predicting coverage the following screen is seen,

Fig. E.7 shows the software processing Duncansby head DGNSS beacon. It has identified that there are 16 beacons which can potentially cause interference via groundwave and 5 which may do so via their skywave signal. The interferers are identified on screen and recorded in a file (int.dat, located in the files directory) to enable further investigation if necessary. In addition to this, the penultimate line is the field strength of Duncansby head at an entered check point. The last line 'FOM' is the figure of merit calculation.

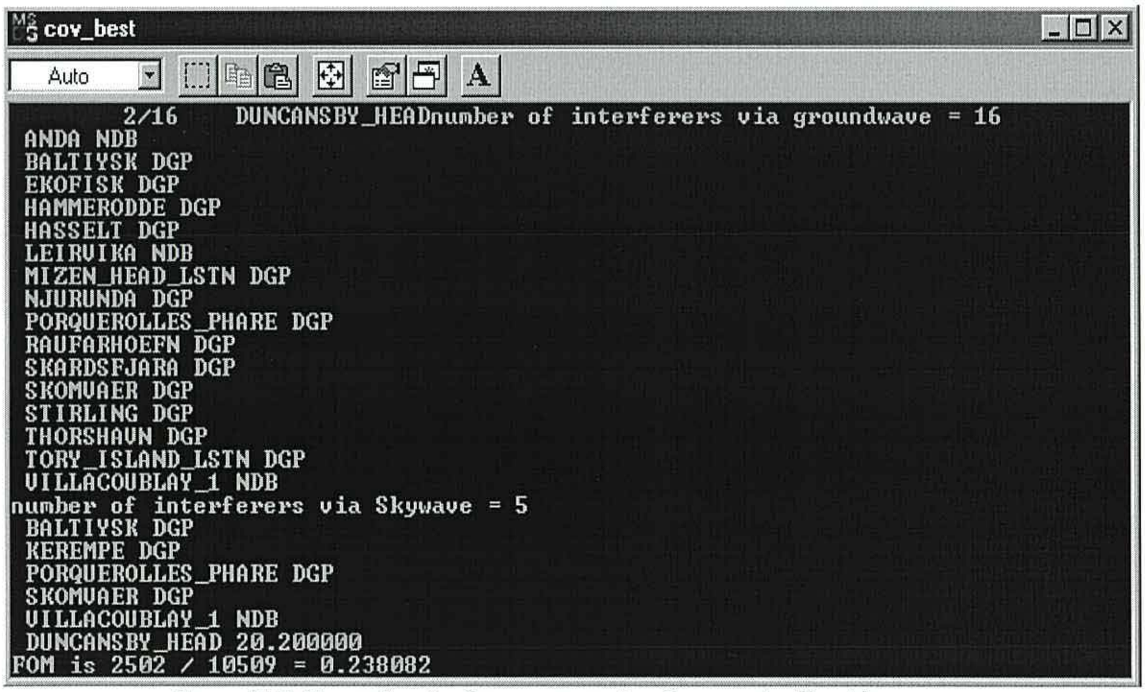

Figure E.7: Example of software processing Duncansby Head beacon.

E.4.1 Outputted files

The software outputs the following files, (PPM)

File name	Contents
combined	Plots the coverage.
avail	Plots the availability.
cont	Plots the continuity.
distance	Plots the best beacon selected by the nearest beacon strategy.
strength	Plots the best beacon selected by the strongest strategy.
multi	Plots the number of beacons providing simultaneous coverage to each location.
diff_stren_dist	plots the difference between the beacons selected using the strongest and nearest methods.
quality	Plots the best beacon selected by quality strategy
quality_alt	Plots the alternate beacon selected by the quality strategy.
dist_qual	Plots the best beacon selected by the Post-SA strategy.
dist_qual2	Plots the alternate beacon selected by the Post-SA strategy.
diff_qual_dist	Plots the difference between the beacons selected using the quality method and the nearest method.
diff_quald_dist	Plots the difference in the beacons selected between the Post-SA method and the nearest method.

Table E.1: PPM files output by the BARAM software.

Along with these PPM files, the following data files are also produced.

File name	Contents
avail_st.dat	array of availability figures.
multi.dat	array of number of beacons.
alternate.dat	List of best beacon and alternate beacon for each location.
availability.dat	List of availability for each location
output.avl	array of availability figures for use with output_type.exe
output.cnt	array of continuity figures for use with output_type.exe
combined.dgp	array of coverage figures.

Table E.2: Data files output by the software.

E.4.2 Mapping

The outputted PPM files contain only the coverage areas, no map is included. To add the map, the outputted PPM files are layered on top of maps extracted from the GEBCO world atlas. This is done by extracting the map from the GEBCO application and combining the two in an art package.

E.5 Output_type.exe

This application is used to calculate the availability over two years. It combines the two *output.avl* data files, one produced by the daytime run and the other by the night time run (which need to be placed into the appropriate folder within the combined folder). These are then combined together at the appropriate ratio and a new output *ppm* file is created.

E.6 Software alterations

This software is the result of development with a research project. Its location is focused on the European Maritime Area, however this may be altered by changing the location settings in the top of the source code. If this is done, then the array size must also be checked to ensure that it will be sufficient, no other changes are needed.

At present the software uses the IALA minimum availability of 99.5% for all beacons. Should the software be used as a post-processing tool, then alterations would be needed within the source code for each station to have it's own availability listed – however, this should be a simple task.

Appendix F

Software Structure

This appendix gives a brief overview of the structure of the BARAM software. Figures F.1 and F.2 show the main events and the order in which they are processed.

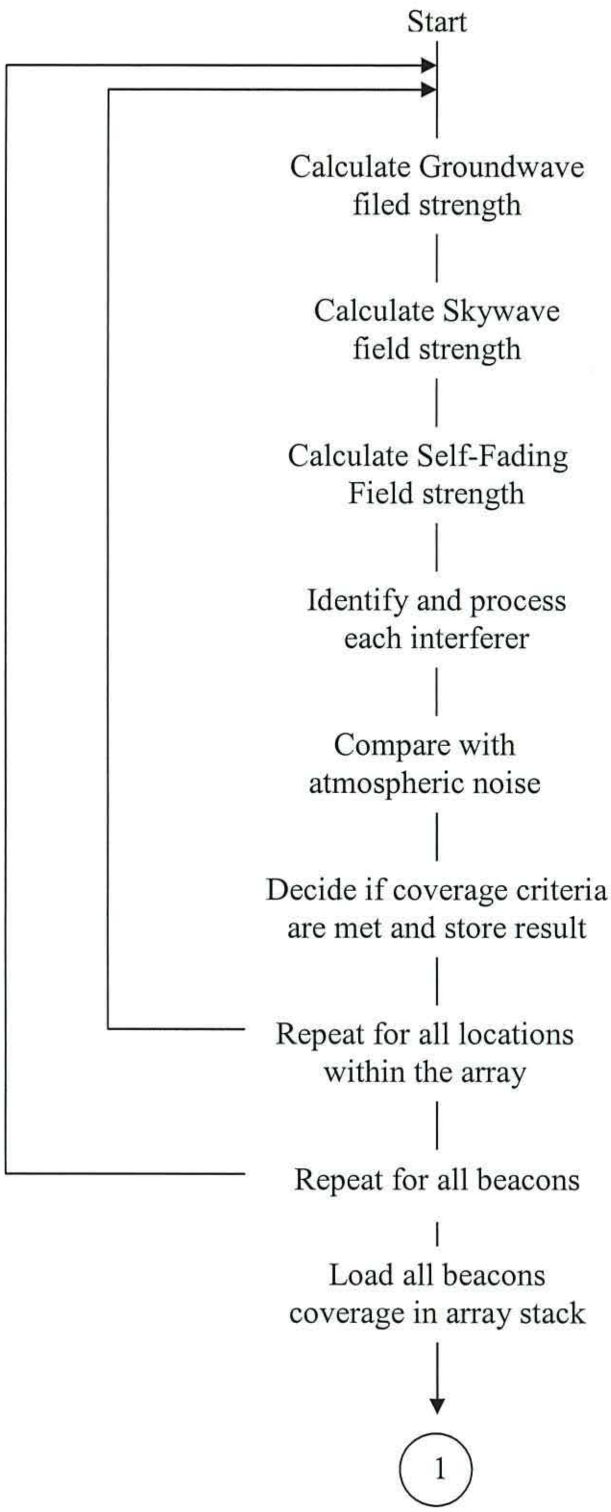

Figure F.1: Top level process diagram showing the order in which the BARAM software processes different tasks (Top half).

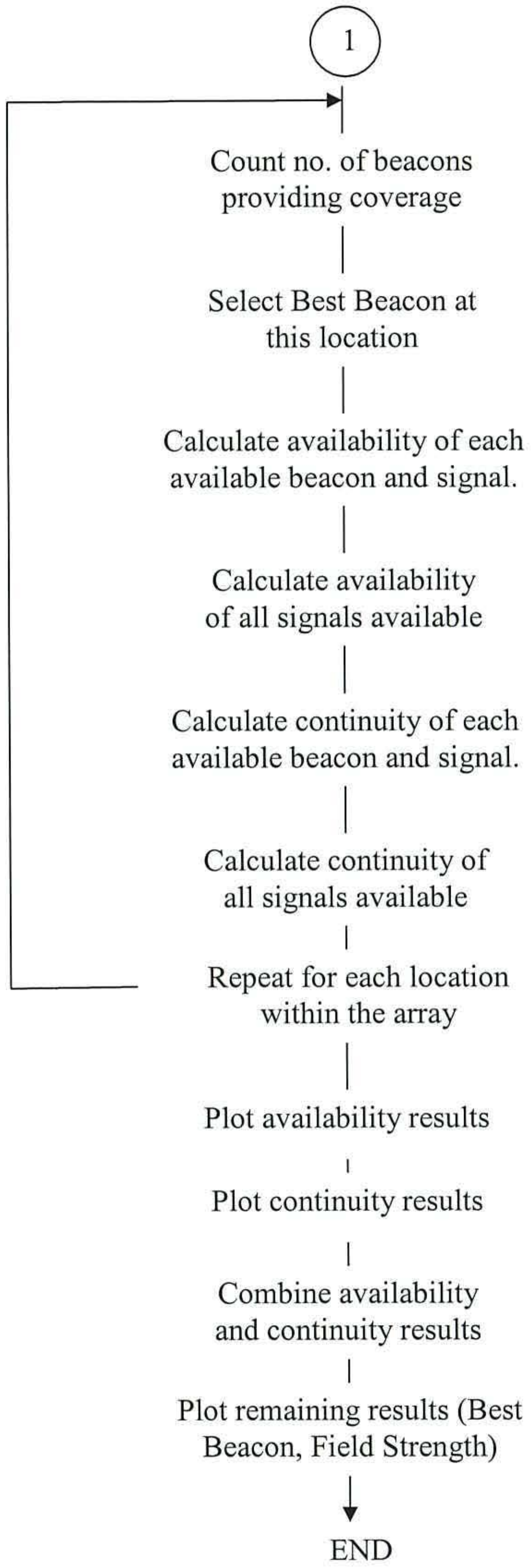

Figure F.2: Top level process diagram showing the order in which the BARAM software processes different tasks (Bottom half).

Appendix G

Publications co-authored by candidate

A list of the publications co-authored by the candidate during the course of this research is given below. The full text of these papers follows, in Section F.2.

G.1 Journal Publications

- Last, J.D. & Grant, A., *'Optimum choice of beacon in maritime DGNSS systems'*, Journal of the Royal Institute of Navigation, Spring 2002

G.2 Conference Papers

- Last, J.D., Grant, A. & Ward, N., *'Radiobeacon DGNSS station selection strategies - can we do better?'*, National Technical Meeting 2001, Institute of Navigation (USA), Long Beach, CA 22-24 Jan, 2001.

- Grant, A., Last, J.D. & Ward, N., *'Quality criteria for the maritime DGNSS system in a world without SA'*, GNSS2001 Conference, Seville, Spain, 8-11 May 2001.

- Roberts, G., Last, J.D. & Grant, A., *'Radiobeacon DGNSS coverage planning – a national case study'*, IEEE Oceans01 Conf, Hawaii, Nov 2001.

- Last, J.D., & Grant, A., *'Understanding radiobeacon DGNSS standards, post-SA'*, NAV01 Location and Navigation Conference, Royal Institute of Navigation, London, 6-8 November, 2001.

- Grant, A., Last, J.D., & Ward, N., *'Understanding and predicting the availabilities of radiobeacon DGNSS systems'*, National Technical Meeting 2002, Institute of Navigation (USA), San Diego, CA, 28-30 Jan, 2002.

- Grant, A., Last, J.D., & Ward, N., *'Marine radiobeacon DGNSS service - predicting availability and continuity'*, ION GPS 2002, Institute of Navigation (USA), Portland, Oregon, 24-27th September, 2002.

- Last, J.D., Grant, A., Williams, A.I., & Ward, N., *'Enhanced accuracy by regional operation of Europe's new radiobeacon differential system'*, ION GPS 2002, Institute of Navigation (USA), Portland, Oregon, 24-27th September, 2002.

THE JOURNAL OF NAVIGATION (2002), 55, 249–262. © The Royal Institute of Navigation
DOI: 10.1017/S0373463302001698 Printed in the United Kingdom

Optimum Choice of Beacon in Maritime DGNSS Systems

David Last and Alan Grant

(*University of Wales, Bangor*)

Marine radiobeacons are widely used by the maritime community worldwide as an efficient means of broadcasting differential GPS data to users at sea. In Europe and North America, large numbers of these beacons now serve coastal regions, waterways, and some inland areas. Frequently there is overlapping coverage and a choice of stations. But users receive little guidance as to how to select the beacon that gives the highest quality service. Receivers that choose a beacon automatically generally select either the nearest station or the strongest signal. But the performance of the data-link is optimised by choosing the station received with the highest ratio of signal to either noise or interference. With Selective Availability set to zero, spatial dilution and time-to-alarm have become key factors. This paper compares four beacon selection strategies by means of a computer model based on well-established coverage analysis and system design techniques. We recommend a new 'post-SA' beacon selection method that chooses the nearest station that meets the time-to-alarm requirement. This strategy has been used to identify the 'best beacon' throughout the European Maritime Area, with stations operating in accordance with the new band-plan adopted last September. We also identify the alternate beacon to use if the preferred station should fail.

KEY WORDS

1. GPS. 2. Differential GNSS. 3. Marine Radiobeacons.

1. INTRODUCTION. Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be determined by using reference stations at known locations to measure pseudorange errors. When transformed, these errors can be transmitted as corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, the marine radiobeacon, is widely employed to transmit DGNSS corrections for maritime users.[1,2] In many areas of Europe and North America, more than one DGNSS beacon is available.[3] With many older beacon receivers, the user must select a station manually, but there is little guidance as to how to make that choice. Many newer types of receiver perform the selection automatically, some choosing the nearest station, others the beacon that provides the strongest signal.

This paper considers the choice of 'best beacon', for both manual and automatic receivers. It compares the results of the commonly used *nearest beacon* and *strongest beacon* strategies. It then introduces two novel approaches: a selection based on signal *quality*, and a strategy tailored to the *post-Selective Availability (SA)* world.

2. INDIVIDUAL RADIOBEACON COVERAGE. The radiobeacon frequency band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). Within the European Maritime Area (EMA) of the International Telecommunication Union (ITU) Region 1, a geographical point is deemed to lie within the coverage of a DGNSS beacon, if the beacon's field strength is not less than 10 μV/m (or a higher figure specified by the national administration) and the signal-to-noise ratio (SNR) not less than 7 dB.[4] In addition, no interfering signal may exceed protection ratios defined by the International Electrotechnical Commission (IEC).[5]

A tool that is widely-used for predicting the coverage of marine radio beacons is the Bangor Coverage Prediction Software.[6] This suite of programs models the coverage areas of single beacons or groups of beacons, taking into account groundwave and skywave propagation, own-skywave fading, and interference, If we are to consider the choice of beacon at a location where more than one signal is available, we need data on all these factors for all candidate beacons simultaneously. Achieving this has required the development of new software that employs a multi-layer array architecture.[7] This new software can still be used to predict the coverage areas of single beacons, as previously. An example is shown at Figure 1 where the outer boundary is the limit of daytime, interference-free, coverage. But in addition, the new software can model the results of various strategies for selecting the best beacon, allowing us to compare them.

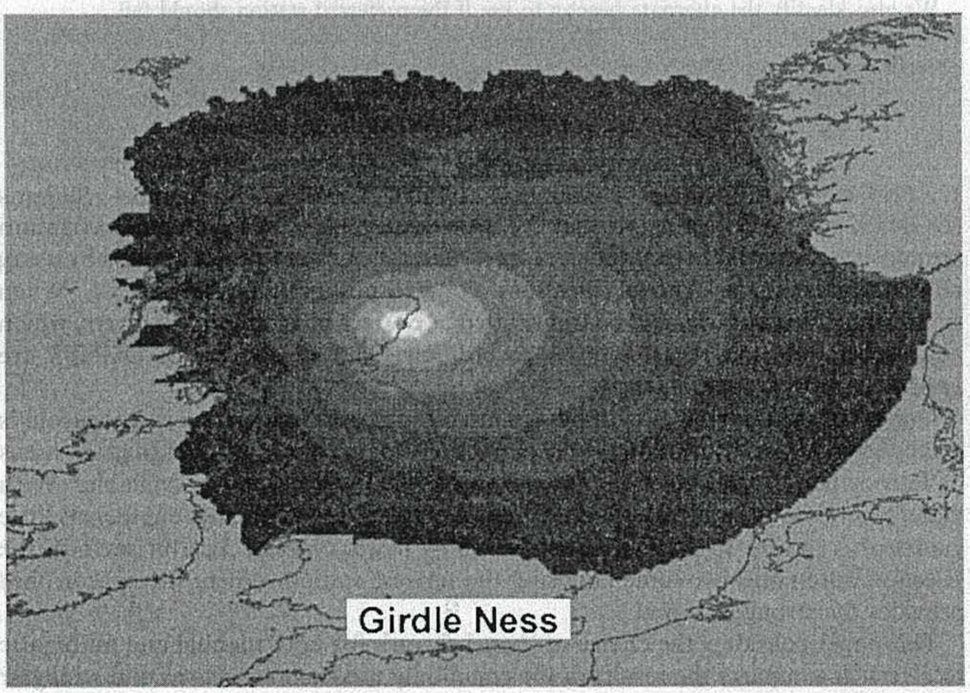

Figure 1. Groundwave field strength contours of a beacon at Girdle Ness, Scotland. Outer boundary is daytime interference-free coverage.

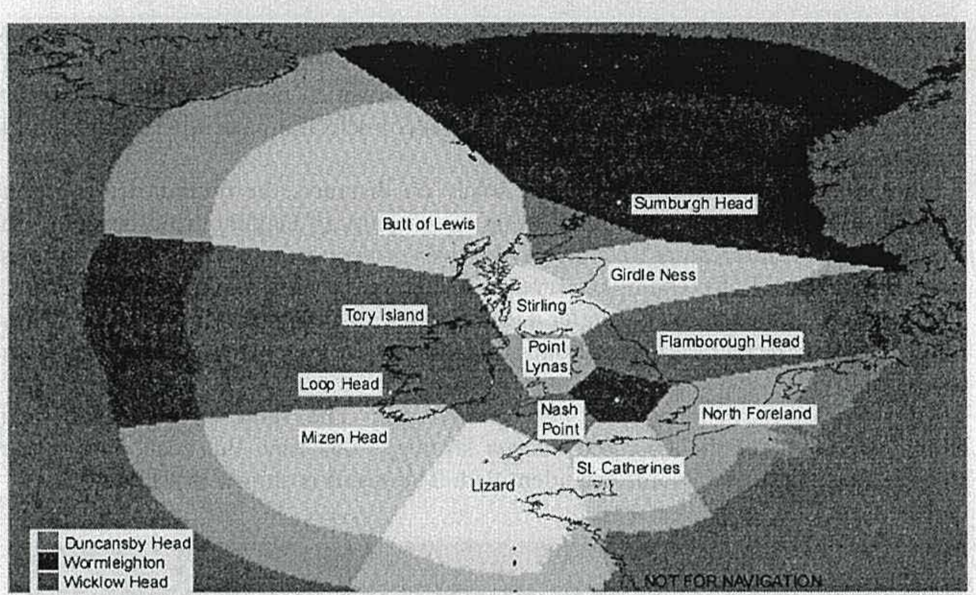

Figure 2. Beacon selection using *nearest beacon* strategy, for the 16 United Kingdom and Ireland DGNSS stations only. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent. (This and later similar charts are also published in colour.)

3. MODELLING BEACON SELECTION STRATEGIES. Currently, two strategies for selecting the beacon to use are commonly employed in DGNSS receivers: the *nearest beacon* and the *strongest beacon* strategies.

When a receiver employs the *nearest beacon* strategy, it ignores all attributes of the beacon's signal. Thus it will sometimes select a nearby weak station – possibly one whose signal has arrived via a land path of high attenuation – and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case, the more distant beacon's signal would have a higher SNR than the nearest one. So choosing the nearest signal in this way could result in more data errors and thus greater delays in receiving correction updates.

In contrast, selecting the station using the alternative *strongest beacon* strategy would mean that the stronger, more distant beacon was chosen. However, this might result in greater position errors due to increased spatial dilution of precision.

We will first employ our software to map the choices of best beacon made by these two strategies, and then examine whether they generate significantly different choices. We will do so using the system of 16 beacons designed to serve the United Kingdom and Ireland. Note that the sets of British Isles and EMA beacons used in this paper, and the frequencies they employ, are taken from the new band-plan introduced in September 2001.[9] Coverage by beacons outside the UK is omitted in these examples.

3.1. *Modelling the nearest beacon strategy*. The process starts by computing the coverage areas of each of the 16 beacons. Then, point-by-point throughout these areas, we identify the nearest beacon. When all points have been examined, we produce an output plot (Figure 2), with a different colour (though here a level of grey) to distinguish the area within which each beacon has been chosen.

Figure 2 also distinguishes between the extent of coverage available by day (outer boundary) and at night (inner, lighter, region). The night-time coverage is less than the daytime because of fading due to skywave cancellation of the wanted beacon's signal. This form of diagram is designed for navigators who must input the choice of beacon into their receivers manually. It tells them which beacon to use by day or night, where on a voyage they should change beacon selection, and where they should cease to rely on coverage from the system.

Since this beacon selection is based solely on distance, the boundaries between adjacent areas are the straight lines along which pairs of neighbouring beacons are equidistant. It is interesting to compare the sizes of the coverage areas of the various stations. Sumburgh, for example, serves a much larger region than does Nash Point. This is partly explained by its greater nominal range, 370 km as compared to 277 km, but more so by the fact that Nash Point's neighbours are simply much closer to it than are Sumburgh's.

3.2. *Modelling the strongest beacon strategy.* The same process was then employed to model the *strongest beacon* strategy; this time the beacon with the strongest signal at each point was identified. The result is shown in Figure 3.

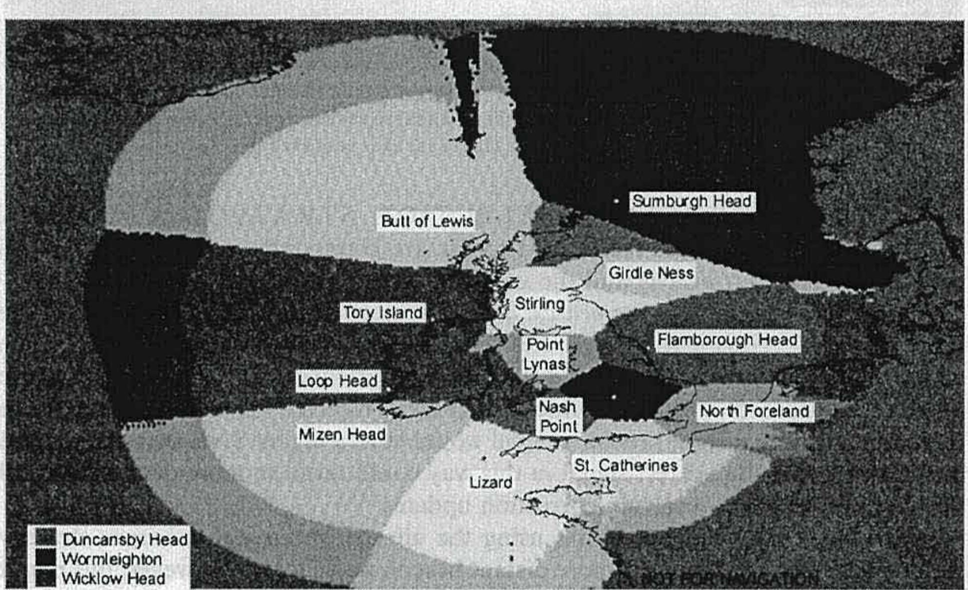

Figure 3. Beacon selection using *strongest beacon* strategy, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.

The beacons this strategy chooses appear to be significantly different from those chosen by the *nearest beacon* strategy (Figure 2). The lighter areas in Figure 4 are the regions in which the two strategies produce different results; they constitute 15% of the total daytime coverage.

To understand the reasons for these areas of difference, consider the large sector west of Ireland along the Tory Island/Loop Head boundary. Here the signal from Tory Island is the stronger, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head. But even where two stations of equal power do compete, the *nearest beacon* strategy frequently selects the weaker signal. For example, the Stirling/Tory Island boundary up the west coast

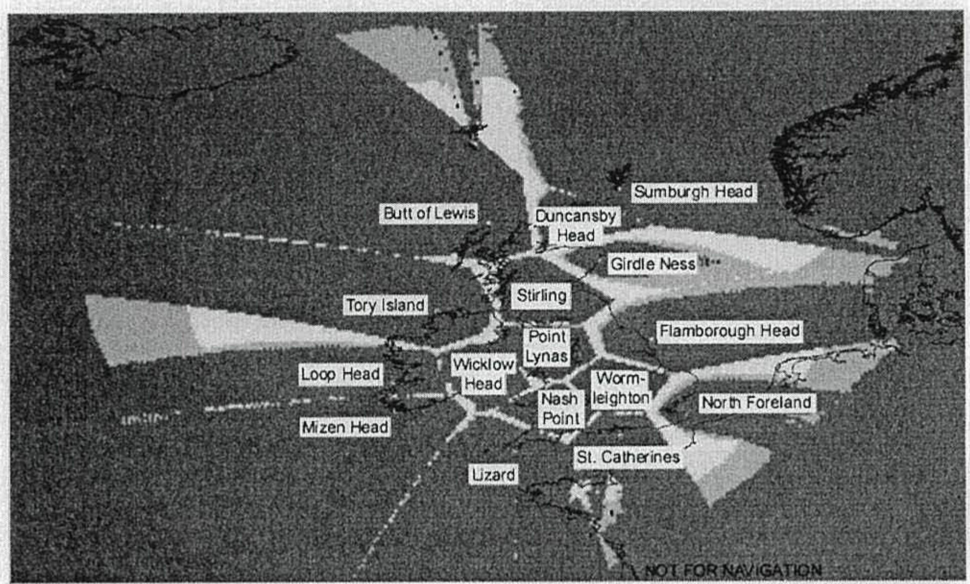

Figure 4. The lighter areas identify regions in which the *nearest beacon* and *strongest beacon* strategies select different beacons.

of mainland Scotland lies much closer to Stirling than to equally powerful Tory Island. But the Stirling signals arrive via land paths of high attenuation, while the signals from Tory Island signal come via longer paths, but over the sea, and are stronger.

In these, and other fairly extensive regions, the *nearest beacon* strategy fails to select the station with the strongest signal. The consequences are a lower SNR, a higher message error rate, and greater message latency, than the *strongest beacon* would offer. With SA active, latency was the major constraint: the greater the latency, the greater the pseudo-range error that built up before the next correction was received, and so the greater the resulting position error.

4. BEACON SELECTION BY SIGNAL QUALITY. The logical conclusion of the previous argument is that we should always choose the beacon whose signal has the highest signal-to-noise ratio. There are two sources of noise – firstly, atmospheric noise; its level at any time is essentially the same on all channels across the radiobeacon frequency band. Thus, choosing the *strongest beacon* automatically gives the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – the dominant noise source for radiobeacon coverage in Europe at night.[8] One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength, but on a different frequency, might have much less interference, and so a higher SNR. Thus, in selecting our beacon, we should take into account not only atmospheric noise but also interference. And we should use as our measure of quality the overall SNR. That is, the ratio between a beacon's signal strength and either atmospheric noise or interference, whichever is the greater. This is our *quality strategy*.

Our software provides all the information we need to assess beacons' SNRs in this way: the groundwave and skywave strengths of the wanted beacon, the atmospheric

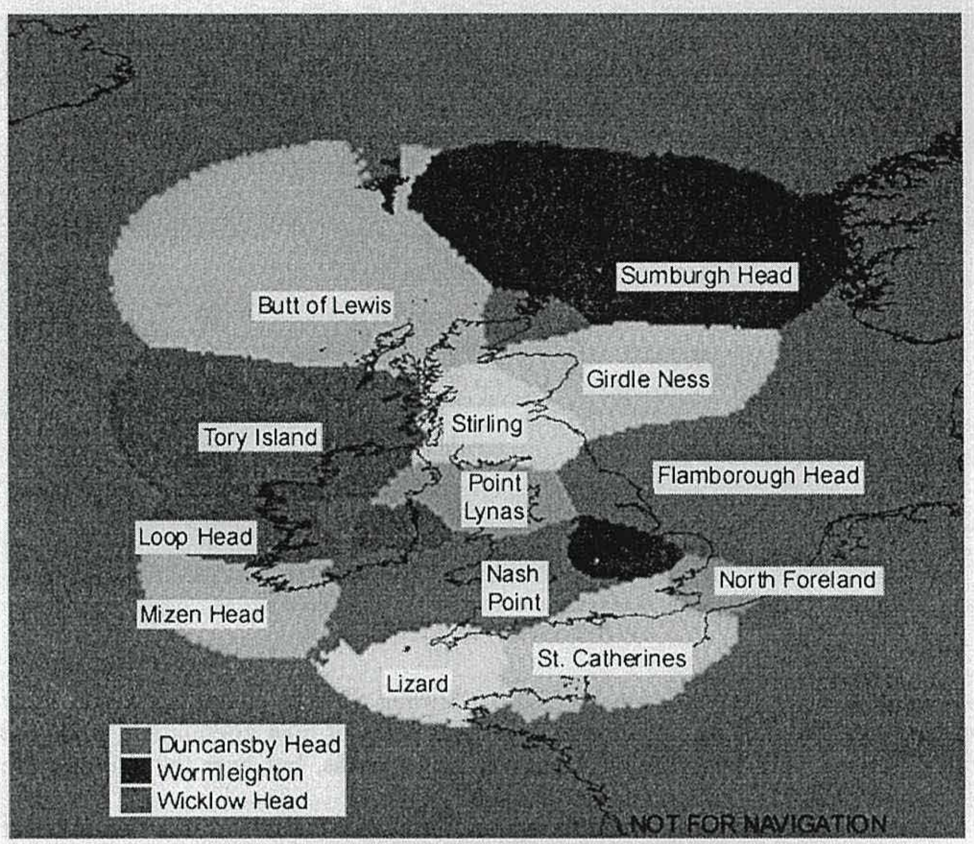

Figure 5. Beacon selection using the *quality strategy* for the 16 beacons of the UK and Ireland, under night-time conditions with interference.

noise level, and the strengths of all interfering components on all channels. Thus we can compute the SNR of each beacon's signal at any point and so identify the best beacon according to this *quality strategy*. Figure 5 shows the results for the British Isles beacons. This figure is plotted under worst-case conditions: that is, at night when interference capable of reducing coverage can be received via sky-wave propagation from other beacons up to 4200 km away. In consequence, not only is night-time coverage smaller than by day, but the effect of interference on the choice of beacon is greatest then.

In contrast, the *nearest beacon* strategy ignores all interference. In the lighter areas of Figure 6, which total 14% of the night-time service area of the system, the new *quality strategy* has chosen beacons of higher SNR than did the *nearest beacon* strategy. Clearly, the *nearest beacon* method fails to provide the user with the highest quality signal over substantial and important areas.

5. THE ENDING OF SELECTIVE AVAILABILITY. In May 2000, SA was set to zero. What effect does this have on beacon selection strategy? Now the dominant position error sources in GPS become ionospheric and tropospheric delays. Both

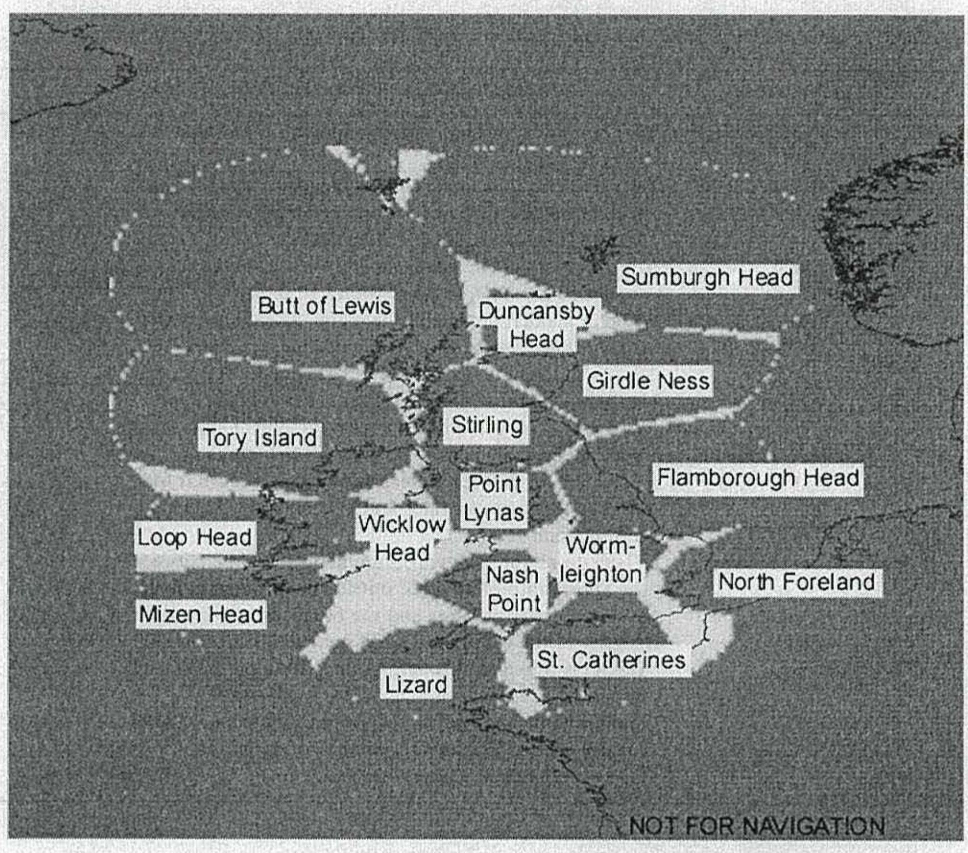

Figure 6. The lighter areas identify regions in which different beacons are selected by the *nearest beacon* and *quality* strategies.

types of error change much less rapidly than did the previously dominant SA. Therefore, correction messages remain valid for longer periods of time; indeed, they may be usable for tens, or even hundreds, of seconds. So the effect of latency on the reception of corrections is markedly reduced, and much lower beacon SNR values can be tolerated than before. Receiving the station with the highest SNR, or even the strongest one, would appear to be much less important than before.

On the other hand, as the separation between reference station and receiver increases, the dominant error source soon becomes spatial dilution of precision. These errors result from the user and the reference station experiencing different ionospheric and tropospheric delays. So it would appear that a simple *nearest beacon* selection strategy is all that is now required.

But the situation is complicated by a third factor! Correction messages also carry alarms to warn the user of unhealthy satellites or failures of reference stations. Indeed, enhancement of integrity is now a much more important benefit of differential operation for many users than enhancement of accuracy. So it may not, in fact, be acceptable to choose a nearest beacon with minimal spatial dilution but low SNR, since this would result in increased message latency and, possibly, an excessive time-to-alarm.

Table 1. Time-to-alarm definitions and specifications. Italics show discrepancies and ambiguities.

Authority	Statement regarding time-to-alarm (TTA)
IMO (A.815)[10]	A warning of *system malfunction* should be *provided to users* within *10 seconds.*
IMO (A.860)[11]	Time-to-alarm is *the time elapsed between the occurrence of a failure in the system and its presentation on the bridge.* Time-to-alarm < = *10 seconds.*
IALA[12]	A warning of *system non-availability or discontinuity* should be provided to users within *10 seconds.*
IEC[5]	While in manual mode and the manually *selected station is unhealthy, unmonitored, or signal quality is below threshold,* then an alarm shall be activated.
USCG[13]	1. (*Time-to-alarm is*) the time from when *a protection limit is exceeded* to when the user equipment suite/user is alarmed by the broadcast. (It shall be) less than 2 seconds for 200 bps transmission rates, *4 seconds* for 100 bps transmission rates and 8 seconds for 50 bps transmission rates. 2. Time-to-alarm: The maximum allowable time between the appearance of an error outside the protection limit at the integrity monitor and the broadcast of the alarm.
FRP[14]	Integrity of the Maritime DGPS service operated by the USCG is provided through an integrity monitor at each broadcast site. Each broadcast site is remotely monitored and controlled 24 hours a day from a DGPS control centre. *Users will be notified* of *an out-of-tolerance condition* within *6 seconds.*

6. TIME-TO-ALARM SPECIFICATIONS. Recognising this issue led us to study the time-to-alarm (TTA) specifications in the published radiobeacon DGNSS international, and US national, standards. Table 1 shows the requirements set by five authorities: the International Maritime Organisation (IMO);[10,11] the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA);[12] the International Electrotechnical Commission (IEC);[5] the United States Coast Guard (USCG);[13] and the US Federal Radionavigation Plan (FRP).[14] The ambiguities in the statements and discrepancies between them, both shown in italics in the table, are significant.

The first ambiguity is as follows: IMO A.815[10] and IALA[12] speak of a warning being 'provided to users', and the FRP[14] states that 'users will be notified' within the TTA. Does this mean that the user's receiver will *display* a warning within the TTA, as users might reasonably expect? Or does it mean simply that the reference station will *transmit* that warning, as some administrations appear to believe? The difference is very significant: it is the time the warning takes to pass through the transmission system and for the receiver to respond to it. This delay may be several seconds. Also, its magnitude depends in part on a latency determined by the SNR, and hence on the beacon selection strategy employed. The USCG document appears to define TTA in both ways: in Chapter 4, the TTA lasts until 'the user equipment suite/user is alarmed'; but in the *Definitions* section, the TTA lasts until 'the broadcast of the alarm'.[13] As far as IMO is concerned, and IALA which bases its document on IMO,

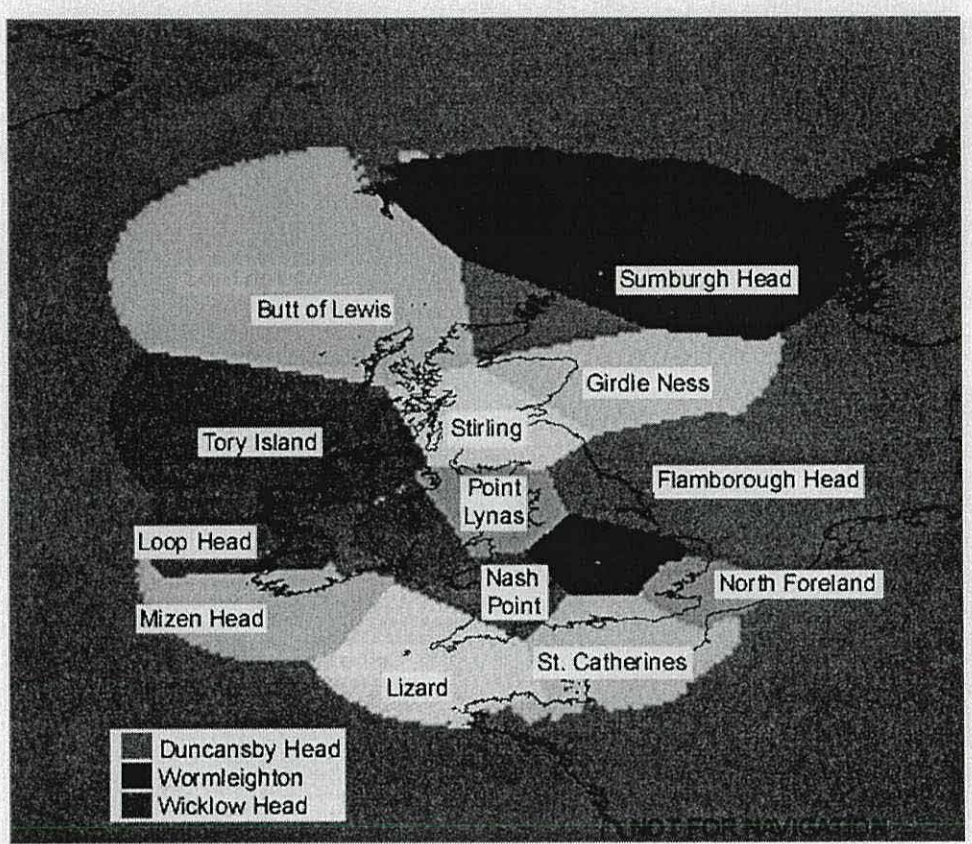

Figure 7. Beacon selection using the new *post-SA* strategy for the 16 beacons of the UK and Ireland, under night-time conditions with interference.

this ambiguity can be resolved by IMO A.860.[11] This defines time-to-alarm as 'the time elapsed between the occurrence of a failure in the system and its presentation on the bridge'.

The second ambiguity is whether the 'system malfunction' in IMO A815[10] means precisely the same as IALA's 'system non-availability or discontinuity',[12] or the IEC's 'selected station is unhealthy, unmonitored, or signal quality is below threshold',[5] or the USCG's 'protection limit is exceeded',[13] or the FRP's 'out of tolerance condition'.[14] The IEC offer yet another statement that applies just to automatic receivers. These multiple ambiguities concern the causes of alarms only and so have no implications for the choice of beacon selection strategy. The resulting confusion could, however, be significant for administrations operating marine radiobeacons.

A major quantitative discrepancy is the time-to-alarm limit itself. For 100 bps transmission, IMO A.815[10] and A.860[11], and IALA[12], all specify 10 seconds. The USCG[13] specify 4 s, the FRP[14] 6 s, while the IEC[5] give no specification. Clearly, the USCG's 4 s, measured from when the protection limit is exceeded to when the user's equipment (or the user) is alerted, is the most stringent of the TTAs and so demands the highest SNR. Finally, only the USCG specify a maximum range (300 statute miles) at which a radiobeacon's signals should be used without warning.

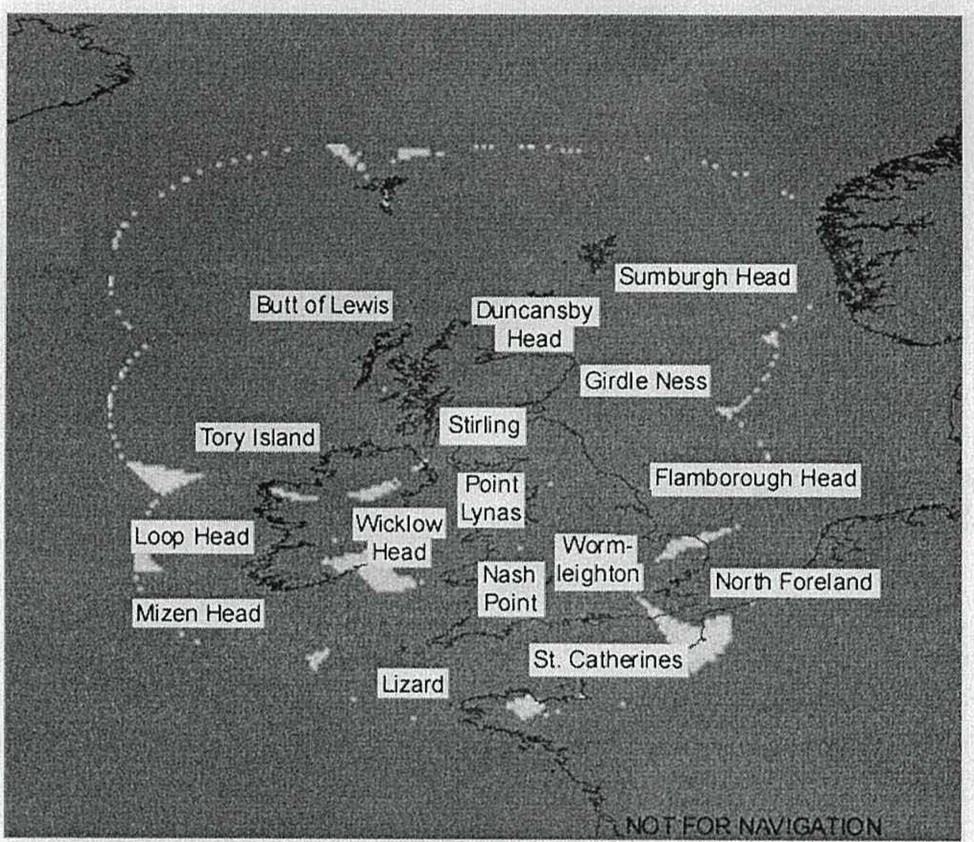

Figure 8. Lighter areas identify regions in which the *post-SA* and *nearest beacon* strategies select different beacons.

We have chosen to interpret these confusing specifications as follows. We have assumed that the maximum TTA is that experienced by the receiver, in accordance with IMO A.860.[11] This is the most conservative assumption, but also the common-sense one! It means that the TTA must include latency delays due to noise and interference. Secondly, for assessing beacon selection strategies and making coverage predictions in Europe, we have adopted the IMO/IALA 10 second TTA requirement. Different values would be required for USCG systems that meet the FRP requirements. Finally, we decided to seek to minimise spatial dilution of precision.

7. BEACON SELECTION BY THE *POST-SA* STRATEGY. A simple *nearest beacon* strategy would not guarantee that the TTA requirement was met. A quality strategy would not minimise spatial dilution. So we propose a post-SA strategy based on the following principle: the beacon to be selected is the nearest one that can meet the quality measure required for a 10 second TTA.

Measurements relating the signal word error rate to SNR have established that a signal of 7 dB minimum *signal-to-noise-or-interference ratio* will have sufficiently low latency to give a high probability of successful message reception within 10 seconds.[6] Indeed, this minimum SNR was included in the specification of beacons originally in order to ensure the 10 s message updates required to achieve acceptably-low position

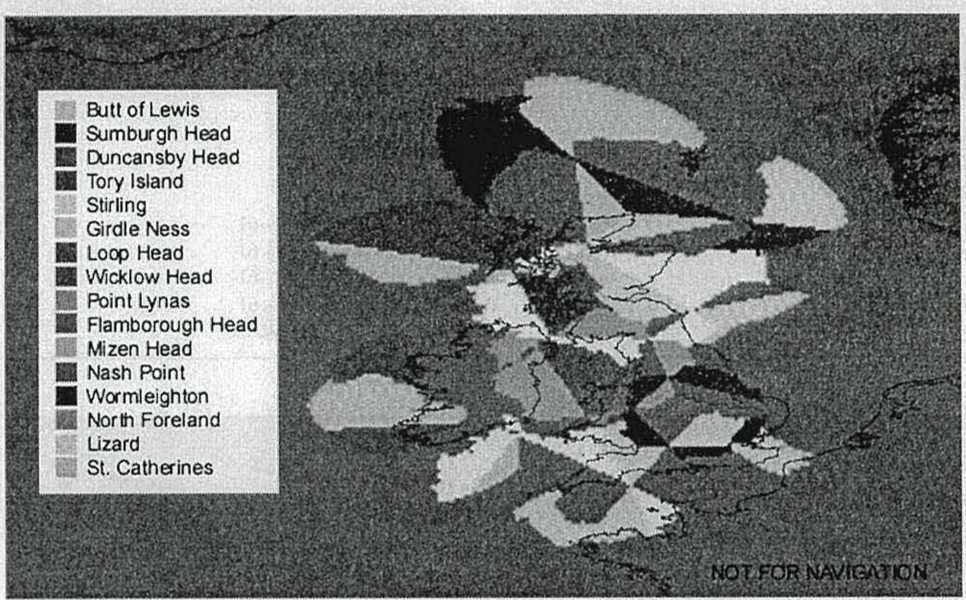

Figure 9. Choice of alternate beacon – the one to use if the best beacon should be unavailable.

errors when SA was in operation. So our post-SA strategy retains this minimum SNR.

The result of applying this strategy to the 16 British Isles beacons is shown in Figure 7. This figure is again plotted under the worst-case conditions of night-time, with interference. The results are strongly influenced by the differences of interference levels on the various beacons' channels. For example, the coverage of North Foreland is reduced by skywave interference from a distant station in the Mediterranean region. As a result, St. Catherine's is selected as the best beacon to use when following sections of the busy sea-lanes in the English Channel, even though North Foreland is the nearest beacon.

This point is clearly illustrated in Figure 8 in which the lighter areas are those where the *post-SA strategy* and the *nearest beacon* strategy give different results. Within these regions the nearest beacon should not be used at night since its signal fails to meet the time-to-alarm criterion.

Our new post-SA strategy happily turns out to be very similar to one recently proposed by the IEC.[5] However, whereas the IEC take only the signal-to-*atmospheric* noise ratio into account, our strategy ensures that *interferers* also do not exceed the minimum protection ratios.

7.1. *Alternate beacons.* This paper has presented strategies for identifying the best beacon to use at any location. But, if that beacon should be unavailable because of a scheduled or unscheduled outage, it is far from obvious to the user which station to select as the alternate. Our new software also allows us to answer that question. We run the same process as for choosing the best beacon, but this time select the second best. The alternate beacon results from the *post-SA* strategy are presented in Figure 9.

7.2. *Data in tabular form.* The maps shown in Figures 2, 3, 5, 7 and 9 are in a

Table 2. Part of a tabulated data set of beacon selections made using the *post-SA* strategy.

60 -	NASH_POINT
61 -	WICKLOW_HEAD
62 -	POINT_LYNAS
:	
:	
Lat: 53·2 Long: - 4·1	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 4·0	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·9	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·8	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·7	Primary - 62 Secondary - 61

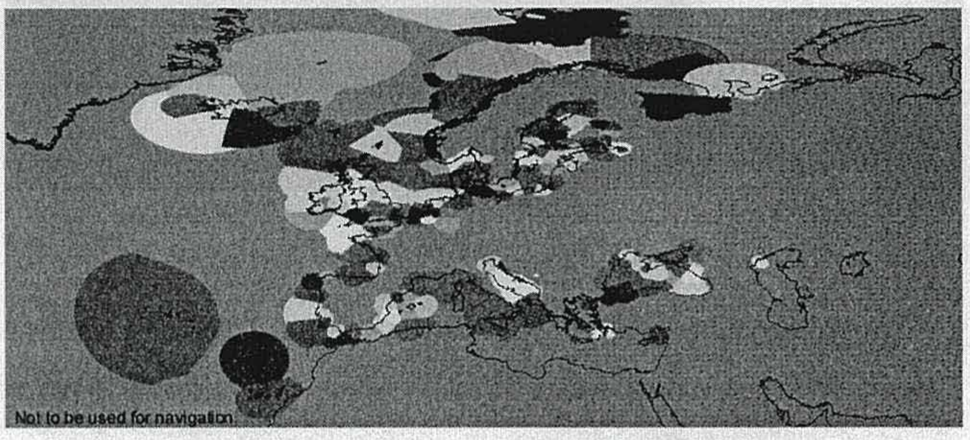

Figure 10. Beacon selection using the new *post-SA* strategy for the whole European Maritime Area (daytime, with interference).[8]

format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. To allow 'automatic' receivers to employ the same information, we have produced it in a tabular form that manufacturers can store within their receivers. Table 2 shows part of this data set: it lists at each location specified by latitude and longitude the best beacon computed using the *post-SA strategy* (Primary), and the alternate (Secondary).

7.3. *Beacon selection across the EMA.* In Figure 10, we show the result of using the new *post-SA* strategy to identify the best beacon everywhere throughout the entire European Maritime Area (30–72°N, 30°W–55°E).[8] The figure shows, for the first time, the combined coverage of all 158 differential GNSS radiobeacons in the EMA, identifying point-by-point the radiobeacon with the lowest spatial dilution whose signal meets the time-to-alarm criterion.

8. CONCLUSIONS. This paper has compared competing strategies for selecting the radiobeacon to be used where more than one is available. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a *quality strategy* has been studied in which the best beacon is deemed to be the one with the highest ratio of signal-to-atmospheric noise, or interference.

With the ending of SA, however, the constraints on beacon selection have changed dramatically. We have proposed a new strategy in which the best beacon is the nearest one (i.e. with least spatial dilution) whose signal quality meets the time-to-alarm requirements. Since there are multiple ambiguities in the TTA specifications of different international and national bodies, we have judged it most appropriate to interpret the requirement as being that the user is made aware of a fault within 10 seconds of its occurring. Happily our new post-SA strategy turns out to very similar to one being considered by the IEC.

Our results are presented in a pictorial form designed to be convenient for users who are obliged to enter the choice of beacon into their receivers manually. We have shown diagrams for both the British Isles and, for the first time, the whole European Maritime Area. An example is also presented of the data in a tabular form that can be built into receivers at the time of manufacture. Both forms of presentation indicate not only the choice of best beacon, but also the alternate to be employed when the best station is unavailable.

Finally, we strongly recommend that steps be taken to eliminate the discrepancies between the specifications published by the various authorities, and the ambiguities within them.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland.

REFERENCES

[1] Enge, P. K. and Olsen, K. E. (1990). *Medium Frequency Broadcast of Differential GPS Data*, IEEE Transactions on Aerospace and Electronic Systems, Vol. 26, No. 4, July, pp. 607–617.

[2] Enge, P. K. and Ruane, M. F. (1986). *Marine Radiobeacons for the Broadcast of Differential GPS Data*, Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November.

[3] *List of Radionavigation Services* (1999). International Association of Lighthouse Authorities, Issue 7 – August.

[4] *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area* (1985). International Telecommunication Union, Geneva.

[5] *Shipborne DGPS and DGLONASS Maritime Radiobeacon Receiver Equipment* (2000). International Electrotechnical Commission, Technical Committee No. 80, Maritime navigation and radio communications equipment and systems. IEC 61108-4: 2001, TC80/WG1 (DRAFT No 8), July.

[6] Poppe, D. C. (1995). *Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions*, Ph.D. Thesis, University of Wales, Bangor, October.

[7] Last, J. D, Grant A. J. and Ward, N. (2001). *Radiobeacon DGNSS station selection strategies – can we do better?* ION National Technical Meeting, Long Beach, CA, USA, 22–24 January.

[8] Last, J. D., Turhan, B. E. and Ward, N. *IALA's new European DGNSS radiobeacon plan*, International Association of Institutes of Navigation/Institute of Navigation (USA), IAIN/ION 25th Anniversary World Congress, San Diego, CA, 26–28 June 2000.

[9] Last, J. D. and Turhan, B. E. (1999). *European radiobeacon DGNSS - Making the most of the frequency band.* This *Journal* **52**, 2, pp. 176–188, May.

[10] *World-Wide Radionavigation System* (1995). International Maritime Organisation, Resolution A.815 (19), November.

[11] *Maritime policy for a future global navigation satellite system (GNSS)* (1997). International Maritime Organisation, Resolution A.860 (20), November.

[12] Draft revision of IMO resolution A.815(19) (2001). International Association of Marine Aids to Navigation and Lighthouse Authorities, Sub-Committee on Safety of Navigation, 31 March.

[13] Broadcast Standard for the USCG DGPS navigation service (1993). US Department of Transportation, United States Coast Guard, COMDTINST M16577.1, April.

[14] *1999 Federal Radionavigation Plan* (1999). US Department of Transportation and US Department of Defense, December.

Radiobeacon DGNSS station selection strategies – can we do better?

David Last and Alan Grant, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*

BIOGRAPHIES

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Board Member of the International Loran Association, a Fellow and Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999. He is currently studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institute of Electrical Engineers and the Institute of Electrical and Electronic Engineers. His research interests include Radiobeacon DGPS and computer modelling.

Dr Nick Ward is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in Radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

ABSTRACT

Maritime radiobeacons are used by the marine community world-wide as an efficient means of broadcasting differential data to users at sea. In Europe and North America large numbers of these DGNSS beacons now serve not only coastal regions and waterways but also substantial inland areas. As a result, there is often overlapping coverage and a choice of stations. Choosing the best beacon ensures the highest quality of DGNSS service.

With many receivers, the user must select the station manually, but there is little guidance as to how to make that choice. Other receivers perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

In this paper we also investigate a third approach: the best station is the one with the best signal-to-noise ratio (SNR) and hence the highest quality of data link performance. We develop a computer model to compare the three strategies and implement this novel approach. The computation is based on well-established techniques for DGNSS radiobeacon coverage analysis and system design. At each geographical point we estimate the signal strength of each beacon, of the atmospheric noise, and of the interference from the other stations in the band, and thus compute each beacon's SNR. Using this model, the "best beacon" choices made by the three strategies are mapped across the area (the British Isles in this case).

The paper identifies the regions in which receivers that employ the current *nearest beacon* or *strongest beacon* strategies fail to select the beacon with the highest SNR. It shows that these simplified methods choose non-optimal stations across a significant proportion of the region examined. As a result, users in those areas may not be receiving the beacon that provides the best service.

The paper also shows how to identify the optimum choice of alternate beacon to be used should the preferred station fail.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error within satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations that measure the errors. They transmit them to users' receivers which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest aids-to-navigation technologies, the marine radiobeacon, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, more than one DGNSS beacon can generally be received [3]. With many receivers, the user must select a station manually, but there is little guidance as to how to make that choice. Other types of receiver perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

This paper considers the choice of best beacon, both for users who enter the choice manually and for receivers that make the selection automatically. It compares the results of the *nearest beacon* and *strongest beacon* strategies and proposes a third approach: choosing the beacon that offers the highest signal-to-noise ratio (SNR), and hence the lowest message error rate. This study is based on well-established software developed to predict the coverage and performance of individual DGNSS radiobeacons [4-6]. Let us first consider that software.

INDIVIDUAL RADIOBEACON COVERAGE

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). The area within which the signal of any of these services provides satisfactory coverage is determined by minimum standards laid down by the International Telecommunication Union (ITU), the International Civil Aviation Organisation (ICAO), the International Association of Lighthouse Authorities (IALA) or, in the US, the US Coast Guard [7-11]. Within the European Maritime Area (EMA) of the ITU Region 1 [7], the field strength and signal-to-atmospheric noise ratio of each service must exceed the minima shown in Table 1 [9,10]. The signal-to-interference ratio (SIR) must exceed the appropriate protection ratio in Table 2; these values are derived from the minimum performance standards for receivers [12]. For a geographical point to be deemed to lie within the coverage of a DGNSS beacon, the beacon's field strength there must be not less than 10μV/m (or a higher figure specified by the national administration) and the SNR not less than 7dB. In addition, no interfering signal may exceed the protection ratio shown in Table 2.

In computing the coverage area of a beacon we estimate the level of its signal point-by-point throughout an array centred on the station. By day, this strength depends on the radiated power of the station, the range of the point from it and the nature of the propagation path between them. At night, signal components are also received via skywave propagation. Skywave intensity depends on range, latitude, time of day and season of the year. The skywave can interfere with the groundwave, causing fading. We customarily compute the signal level from the beacon that can be guaranteed for 95% of the time at night; a value that is weaker than the daytime groundwave. The intensity of the atmospheric noise is also estimated at the point; it varies in a random fashion, its mean value over an interval being a function of geographical location, time of day and season of the year.

The values of the wanted signal and the atmospheric noise determine whether or not the point lies within the 'interference-free' coverage of the station. It is customary to compute the daytime and night-time coverages separately. Daytime coverage is determined by the groundwave signal strength and night-time coverage by the weaker 95%-ile of the fading signal.

At each point we also estimate the level of any interference from stations on the same frequency as the beacon, or on adjacent frequencies. Interference may be received via either groundwave or skywave propagation paths, or both. We assess whether the strength of the interference relative to that of the wanted beacon exceed the protection ratio in Table 2, taking both the transmission types of the two stations and their frequency difference into consideration. With skywave interference, we use the level not exceeded more than 5% of the time. The coverage of the beacon is then that part of the interference-free coverage within which no protection ratio is infringed. These are the techniques are employed in the Bangor Coverage Prediction Software for DGNSS Beacons [4-6].

Table 1

	Units	Marine (MB)		Aero (NDB)	DGNSS
Minimum Field Strength	μV/m	N of 43°N	50	70	10
		S of 43°N	75		
	dBμV/m	N of 43°N	34	37	20
		S of 43°N	37.5		
Minimum Signal-to-Noise Ratio (SNR)	dB		15	15	7

Minimum field strength and signal-to-noise ratio for marine, aeronautical and DGNSS beacons in the European Maritime Area

This three-dimensional, multi-layer array, is the tool we need to help us choose the best beacon at any point. It lets us access all the relevant data there by extracting it from the various levels of the array. These must be extensive enough to hold the data of all the DGNSS beacons in the region (in this case the EMA). Thus the array boundaries must be set sufficiently outside the boundaries of the EMA itself (30°-72°N and 30°W-55°E) to accommodate these beacons' coverages. The outer limits were set at 24°-78°N and 49°W-74°E.

The new architecture will now be used to model the various strategies for selecting the best beacon to use, so allowing us to compare the results.

MODELLING BEACON SELECTION STRATEGIES

Currently two strategies for selecting the beacon to receive are in common use in DGNSS receivers: the *nearest beacon* and *strongest beacon* strategies. The use of the *nearest beacon* strategy is favoured in a draft document from the International Electrotechnical Commission (IEC) for receivers that automatically tune to beacons [12]. We will investigate how effective this recommended strategy is.

When a receiver employs this strategy it ignores all attributes of the beacon's signal. Thus it will select a nearby weak station – possibly one whose signal has arrived over a land path of high attenuation - and ignore a more powerful signal from a beacon a little further away, perhaps one whose signal has arrived over a sea-water path. In this case the slightly more distant beacon's signal would have a higher SNR than the nearest one, therefore choosing the nearest signal could result in a greater number of message errors and greater delays in the correction updates.

Alternatively, selecting the station using *strongest beacon* strategy could mean that a more distant one is chosen, resulting greater position errors due to spatial dilution of precision.

We will first employ our software model to map the choices of best beacon made by these two strategies, and then examine whether they generate significantly different choices. We will do so using the system of 12 beacons designed to serve the United Kingdom and Ireland.

Modelling the *nearest beacon* strategy

We are only interested in selecting a best beacon at those locations where at least one beacon actually provides an acceptable signal! Thus, the process starts by computing the coverage areas of each of the 12 beacons in the manner described above and writing the results for each into a separate layer in the array. Then, all the data used to compute the coverages is removed from the array except for these 12 results layers. We now examine this set of layers point-by point to see whether at least one beacon provides coverage at the point. If so, we calculate the range of the point from each beacon that does so. The nearest beacon is then identified and its identity noted in an additional results layer. When all array points have been examined, we produce an output plot (Fig. 3) from that layer, with different colours used to distinguish the area within which each beacon has been chosen.

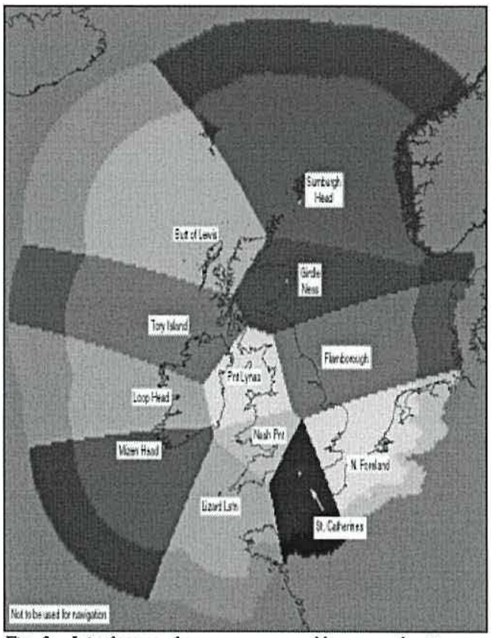

*Fig. 3 – Interference-free coverage, and beacon selection according to the **nearest beacon** strategy, for the 12 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime. Inner boundary: night-time.*

Fig. 3 also distinguishes between the extent of the coverage available by day (outer boundary) and that at night (inner, lighter, region). The night-time coverage is, of course, less than the daytime coverage because of fading due to skywave cancellation of the beacons' signals. This is a valuable diagram for those navigators who input the choice of beacon into their receivers manually. For the first time it tells them which beacon to use (by day or night), where on a journey they should change the beacon selection, and where they should cease to rely on coverage from the system.

Since the selection is based solely on distance, the boundaries between adjacent areas are the straight lines along which pairs of neighbouring beacons are equidistant. It is interesting to compare the sizes of the coverage areas of the various stations: Sumburgh, for example, serves a much larger region than does Nash

NEW ARCHITECTURE

The Bangor Coverage Prediction Software was designed to identify the coverage area of a single beacon. By computing the coverage of each member of a group of beacons in turn it can also generate their combined coverage. But if we are to consider the choice of beacon at a point where more than one signal is available, we require the data at that point for all those beacons to be available to us simultaneously. Achieving that has required the development of a new and different software architecture that will now be described.

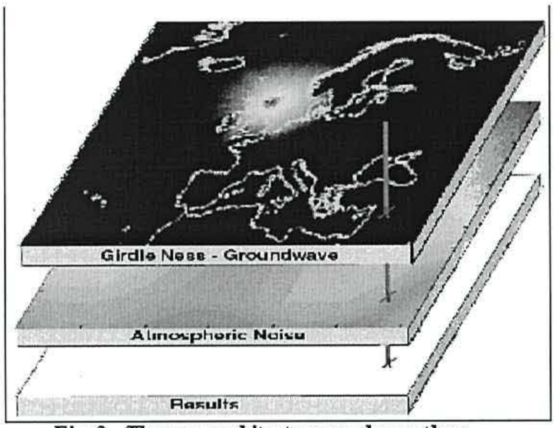

Fig. 2 - The new architecture employs a three-dimensional array. This simple example has just three layers that hold the groundwave strength of a single beacon, the atmospheric noise, and (in the results layer) a coverage computed using the first two.

The factors that determine the coverage of a beacon have been identified as the field strengths of: the groundwave, skywave, and atmospheric noise, and of the groundwave and skywave components of the interference. The groundwave and skywave field strength distributions of each beacon are computed at every point in a large array, spaced by 0.1° of latitude by 0.1° longitude, and covering an area exceeding that of the European Maritime Area (EMA).

This array (Fig. 1) is three-dimensional. The computed groundwave distribution of each beacon is stored in a single level of the array (the top level in this figure). Since there are hundreds of beacons the array must be capable of accommodating hundreds of such levels. The skywave distributions are stored in a further such set of levels. The atmospheric noise distribution across the area is contained in a single additional level (the middle one in this figure).

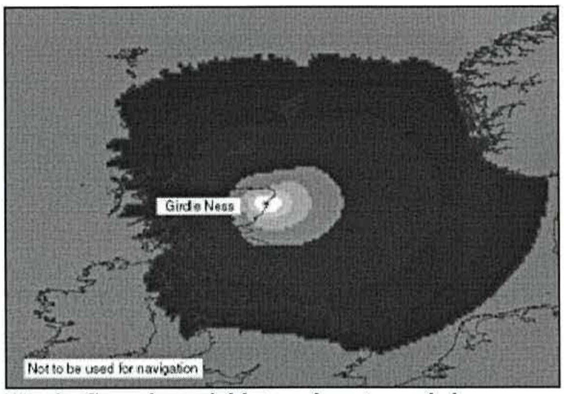

Fig. 2 - Groundwave field strength contours of a beacon at Girdle Ness, Scotland. The outer boundary is the limit of daytime interference-free coverage computed using data from top two layers in Fig. 1.

We can choose to extract and plot the data from a single layer, as in Fig. 2 which shows contours of the groundwave field strength of a beacon, taken from the top layer in Fig. 1. Likewise, by accessing point-by-point the groundwave, skywave, atmospheric noise and the interference relevant to a single beacon, we can plot its coverage. For example, the top two layers in the figure contain sufficient data for producing a plot of the simple interference-free groundwave coverage. In Fig. 2 the region within the outer boundary of the contour plot is that coverage. At all points within it both the field strength (top layer) and signal-to-atmospheric noise ratio (top and second layers) meet the international standards.

Table 2

Wanted Signal:	**Marine (MB)**	**Aero (NDB)**	**DGNSS**	
Interfering Signal:	**Any**	**Any**	**MB or NDB**	**DGNSS**
Separation (kHz)				
0.0	15	15	15	15
0.5	-39	15	-25	-22
1.0	-60	9	-45	-36
1.5	-60	2	-50	-42
2.0	-60	-5	-55	-47
2.5	-	-12.5	-	-
3.0	-	-20	-	-

Protection ratios (in dB) limiting interference between beacons

Point. This is partly explained by its greater nominal range, 277km as compared to 185km, but more so by the fact that Nash Point's neighbours are simply much closer to it than are Sumburgh's.

Modelling the *strongest beacon* strategy

The coverages of the 12 beacons were again stored in separate layers of the array and the points at which at least one beacon provided coverage located. But this time the layers that held the beacons' field strength were retained and at each point within coverage the beacon with the strongest signal was identified. The result is shown in Fig. 4.

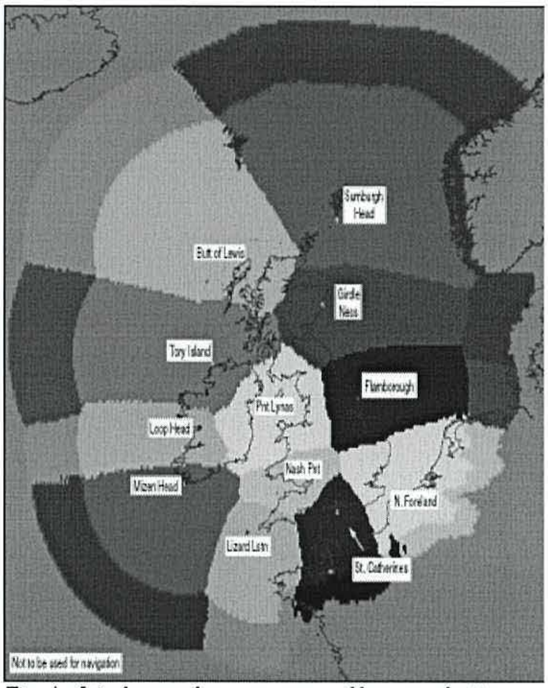

*Fig. 4 – Interference-free coverage, and beacon selection according to the **strongest beacon** strategy, for the 12 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime. Inner boundary: night-time.*

The results shown here from this *strongest beacon* strategy appear significantly different from those of the *nearest beacon* strategy in Fig. 3. But let us identify the areas of difference precisely. The results layers produced using the two strategies are entered into the array and those points at which different beacons were selected are noted. The result is shown in Fig. 5: the areas in yellow are those where the two strategies produce different results. They are extensive; indeed, they constitute 8% of the total daytime coverage.

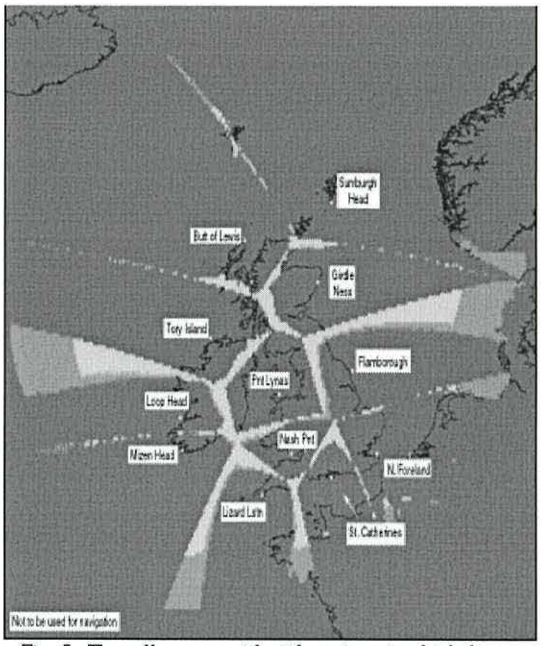

Fig. 5 - The yellow areas identify regions in which the two strategies select different beacons.

To understand the reason for the areas of difference, consider the large region west of Ireland that straddles the boundary between the coverages of Tory Island and Loop Head. Here the signal from Tory Island is stronger than that from Loop Head, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head.

But even where two stations of equal power compete, it is frequently the case that the *nearest beacon* strategy selects the weaker signal. Consider the inland section of the yellow area that straddles the boundary between the regions served by Sumburgh and Girdle Ness. Fig. 3 shows that Girdle Ness is the nearest beacon here. But its signal arrives via a land path of relatively high attenuation. The signal from the slightly more distant Sumburgh arrives over a sea path and is the stronger.

In this and other fairly extensive regions, therefore, the result of using the *nearest* beacon strategy is to fail to select the station with the strongest signal. The consequence is a lower SNR, a higher message error rate, and greater message latency, than the *strongest* beacon would offer.

BEACON SELECTION BY SIGNAL QUALITY

The logical conclusion of this argument is that we should always choose the beacon whose signal has the highest SNR. Now so far, the only noise we have taken into account is atmospheric noise. Since the level of atmospheric noise at any time is essentially the same on all channels across the radio-beacon frequency band, choosing the *strongest beacon* automatically results in the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – a significant factor for radio-beacons in Europe [13]. One beacon might suffer significant interference from a distant station on its frequency; another beacon of equal strength on a different frequency might have much less interference, and so a higher SNR. Thus we should take into account in our selection of beacons not only atmospheric noise but also interference. We should use as our measure of quality its SNR, that is, the ratio between its signal strength and the greater of atmospheric noise or interference.

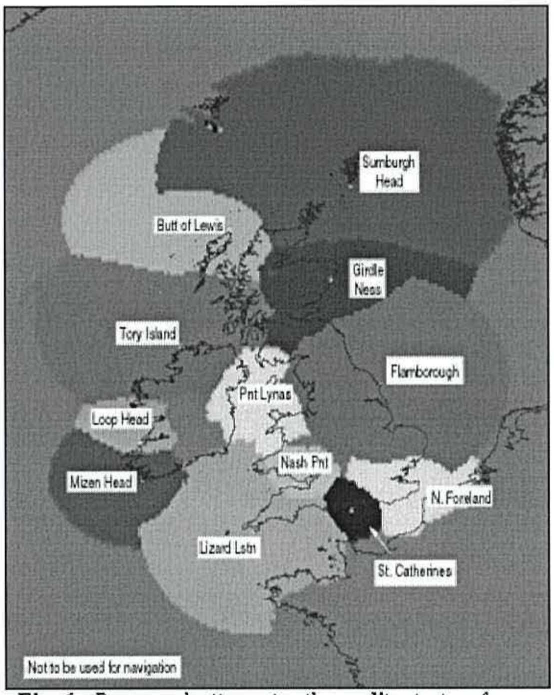

Fig. 6. *- Beacon selection using the* ***quality strategy*** *for the 12 beacons of the UK and Ireland, under night-time conditions with interference.*

Fortunately, our software provides us with data layers that contain all the information we need to assess SNR in this way: that is, the groundwave and skywave strengths of each beacon, the atmospheric noise level and the strengths of all interfering components on all channels. It is thus possible for us to compute the SNR of each beacon's signal at any point and so identify the best beacon there according to this *quality strategy*. Applying that process to our 12 British Isles beacons gives the result shown in Fig. 6.

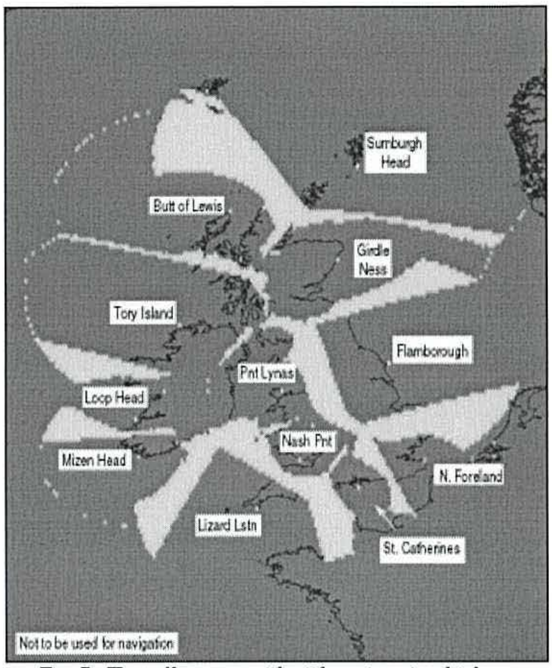

Fig. 7 - The yellow areas identify regions in which different beacons are selected by the ***nearest beacon*** *and* ***quality*** *strategies.*

This figure is plotted under worst-case conditions: that is, at night when the strongest interference is being received. Interference arrives at night as skywave signals from beacons up to 2000km away. In consequence, not only is coverage smaller than by day, but the effect of interference on the choice of beacon is greatest. To judge how significant interference can be, see how greatly the area in which Loop Head is judged to be the best beacon has fallen compared to Fig. 4. Loop Head's field strength is no less than it was before, but its coverage is now substantially reduced by interference from a marine radiobeacon at Eckmuhl Phare in France. Further, the level of interference on its frequency happens to be much greater than the interference on the frequencies of its neighbours, Tory Island and Mizen Head. So, they take over as best beacon throughout much of Loop Head's former coverage.

The current *nearest beacon* strategy, in contrast, does not take interference into account. In consequence it chooses beacons of lower signal-to-interference ratio than does this new *quality strategy* in all the regions coloured yellow in Fig. 7. In these extensive areas, which total 19% of the night-time service area of the system, the *nearest beacon* strategy fails to provide the user with the highest quality signal.

ALTERNATE BEACONS

This paper has presented strategies for identifying the best beacon to use at any location and has mapped the results in a form convenient for use by navigators. But, if the best beacon should be unavailable, because of a scheduled or unscheduled outage, it is far from obvious to the user which station to select as the alternate. Our new software also allows us to answer that question. We run the same process as for choosing the best beacon, but this time we select the second best. The results are presented in Fig. 8, the strategy for selection shown there being the *quality strategy*, ie the highest SNR.

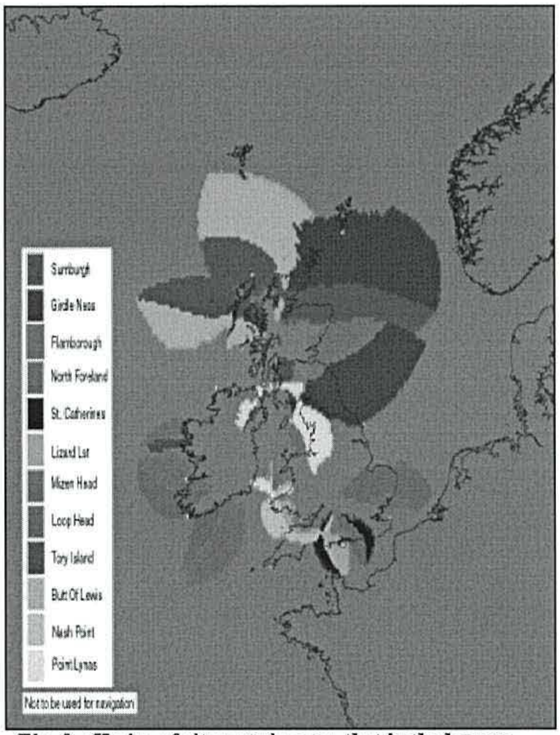

Fig. 8 - Choice of** alternate beacon, **that is, the beacon to use should the best beacon be unavailable. The** quality strategy **has been employed.

DATA IN TABULAR FORM

The maps shown in Figs. 3, 4, 6 and 8 are in a format designed to be convenient for users who enter beacon selections into their receivers manually. To allow "automatic" receivers to employ the information, we have produced it in a tabular form that manufacturers can store in the receivers themselves. Table 3 shows a part of the data set: for each location, specified by latitude and longitude, the best beacon (Primary) and the alternate (Secondary) are listed. Both have been computed using the *quality strategy*.

0 - NO BEACON SELECTED
1 - POINT_LYNAS
2 - TORY_ISLAND
3 - FLAMBOROUGH
:

:
lat: 53.2 Lon: -4.6 Primary- 1 Secondary- 2
lat: 53.2 Lon: -4.5 Primary- 1 Secondary- 2
lat: 53.2 Lon: -4.4 Primary- 1 Secondary- 2
lat: 53.2 Lon: -4.3 Primary- 1 Secondary- 3
lat: 53.2 Lon: -4.2 Primary- 1 Secondary- 3
lat: 53.2 Lon: -4.1 Primary- 1 Secondary- 3
lat: 53.2 Lon: -4.0 Primary- 1 Secondary- 3

*Table 3: Example section of a tabulated data set for beacon selection, employing the **quality strategy**.*

SPATIAL DILUTION OF PRECISION

The present *nearest beacon* and *strongest beacon* strategies, and the new *quality strategy* investigated above, do not take spatial dilution of precision into account although, clearly, it is minimised by the choice of the nearest beacon. This research is continuing with a study of the significance of spatial dilution for the choice of best beacon, taking into account the change of circumstances resulting from the setting to zero of Selective Availability.

CONCLUSIONS

The software described in this paper has been developed for modelling competing strategies for selecting the radio-beacon to be used where more than one is available. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a new *quality strategy* is proposed in which the best beacon is deemed to be the one with the highest ration of signal to atmospheric noise, or interference.

Results are presented when each of the three strategies is applied to the set of 12 beacons designed to serve the United Kingdom and Ireland. There are significant differences between the beacons they choose. In particular, *nearest beacon* strategy, proposed in some papers is seen frequently to select beacons that have lower SNRs than alternatives available. When interference is taken into account, as it is essential to do in Europe, a new strategy is required. This is the *quality strategy* proposed, which guarantees that receivers enjoy the best signal quality.

The results are presented in a pictorial form designed to be convenient for users who enter the choice of beacon into their receivers manually. Alternatively, an example is shown of a tabular form of presentation that can be built into receivers at the time of manufacture. Both forms of presentation indicate not only the choice of best beacon, but also the choice of alternate to be employed when the best station is unavailable.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences

Research Council and from the General Lighthouse Authorities of the UK and Ireland.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data,* IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radio-Beacons for the Broadcast of Differential GPS Data,* Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services*, Issue 7 – August 1999.
4. Last, J.D. & Poppe, D.C., *A coverage prediction model for radio beacon differential satellite navigation system,* Navigation (USA) - Journal of the Institute of Navigation, Vol.43, No.4, pp.451-467, Winter 1996-1997.
5. Roberts, G.R., Last, J.D. & Poppe, D.C., *Designing radiobeacon differential satellite navigation systems using the Bangor coverage prediction model*, 4th St. Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Russia, 26-29 May 1997.
6. Poppe, D.C., *Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions*, Ph.D. Thesis, University of Wales, Bangor, October 1995.
7. International Telecommunication Union, *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area,* Geneva, 1985.
8. International Association of Lighthouse Authorities, *Interfering Distances of Maritime Radiobeacons in the European Maritime Area of Region 1*, Technical Report, YBSAAV 1985.
9. ICAO, *ICAO Frequency Assignment for NDBs*, April 1990
10. International Telecommunication Union, *Technical Characteristics of Differential Transmissions for Global Navigation Satellite Systems (GNSS) for Maritime Radio Beacons in the Frequency Band 285-325 kHz (283.5-315 kHz in Region 1),* Draft Revision of Recommendation M.823, Geneva, 1995.
11. DOT (Department of Transport) and USCG (United States Coast Guard), *Broadcast Standard for the USCG DGPS Navigation Service,* Technical Report, USCG, COMDTNIST M16577.1, 1993.
12. International Electrotechnical Commission, *Shipborne DGPS and DGLONASS Maritime Radiobeacon Receiver Equipment,* Technical committee No. 80, Maritime navigation and radio communications equipment and systems. IEC 61108-4: 2001, TC80/WG1 (DRAFT No 8), July 2000.
13. Last, J.D. & Turhan, B.E., 'European radiobeacon DGNSS - Making the most of the frequency band', Journal of the Royal Institute of Navigation, 52, 2, pp176-188, May 1999

Quality criteria for the maritime DGNSS system in a world without SA

Alan Grant* and David Last, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*
**E-mail: ajgrant@informatics.bangor.ac.uk*

BIOGRAPHIES

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institute of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer, and a Board Member of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

Dr Nick Ward is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in Radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

ABSTRACT

Marine radiobeacons are used by the maritime community world-wide as an efficient means of broadcasting differential GPS data to users at sea. In Europe and North America large numbers of these DGNSS beacons now serve not only coastal regions and waterways but also substantial inland areas. As a result, there is often overlapping coverage and a choice of stations. Choosing the best beacon ensures the highest quality of DGNSS service.

With many receivers, the user must select the station manually, but receives little guidance as to how to make that choice. Other receivers perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

In this paper we investigate a third approach: the best station is the beacon with the highest signal-to-noise ratio (SNR) and hence the highest quality of data link performance. We show that this strategy was optimal for DGNSS with Selective Availability (SA) in operation. But the setting of SA to zero has required the development of a new "post-SA" strategy, since spatial dilution of precision and time-to-alarm considerations now become dominant.

A computer model, based on well-established techniques for DGNSS radiobeacon coverage analysis and system design, is used to compare these four strategies. The "best beacon" choices they make are mapped across the British Isles and compared. Then, the results of the post-SA strategy are plotted for the entire European Maritime Area. We also show how to identify the best alternate beacon should the preferred station fail.

The paper identifies those regions in which receivers that employ the current *nearest beacon* or *strongest beacon* strategies fail to select the beacon offering the lowest spatial dilution of precision while meeting the time-to-alarm requirement in a post-SA world.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the pseudorange errors. They transmit corrections to users' receivers which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, the marine radiobeacon, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, more than one DGNSS beacon can generally be received [3]. With many receivers, the user must select a station manually, but there is little guidance as to how to make that choice. Other types of receiver perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

This paper considers the choice of best beacon, for both manual and automatic receivers. It compares the results of the *nearest beacon* and *strongest beacon* strategies that are commonly used at present. It then compares two new approaches: a selection based on signal *quality* and a *post-SA* strategy.

INDIVIDUAL RADIOBEACON COVERAGE

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). Within the European Maritime Area (EMA) of the ITU Region 1 [4], a geographical point is deemed to lie within the coverage of a DGNSS beacon, if the beacon's field strength there is not less than 10µV/m (or a higher figure specified by the national administration) and the SNR not less than 7dB [4]. In addition, no interfering signal may exceed the protection ratios defined in [5].

Coverage prediction is described further in [6]. A widely-used tool for predicting coverage that takes into account skywave and groundwave propagation, own-skywave fading, and interference, is the Bangor Coverage Prediction Software. This software models the coverage area of single beacons or a group of beacons. If, however, we are to consider the choice of beacon at a location where more than one signal is available, we need simultaneous data on all those beacons. Achieving this has required the development of new software employing a different architecture [6] which embodies a multi-layer array approach.

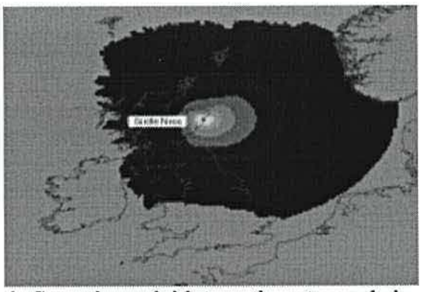

Fig. 1: Groundwave field strength contours of a beacon at Girdle Ness, Scotland. Outer boundary is daytime interference-free coverage.

This new software can be used, as previously, to predict the coverage areas of single beacons. An example is Fig. 1 where the outer boundary is the limit of daytime, interference-free, coverage. The software can also be used to model the results of the various strategies for selecting the best beacon, allowing us to compare them.

MODELLING BEACON SELECTION STRATEGIES

Currently two strategies for selecting the beacon to use are commonly employed in DGNSS receivers: the *nearest beacon* and the *strongest beacon* strategies.

When a receiver employs the *nearest beacon* strategy it ignores all attributes of the beacon's signal. Thus it will select a nearby weak station – possibly one whose signal has arrived over a land path of high attenuation - and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case the more distant beacon's signal would have a higher SNR than the nearest one. Choosing the nearest signal could result in more data errors and greater delays in receiving correction updates.

In contrast, selecting the station using the alternative *strongest beacon* strategy would mean that the stronger, more distant one was chosen. However, this might result in greater position errors due to increased spatial dilution of precision.

We will first employ our software to map the choices of best beacon made by these two strategies, and then examine whether they generate significantly different choices. We will do so using the system of 12 beacons designed to serve the United Kingdom and Ireland. Note that the set of UK and EMA beacons used in this paper, and the frequencies they employ, are the current ones and not the expanded system, with its new band-plan, to be introduced later in 2001.

Modelling the *nearest beacon* strategy

The process starts by computing the coverage areas of each of the 12 beacons. Then, point-by-point throughout these areas, we identify the nearest beacon. When all points have been examined, we produce an output plot (Fig. 2), with different colours used to distinguish the area within which each beacon has been chosen.

Fig. 2 also distinguishes between the extent of the coverage available by day (outer boundary) and at night (inner, lighter, region). The night-time coverage is less than the daytime because of fading due to skywave cancellation of the beacons' signals. This is a valuable diagram for those navigators who must input the choice of beacon into their receivers manually. It tells them which beacon to use (by day or night), where on a journey they should change the beacon selection, and where they should cease to rely on coverage from the system.

Since the selection is based solely on distance, the boundaries between adjacent areas are the straight lines along which pairs of neighbouring beacons are equidistant. It is interesting to compare the sizes of the coverage areas of the various stations: Sumburgh, for example, serves a much larger region than does Nash Point. This is partly explained by its greater nominal range, 277km as compared to 185km, but more so by the fact that Nash Point's neighbours are simply much closer to it than are Sumburgh's.

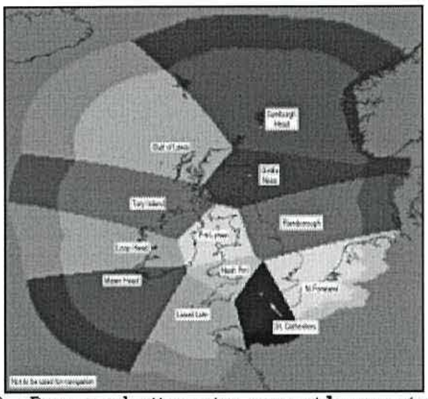

*Fig. 2 – Beacon selection using **nearest beacon** strategy, for the 12 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.*

Modelling the *strongest beacon* strategy

The same process was then employed to model the *strongest beacon* strategy; this time the beacon with the strongest signal at each point was identified. The result is shown in Fig. 3.

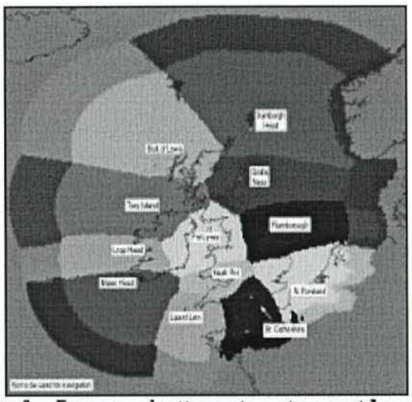

*Fig. 3 – Beacon selection using **strongest beacon** strategy, for the 12 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.*

The results from this strategy appear to be significantly different from those of the *nearest beacon* strategy in Fig. 2. The software has been used to generate Fig. 4 in which the yellow areas are where the two strategies produced different result; they constitute 8% of the total daytime coverage.

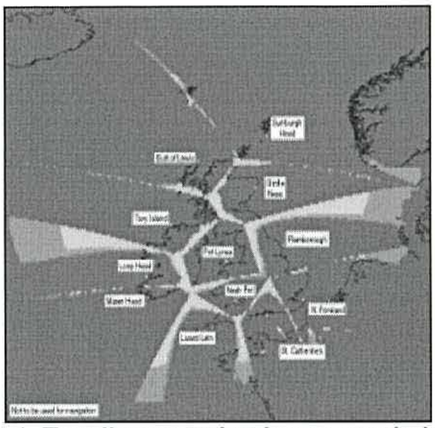

Fig. 4 - The yellow areas identify regions in which the two strategies selected different beacons.

To understand the reason for the areas of difference, consider the large region west of Ireland that straddles the boundary between the coverages of Tory Island and Loop Head. Here the signal from Tory Island is the stronger, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head. But even where two stations of equal power compete, the *nearest beacon* strategy frequently selects the weaker signal. Consider the inland section of the yellow area that straddles the Sumburgh/Girdle Ness boundary. Fig. 2 shows that Girdle Ness is the nearest beacon here. But its signal arrives via a land path of relatively high attenuation. The signal from the slightly more distant Sumburgh arrives over a sea path and is the stronger.

In this, and other fairly extensive regions, the *nearest beacon* strategy fails to select the station with the strongest signal. The consequences are a lower SNR, a higher message error rate, and greater message latency, than the *strongest beacon* would offer. With SA active, latency was the major constraint: the greater the latency, the greater the pseudorange error that built up before the next correction was received, and so the greater the resulting position error.

BEACON SELECTION BY SIGNAL QUALITY

The logical conclusion of the previous argument is that we should always choose the beacon whose signal has the highest SNR. So far, the only noise taken into account has been atmospheric noise. Since its level at any time is essentially the same on all channels across the radio-beacon frequency band, choosing the *strongest beacon* automatically gives the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – a significant factor for radio-beacons in Europe [7]. One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength on a different frequency might have much less interference, and so a higher SNR. Thus we should take into account in selecting our beacon not only atmospheric noise but also interference. We should use as our measure of quality the SNR, that is, the ratio between a beacon's signal strength and atmospheric noise or interference, whichever is the greater. That is our *quality strategy*.

Our software provides all the information we need to assess beacons' SNRs in this way: the groundwave and skywave strengths of one, the atmospheric noise level and the strengths of all interfering components on all channels. We can compute the SNR of each beacon's signal at each point and so identify the best beacon there according to this *quality strategy*. Fig. 5 shows the results for the British Isles beacons.

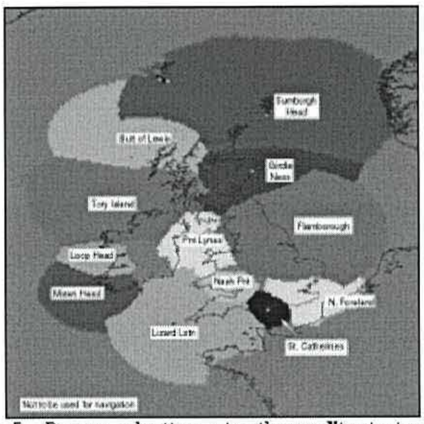

Fig. 5. - Beacon selection using the ***quality strategy*** *for the 12 beacons of the UK and Ireland, under night-time conditions with interference.*

This figure is plotted under worst-case conditions: at night. Interference can be received via sky-wave propagation at night from other beacons up to 2000km away. In consequence, not only is coverage smaller than by day, but the effect of interference on the choice of beacon is greatest.

In contrast, the *nearest beacon* strategy ignores interference. In the yellow areas of Fig. 6, which total 19% of the night-time service area of the system, the new *quality strategy* has chosen beacons of higher SNR than has the *nearest beacon* strategy. Clearly, the *nearest beacon* approach fails to provide the user with the highest quality signal over substantial areas.

THE ENDING OF SA

In May 2000 selective availability was set to zero. What effect does this have on beacon selection strategy? Now the dominant position error sources in GPS are ionospheric and tropospheric effects. Both types of error change much less rapidly than did SA. Therefore, correction messages remain valid for longer periods of time; indeed, they may be usable for tens, or even hundreds, of seconds. The effect of latency on the reception of corrections is markedly reduced and so much lower SNR values can be tolerated than before. Receiving the strongest beacon, or the one with the highest SNR, would now appear to be much less important.

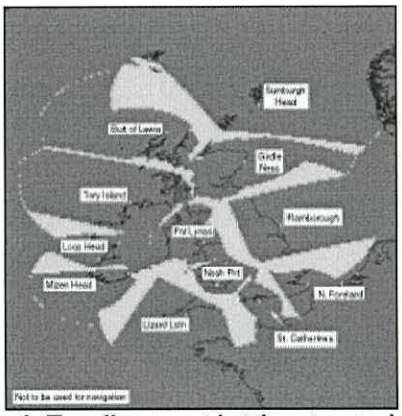

Fig. 6 - The yellow areas identify regions in which different beacons are selected by the ***nearest beacon*** *and* ***quality*** *strategies.*

On the other hand, as the separation between reference station and receiver increases, the dominant error soon becomes that due to spatial dilution of precision. It would appear that a simple *nearest beacon* selection strategy is all that is now required.

However, the situation is complicated by a third factor. Correction messages also carry alarms to warn the user of unhealthy satellites or failures of reference stations. The minimum time-to-alarm (TTA) specified by the International Maritime Organisation is 10s [9]. In order to meet this requirement, a high SNR is once again required - favouring a quality strategy! So how do we balance the constraints of spatial dilution and TTA? We propose a new post-SA strategy that does so.

BEACON SELECTION BY THE *POST-SA* STRATEGY

The new strategy selects the nearest beacon that can meet the quality measure required for a 10s TTA: that is, an SNR of 7dB and compliance with the minimum interference protection ratios. In that way it minimises spatial dilution errors while meeting the TTA requirement. The result, applied to the 12 British Isles beacons, is shown in Fig. 7.

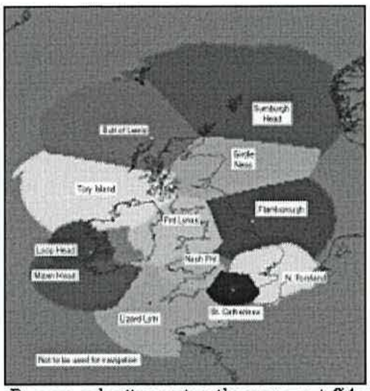

*Fig 7 – Beacon selection using the new **post-SA strategy** for the 12 beacons of the UK and Ireland, under night-time conditions with interference.*

This figure is again plotted under worst-case conditions: at night, with interference. Note how the coverage provided by St. Catherine's Point is reduced by interference; over much of the English Channel, Lizard has been selected although St. Catherine's is the nearest beacon.

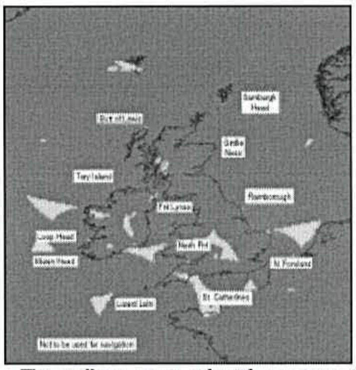

*Fig 8 – The yellow areas identify regions in which different beacons are selected by the **post-SA** and **nearest** strategies.*

The differences between this *post-SA* and the *nearest beacon* strategies are shown as the yellow areas in Fig 8. They constitute 5% of the night-time coverage area. Within these yellow regions, the nearest beacon should not be used since its signal fails to meet the time-to-alarm criteria.

Our new post-SA strategy happily turns out to very similar to that proposed by the IEC in their draft document [5]. However, whereas the IEC take only the signal-to-atmospheric noise ratio into account, our strategy also ensures that interferers do not exceed the minimum protection ratios.

ALTERNATE BEACONS

This paper has presented strategies for identifying the best beacon to use at any location. But if that beacon should be unavailable, because of a scheduled or unscheduled outage, it is far from obvious to the user which station to select as the alternate. Our new software also allows us to answer that question. We run the same process as for choosing the best beacon, but this time we select the second best. The results are presented in Fig. 9, using the *post-SA* strategy.

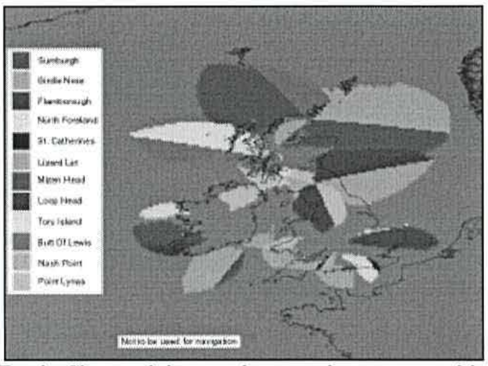

*Fig. 9 - Choice of alternate beacon - the one to use if the best beacon should be unavailable. The **post-SA** strategy has been employed.*

DATA IN TABULAR FORM

The maps shown in Figs. 2, 3, 5, 7 and 9 are in a format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. To allow "automatic" receivers to employ the same information, we have produced it in a tabular form that manufacturers can store within their receivers. Table 1 shows a part of this data set: at each location specified by latitude and longitude, the best beacon (Primary) and the alternate (Secondary), computed using the *post-SA strategy*, are listed.

38 -	NASH_POINT
39 -	N_FORELAND
40 -	POINT_LYNAS
:	
:	
Lat: 53.2 Lon -4.1	Primary- 40
	Secondary- 38
Lat: 53.2 Lon -4.0	Primary- 40
	Secondary- 38
Lat: 53.2 Lon -3.9	Primary- 40
	Secondary- 38

*Table 1: Part of a tabulated data set for beacon selection, employing the **post-SA strategy**.*

BEACON SELECTION ACROSS THE EMA

We now (Fig. 10) apply our software and the new *post-SA strategy* to identify the best beacon across the entire European Maritime Area (30-72°N, 30°W-55°E).

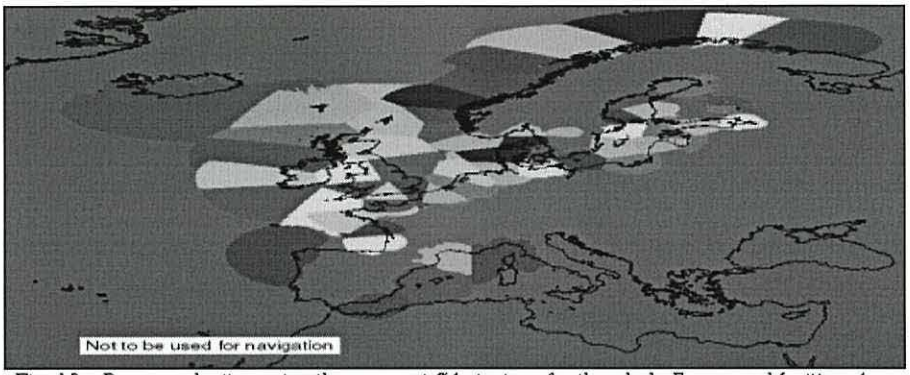

*Fig. 10 – Beacon selection using the new **post-SA strategy** for the whole European Maritime Area (Daytime, with interference).*

Fig. 10 shows, for the first time, the combined coverage of all the present 62 radiobeacons within the EMA, identifying point-by-point the radio-beacon with the lowest spatial dilution whose signal meets the time-to-alarm criteria.

CONCLUSIONS

The software used in this paper has been developed for modelling and comparing the competing strategies for selecting the radio-beacon to be used where more than one is available. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a *quality strategy* is studied in which the best beacon is deemed to be the one with the highest ratio of signal to atmospheric noise, or interference. With the ending of SA, however, the constraints on beacon selection have changed dramatically. These changes are discussed and a new *post-SA selection* strategy is proposed.

Results are presented as each of the four strategies is applied to the set of 12 beacons designed to serve the United Kingdom and Ireland. There are significant differences between the beacons they choose. When interference is taken into account, as it is essential to do in Europe, the *quality strategy* is considered best with SA in operation. However without SA, the best beacon is the nearest one (with minimum spatial dilution) whose signal quality meets the time-to-alarm requirements. Our new post-SA strategy happily turns out to very similar to that proposed by the IEC in their draft document [5].

Our results are presented in a pictorial form designed to be convenient for users who are obliged to enter the choice of beacon into their receivers manually. We have shown both British Isles and, for the first time, full European Maritime Area diagrams. An example is also presented of the data in a tabular form that can be built into receivers at the time of manufacture. Both forms of presentation indicate not only the choice of best beacon, but also the choice of an alternate to be employed when the best station is unavailable.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data,* IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radio-Beacons for the Broadcast of Differential GPS Data,* Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services,* Issue 7 – August 1999.
4. International Telecommunication Union, *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area,* Geneva, 1985.
5. International Electrotechnical Commission, *Shipborne DGPS and DGLONASS Maritime Radiobeacon Receiver Equipment,* Technical Committee No. 80, Maritime navigation and radio communications equipment and systems. IEC 61108-4: 2001, TC80/WG1 (DRAFT No 8), July 2000.
6. Last, J.D, Grant A. J. & Ward, N., *Radiobeacon DGNSS station selection strategies – can we do better?,* ION National Technical Meeting, Long Beach, CA, USA, 22-24 January 2001
7. Last, J.D. & Turhan, B.E., 'European radiobeacon DGNSS - Making the most of the frequency band', Journal of the Royal Institute of Navigation, 52, 2, pp176-188, May 1999

8. International Association of Lighthouse Authorities, *DRAFT revision of IMO resolution A815(19)*, Sub-Committee on Safety of Navigation, 31 March 2001

9. International Maritime Organisation, Resolution A.815 (19) World-Wide Radionavigation System, November 1995

Radiobeacon DGNSS Coverage Planning - a National Case Study

Gwyn Roberts
IDB Ltd., University of Wales, Dean Street, Bangor, Gwynedd LL57 1UT, UK

Alan Grant, David Last
School of Informatics, University of Wales, Dean Street, Bangor, Gwynedd LL57 1UT, UK

***Abstract*- 300 kHz marine radiobeacon transmitters are used in some 40 countries for broadcasting Differential Global Navigation Satellite System corrections (radiobeacon DGNSS). In Europe, their widespread adoption led to unforeseen difficulties: significant loss of coverage of many beacons due to interference. This situation has resulted in a re-organisation of radiobeacon frequencies throughout the European Maritime Area, with the objective of minimising mutual interference.**

In this paper we present a case study of one country: Norway. The extent of Norwegian radiobeacon coverage before, and after, the re-assignment of frequencies is computed using the Bangor Coverage Prediction Model. This software package takes into account the effects of beacon power, location, frequency, ground conductivity, fading due to a beacon's own skywave signal, atmospheric noise and also interference received via both groundwave and skywave propagation. It plots the regions within which the resulting signals meet IMO standards.

Where overlapping beacon coverage is available, a key concern is ensuring that the receiver always selects the beacon that provides the best navigation performance. A new beacon selection strategy has been proposed in which the best station is the nearest one that can satisfy the minimum requirements of signal strength, signal-to-atmospheric-noise ratio and signal-to-interference ratio. A modified version of the coverage prediction software is used to identify the best beacon according to this strategy throughout Norwegian coastal waters. The choice of alternate beacon to be employed in the case of failure of the preferred station is also discussed.

I. INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the pseudorange errors. They transmit corrections to users' receivers, which adjust their position measurements accordingly. The differential stations also enhance integrity by providing rapid warning of GPS malfunctions.

For marine navigation, the advantages of the improved accuracy and integrity afforded by DGNSS are unquestionable. Even without Selective Availability, differential operation is still required to meet the 8-10m harbour/harbour approach accuracy target of the International Maritime Organisation (IMO). This precision and the necessary integrity is not available with stand-alone use of either the civil GPS Standard Positioning Service (SPS) or the military Precise Positioning Service (PPS).

The re-use of 300kHz marine radiobeacons for broadcasting DGNSS corrections (radiobeacon DGNSS) has become a world standard, currently implemented in some 40 countries. Marine radiobeacons offer a cost-effective way of distributing data to large numbers of maritime users, especially as many areas of Europe and North America already have numerous existing, licensed, beacons [1]. The National Differential GPS System (NDGPS) aims to provide nation-wide land coverage of the US, with a typical accuracy of 1-3m and a time to indicate GPS failures of 2.5-5s [2]. It will employ a number of existing stations, including United States Coast Guard (USCG) DGNSS beacons, installed to cover the coastlines of US and navigable waterways of the Mississippi River. Radiobeacon DGNSS systems provide a cost-effective ground-based alternative to the Wide Area Augmentation Service (WAAS) or the European Geostationary Navigation Overlay Service (EGNOS).

II. COVERAGE PREDICTION

An accurate coverage-prediction model provides major benefits for both the designer and the user of radiobeacon DGNSS. Coverage prediction allows the *system designer*, tasked with identifying the most cost-effective solution for a given geographical region, to:

- evaluate the coverage areas of existing and proposed systems,
- identify potential problem areas in proposed systems,
- study the effects of variations in atmospheric noise, interference and skywave propagation levels,

- consider "what if" scenarios - e.g. changing beacon frequencies, powers or locations,
- evaluate day, night, summer, winter scenarios.

Coverage prediction allows the *user* to determine:

- areas within which a system may be safely employed,
- which beacons are available at specific locations,
- the reliability and accuracy of the position information,
- the best beacon to use.

The only coverage-limiting factors taken into account by early prediction methods were the beacons' groundwave signals and atmospheric noise [3, 4]. Propagation paths were assumed to lie over sea-water or, at most, over land of a single type. In reality groundwave signal attenuation over land depends strongly on path conductivity and so can vary greatly. Also, interference from other beacons on the same, or adjacent, frequencies may limit coverage more than atmospheric noise does; this is especially the case in Europe. A further important factor is propagation of signals via ionospheric paths at night. The wanted signal may fade due to the interaction between its skywave and groundwave components. Also, interference may be received from distant stations via the ionosphere. Thus it is necessary to estimate the ratio between the wanted signal and the unwanted noise and interference. These factors determine the bit and message error rates and hence the latency of the differential data and the accuracy of the resulting fixes.

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). In the European Maritime Area (EMA) of the ITU Region 1 [5], a geographical point is deemed to lie within the coverage of a DGNSS beacon if the beacon's field strength and SNR are above specified minima [5]. In addition, no interfering signal may exceed the protection ratios defined in [6].

A The Bangor Coverage Prediction Model

A coverage-prediction model that takes all these factors into account has been developed at the University of Wales, Bangor, UK [7, 8, 9]. Its results have been validated by comparison with the measured performance of DGNSS beacon systems in the British Isles and elsewhere. The model is written in C and runs on a PC. It estimates the field strengths of a beacon's signal and of the noise and interference, at each of a grid of calculation points. These points are spaced at 0.1 degree of latitude by 0.1 degree of longitude (approximately 11x7 km in mid latitudes). At each point, the strength of the beacon's signal is computed taking into account both day and night propagation conditions and the effect of land paths. The levels of atmospheric noise and the interference from other stations are also estimated, and in this way the quality of reception at the point determined. The results are compared to the minimum acceptable field strength, signal-to-noise ratio (SNR), and other factors from the relevant Recommendation of the International Telecommunication Union (ITU) [10]. The process also takes into account minimum receiver performance standards published by the International Electrotechnical Commission (IEC) [11]. If all these conditions are met, the point is deemed to lie within the coverage of the station. The computer then draws the area of coverage of the beacon (e.g. Fig. 1). This approach to system design allows the frequency, location or power of any beacon to be changed. Its individual coverage, or that of a group of beacons, may be investigated at various periods of the day and seasons of the year. The principal factors which the model takes into account will now be described in more detail.

Groundwave field strength The signal transmitted by a radiobeacon operating in the 300 kHz frequency band travels principally as a groundwave over the surface of the earth. It is attenuated at a rate that depends on the nature of the terrain. Attenuation is least over sea-water and most over sandy or mountainous ground of poor electrical conductivity. Since many sea areas are served via paths that lie partially over land, this is an important factor in estimating coverage. The model works by determining the Great Circle path from the station to each array point. It then employs a detailed database of ground conductivity values for the region (built up from ITU and other sources [3]) to establish the ground conductivity profile along the path. The signal attenuation of the path is then computed using Millington's method, a technique recommended by ITU [4]. Finally, knowing the power of the radiobeacon, the model computes the strength of its groundwave signal at each point in the area around the station.

Skywave field strength At locations beyond about 100 km from the station its signal may also be received as *skywaves*, that is, by reflections from the ionosphere. These skywaves interfere with the groundwave signals causing fading. Skywave signals are negligible by day but may be strong at night; they also vary with the season of the year [8]. For night-time DGNSS operation the computer model estimates, at each point, the strength of the radiobeacon's signal which is available to the user at least 95% of the time under fading conditions. The skywave factor, which had previously been ignored in planning radiobeacon DGNSS systems, has been shown to be of importance, especially with relatively long-range beacons such as those in the Arabian Gulf [12].

Atmospheric noise The principal source of noise that limits the operating range of radiobeacons is atmospheric. It is caused by electrical discharges, including lightning strikes. Atmospheric noise is strongest in equatorial regions but it propagates over such long distances that it is present at all times everywhere on earth. Its strength varies greatly with the location, the time of day, and the season of the year; so, consequently, do the ranges of DGNSS radiobeacons. The model consults a built-in database of atmospheric noise values (again assembled from ITU sources [8]) to compute the noise level that is not exceeded 95% of the time.

Interference Many marine, aeronautical, and DGNSS radiobeacons share the frequency band and can cause interference to one another. Indeed, in Europe this interference is the principal factor that limits the coverage of DGNSS radiobeacons. The model evaluates the influence of both co-channel and adjacent channel interferers.

We may decide to use the model to plot day or night-time coverage, or to look at coverage under conditions of annual average, or worst-case, atmospheric noise. Day and night-time coverage may differ significantly, since:

- At night, a beacon's range may be *increased* since its signal propagates by skywave as well as by groundwave, or *reduced* by the resulting fading.
- Also at night, propagation of an interfering station's signal by skywave may *reduce* the effective range of a beacon.

A critical aspect of any such modelling system is the user interface. The output from the model links to a proprietary computer-aided design (CAD) package that allows the coverage contour to be displayed graphically on screen. A map of the region of interest is normally overlaid at this stage. If necessary the model may be re-run, perhaps with modified beacon powers or to include a different set of beacons. Results may then be stored or plotted as required.

III. FREQUENCY OPTIMISATION

In Europe some 400 DGNSS, marine, and aeronautical stations share a band of just 64 channels. The Bangor Coverage Prediction Model indicated that some European radiobeacons were losing in excess of 90% of their coverage due to interference. The band-plan had evolved over many years and there was clearly a case for attempting to reduce interference. This was the objective of a frequency optimisation exercise, co-ordinated by the International Association of Lighthouse Authorities and Marine Aids to Navigation (IALA) and conducted at Bangor [13]. The intention was to re-assign the frequencies of all DGNSS and marine radiobeacons in the EMA in such a way as to minimise mutual interference and thus maximise their coverage areas.

The task of re-assigning marine radiobeacon frequencies presented a number of unusual constraints. The first was the 'pairing constraint', according to which co-sited DGNSS and marine radiobeacons must be allocated adjacent channels 0.5kHz apart in order that they may share a transmitter and antenna. Secondly, aeronautical NDBs (whose frequencies are co-ordinated by ICAO) were to remain on their original frequencies. The optimisation process had to take into account skywave-borne interference originating from stations up to several thousand kilometres outside the EMA boundaries. However, stations outside the EMA would not have their frequencies re-assigned.

Before frequency allocations could be optimised, a method of quantifying interference within a network of transmitters was developed [13]. Here is the process used. First, taking a single beacon, the Coverage Prediction Model was used to determine its coverage taking all factors *except interference* into account: that is, its 'interference-free coverage area'. Then the potential of each of the other beacons in the band to reduce that coverage by interference, and the effect of our beacon on them, were estimated. For each such potential interferer, we computed the percentage of points within the original interference-free coverage area that would survived its interference. The result is termed the 'Figure of Merit (FoM)'. No reduction in coverage would give unity FoM, while a total loss of coverage would result in an FoM of zero. An FoM was first calculated assuming that the interfering beacon was co-channel with our beacon. Then a further set of FoMs were computed assuming their frequencies to be separated by 1, 2 ...6 channels. FoMs were generated in this way for each beacon in the band in turn. The result was a set of FoMs that characterised the potential for mutual interference between every pair of beacons. In re-assigning frequencies, the target was to achieve operating FoMs for all beacons as close as possible to unity.

While investigating alternative frequency optimisation algorithms, it became clear that fitting over 400 beacons into a band of only 64 channels with a FoM of unity was not going to be possible. Two alternative optimisation philosophies were considered:

- Try to pack as many beacons as possible into the band with no interference, and then accommodate the rest on the remaining frequencies where they might be subject to severe interference, or
- Allow a degree of interference for every radiobeacon.

The first approach would have given some beacons complete coverage while others would have suffered significant coverage gaps. Some countries' beacons would have suffered high interference levels while other did not; this was considered politically insensitive! The second approach, that of 'equal pain', was more acceptable technically and politically. Distributing the loss of coverage to all beacons as equally as possible would ensure a consistent level of service throughout the network.

Optimisation proceeded by identifying those groups of beacons that could share a channel without their mutual interference exceeding a specified FoM. This target FoM was progressively reduced, starting from unity, until all beacons were just accommodated in the 64 available channels. The most effective algorithm in practice was found to be one in which each co-channel group is built up by starting with the 'most unpopular' beacon [13] (the one that can share with fewest others). Hence, our algorithm is named the "Most Unpopular Algorithm (MUA)". Using the set of FoMs for each beacon pair, the algorithm takes into account interference between beacons when they share a channel and when their frequencies are spaced by up to 6 channels apart.

This band-planning problem has been shown to belong to the "NP-complete" class of problems, for which the search for optimal solutions is intractable due to the large search space. However, it is possible to calculate a lower bound on the number of channels required. Doing so demonstrated that the MUA achieved solutions very close to optimal.

The IALA optimisation was carried out in 1998. In preparing for it, IALA invited all national administrations in the EMA to list their beacon requirements. The result was an almost complete removal of MBs, a dramatic increase in DGNSS beacons, and an overall increase in the total number of beacons. Also, and crucially from the viewpoint of interference, the nominal ranges of many beacons were increased. Several administrations specified nominal ranges of 370km and one beacon had over 500km. These increases in potential interference made optimisation even more essential.

Two coverage-limiting criteria were employed: a minimum signal strength of 34dBμV/m (the so-called "nominal range" strength originally required of MBs); and a minimum signal-to-noise ratio of 7dB. Frequency optimisation resulted in an FoM of over 0.97 across the whole of the EMA. In other words, following optimisation, *all beacons were predicted to provide at least 97% of their interference-free nominal range coverage.*

This new optimised EMA band-plan is due to become operational on 18-19 September 2001.

IV. CASE HISTORY - NORWAY

A Coverage Prediction - Pre-optimisation

The frequency optimisation exercise was carried out on behalf of IALA for the whole of the EMA. However, each individual national administration is primarily concerned with the coverage their own network of radiobeacons provides. They generally regard additional coverage provided by beacons in neighbouring countries as a bonus.

Norway is a nation with an exceptionally long coastline and many DGNSS beacons. Because the coverage of the Norwegian chain of radiobeacons had been modelled previously [7], it was possible to assess the effectiveness of the optimisation process by comparing this with the coverage following optimisation.

Fig. 1 shows the pre-optimisation coverage provided by the network of 10 Norwegian radiobeacons in operation in July 1996. The diagram was generated using the Bangor Coverage Prediction Model. It shows the night-time coverage, with average night-time atmospheric noise. This is the worst-case scenario and so is generally used for system planning. It is evident that the network does not provide unbroken coastal coverage.

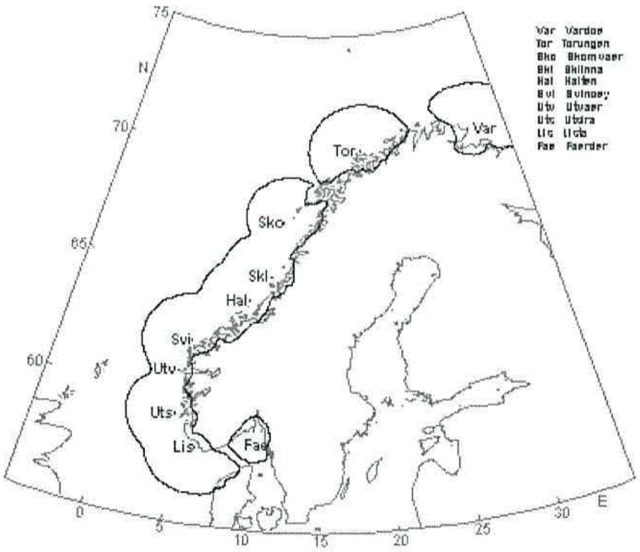

Fig.1. Predicted night-time coverage of Norwegian DGNSS radiobeacons before frequency optimisation. Note the gaps in coastal coverage. Minimum signal strength = 34dBμV/m, minimum SNR = 7dB.

The effect of interference is well illustrated by the Færder beacon (Fae), which clearly does not achieve its nominal range of 300km. The problem is skywave interference from marine beacons at Sklinna (Norway) and Hook of Holland (Netherlands). The result is a significant gap in coverage to the south-west of the beacon in an area of busy shipping channels that link Oslo with the North Sea and ports along the coast to the north.

The Utvaer beacon (Utv) has a lower power than the other beacons, 230km nominal range against 300km. By using the model to calculate its interference-free coverage for comparison, we find that its working range on its present frequency is further reduced by skywave-propagated interference.

There are two significant gaps in coastal coverage north of Skomvaer (Sko). Here, the range is limited not by interference but by skywave self-fading. These gaps in coverage could only be filled by increasing beacon power levels or adding further beacons; frequency re-allocation would not help.

B. Coverage Prediction - Post-optimisation

By September 2001, the following changes will have taken place:

- Frequencies re-assigned as a result of the frequency optimisation process, as discussed earlier,
- Additional beacons at Andenes and Fruholmen,
- Utvaer's nominal range increased to 300km

Fig. 2 shows (in red) the resulting coverage predicted by the model. The original coverage is in green. With the exception of a small region south-west of Andenes (And), around the Lofoten Islands, there is now unbroken coverage along the Norwegian coastline. This small remaining gap requires a further beacon; a frequency was allocated for this in the optimisation process.

Note how the additional beacons, at Andenes and Fruholmen, have filled in the previous coverage gaps in the north. At first sight, one may be surprised that the coverages of Skomvaer, Sklinna and Halten have actually fallen a little. Remember, however, that the optimisation process was designed to share reductions due to interference equitably, not to eliminate interference. See also how greatly Utvaer's coverage has increased. It has benefited from both increased power and frequency optimisation.

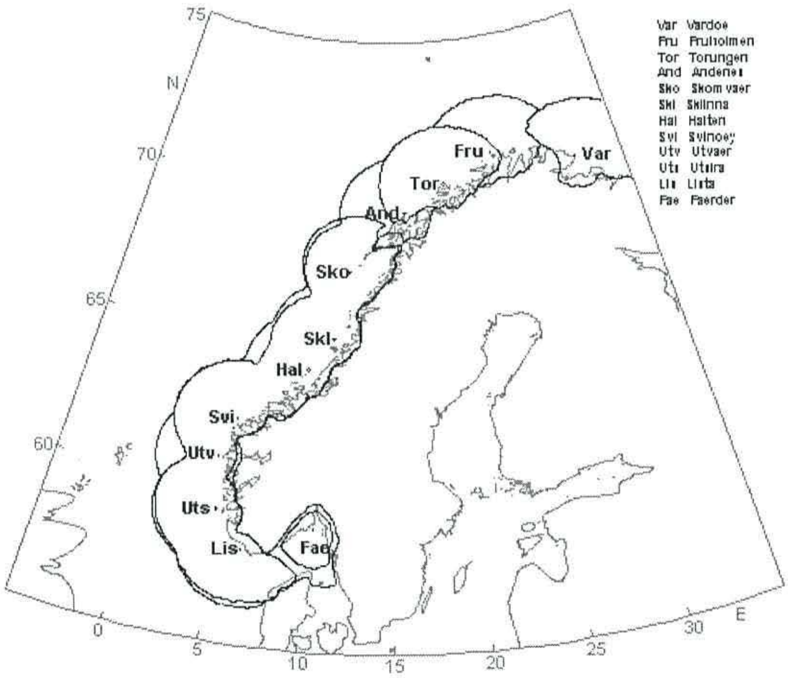

Fig. 2. Red: predicted night-time coverage of Norwegian DGNSS radiobeacons after the addition of stations at Andenes and Fruholmen, an increase in the power of Utvaer, and frequency optimisation. Green: pre-optimisation coverage. Note the increased coverage of Faerder (Fae) and Utvaer (Utv).

The most striking improvement, however, is in the coverage of Faerder which has increased significantly. In fact, it is now achieving its full interference-free coverage. This is illustrated more clearly on the expanded plot of Fig. 3. This range increase is due entirely to frequency re-allocation.

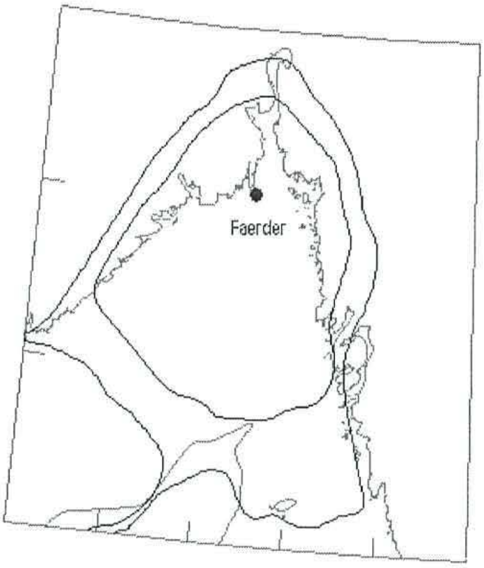

Fig. 3. Night-time coverage of Faerder, after (red), and before (green), optimisation. Frequency re-allocation has removed the gap south-west of the beacon where there are busy shipping lanes.

Two additional frequencies (over and above the one for a beacon in the Lofoten Islands) were allocated in the new plan. These are available for further stations that would provide overlapping coverage, one between Faerder and Lista, the other between Fruholmen and Vardoe.

V. BEACON SELECTION STRATEGIES

In a region where overlapping beacon coverage is the norm, such as Europe or North America, a key concern for the mariner is ensuring that the beacon that provides the best navigation performance is always selected. Fig. 4 illustrates the extent of overlapping coverage within the Norwegian DGNSS coverage area, after frequency optimisation.

Currently two strategies are commonly employed in those DGNSS receivers that select the beacon to use automatically: the *nearest beacon* and the *strongest beacon* strategies.

When a receiver employs the *nearest beacon* it ignores all attributes of that beacon's signal. Thus, it may select a nearby weak station – possibly one whose signal has arrived over a land path of high attenuation - and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case the more distant beacon's signal would have a higher SNR than the nearer one. Choosing the nearest signal could thus result in more data errors and greater delays in receiving correction updates.

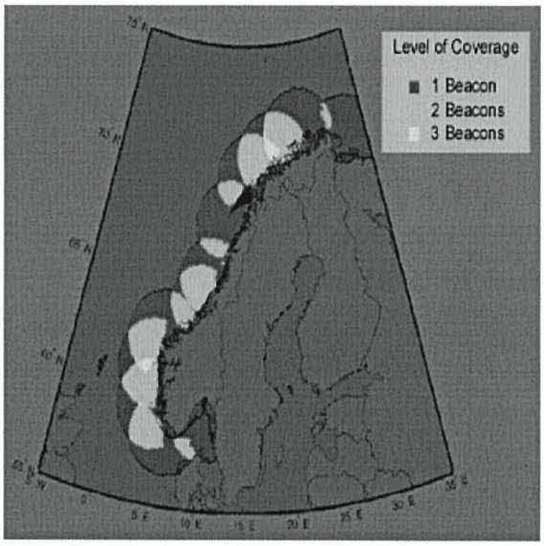

Fig. 4. Number of DGNSS beacons providing coverage at any point. (Night-time values after frequency optimisation).

In contrast, selecting the station by using the alternative *strongest beacon* strategy would mean that the stronger, more distant one was chosen. However, this might result in greater position errors due to increased spatial dilution of precision.

Since the atmospheric noise level at any time is essentially the same on all channels across the radio-beacon frequency band, choosing the *strongest beacon* automatically gives the highest signal-to-*atmospheric noise* ratio. The same is not true, however, for interference, the most significant factor for most radio-beacons in Europe [14]. One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength on a different frequency might have less interference, and so a higher SNR. Thus we should take interference into account. A *quality strategy* is recommended which chooses the beacon with the highest ratio of signal strength to the greater of atmospheric noise or interference. This would maximise the probability of a message getting through, and minimise data latency.

In May 2000 selective availability was set to zero. What effect did this have on beacon selection strategy? Now the dominant sources of position error in GPS are ionospheric and tropospheric effects. Both types of error change much less rapidly than did SA. Therefore, correction messages remain valid for longer periods of time; indeed, they may be usable for tens, or even hundreds, of seconds. The effect of latency on the reception of differential corrections is markedly reduced and so much lower SNR values can be tolerated than before. Receiving the strongest beacon, or the one with the highest SNR, would now appear to be much less important.

On the other hand, as the separation between reference station and receiver increases, the dominant error source soon becomes spatial dilution of precision. It would appear therefore that a simple *nearest beacon* selection strategy is all that is now required.

However, the situation is complicated by a third factor. Correction messages also carry alarms to warn the user of unhealthy satellites or failures of reference stations. Indeed, post-SA the main benefit of differential operation for many users is enhanced integrity. The minimum time-to-alarm (TTA) specified by the International Maritime Organisation is 10s [15]. In order to meet this requirement, a high SNR is required - again favouring a quality strategy! So how do we balance the constraints of spatial dilution and TTA? We have proposed a new post-SA strategy that does so [16].

A. Norwegian Beacon Selection by the Post-SA Strategy

The new strategy selects *the nearest beacon* (to give minimum spatial dilution) *that can meet the quality measure required for a 10s TTA*: that is, an SNR of 7dB and compliance with the minimum interference protection ratios. In that way the choice of beacon minimises spatial dilution errors while meeting the TTA requirement. Fig. 5 shows the *best beacon* of the 12 Norwegian beacons any point according to this strategy.

This figure has again been plotted under worst-case conditions: at night, with interference. Around Andenes, Torsvaag and Fruholmen, and between Lista and Utsira, the boundaries between best beacon regions are straight lines. Thus here, the best beacon is also the nearest. But between Utvaer and Svinoey, and between Skomvaer and Andenes, the shapes of the boundaries are more complex. This shows that here the nearest beacon cannot satisfy the minimum SNR or interference protection limits. In such regions, the performance of a receiver that selected the nearest beacon would fall below the minimum requirements.

Our new post-SA strategy happily turns out to very similar to that proposed by the IEC in their draft document [6]. However, whereas the IEC take only the signal-to-*atmospheric noise* ratio into account, our strategy also ensures that interferers do not exceed the minimum protection ratios.

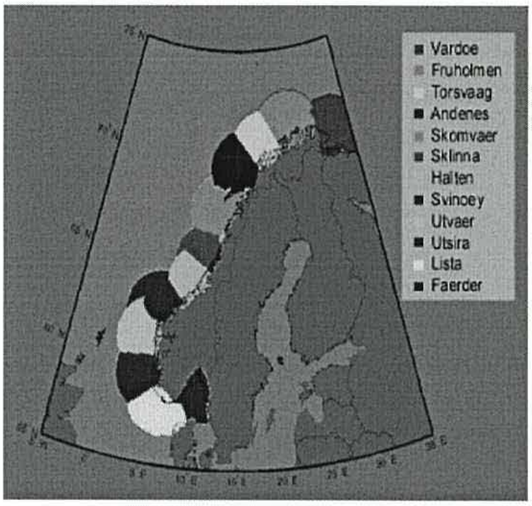

Fig. 5. Best beacon choices in the Norwegian DGNSS coverage region, using the 'post-SA' strategy.

B. Alternative Beacon - Norwegian coast

This paper has presented strategies for identifying the best beacon to use at any location. But if that beacon should be unavailable, because of a scheduled or unscheduled outage, it would not be obvious to the user which station to select as the alternate. Our software also allows us to answer that question. We run the same process as for choosing the best beacon, again using the *post-SA* strategy. But this time we select the second best.

Maps such as that shown in Fig. 5 are in a format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. The same format can be used to display the best alternate beacon.

In order to allow "automatic" receivers to employ this information we may also output the data in a tabular form that manufacturers can store within their receivers. Table 1 shows an example of part of this data set: at each location, specified by latitude and longitude, the best beacon (Primary) and the best alternate (Secondary) are listed, computed using the *post-SA strategy*.

Table 1. Part of a tabulated data set for beacon selection, employing the post-SA strategy

```
0  -      NO BEACON SELECTED
:
9  -      UTVAER
10 -      UTSIRA
11 -      LISTA
12 -      FAERDER

lat:58.4 Lon:3.8 Primary-10  Secondary- 11
lat: 58.4 Lon: 3.9  Primary- 10  Secondary- 11
lat: 58.4 Lon: 4.0  Primary- 10  Secondary- 11
lat: 58.4 Lon: 4.1  Primary- 10  Secondary- 11
lat: 58.4 Lon: 4.2  Primary- 10  Secondary- 11
lat: 58.4 Lon: 4.3  Primary- 10  Secondary- 11
lat: 58.4 Lon: 4.4  Primary- 10  Secondary- 11
```

VI. CONCLUSIONS

Using the Bangor Coverage Prediction Model, the coverage of the Norwegian network of marine radiobeacon DGNSS transmitters has been plotted. The model has taken into account the effects of groundwave and skywave propagation including self-fading, ground conductivity, atmospheric noise and also interference propagated by both groundwave and skywave modes. We have shown that some beacons have been losing significant amounts of coverage due to skywave interference.
An algorithm has been described that optimises the frequency allocations of all beacons in the EMA. We have shown the greatly improved coverage it provides along the Norwegian coastline.

A number of different strategies for selecting the best beacon, in regions where there is overlapping coverage, have been discussed. We recommend using an algorithm that selects the nearest beacon that fulfils the minimum SNR and interference protection ratios. We show the result of using this strategy along the Norwegian coast. We have also identified the best alternate beacon to be used in each location, should the preferred beacon be unavailable.

ACKNOWLEDGMENTS

The coverage-prediction studies described in this paper were carried out on behalf of the Norwegian Coast Directorate, to whom the authors are grateful for permission to reproduce the results. Alan Grant's current research work is funded by EPSRC. The computer model used is this study is based upon earlier work by Dr. Dorothy Poppe and Dr. Erdem Turhan.

REFERENCES

[1] Enge, P. K. and Olsen, K. E., "Medium Frequency Broadcast of Differential GPS Data", *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 26, No. 4, pp607-617, July 1990.

[2] Allen, L.W., "United States' Nationwide Differential Global Positioning System", *2nd European Symposium on Global Navigation Satellite Systems (GNSS98),* Toulouse, France, 20-23 October 1998.

[3] Alsip, D. H., Butler, J. M. and Radice, J. T., "The Coast Guard's Differential GPS Program", *Navigation,* Vol. 39, No. 4, pp345-361, Winter 1992-3.

[4] Enge, P. K., Levin, P., Hansen, A. and Kalafus, R., Coverage of DGPS/Radiobeacons, *Navigation,* Vol. 39, No. 4, pp363-381, 1992.

[5] International Telecommunication Union, *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area,* Geneva, 1985.

[6] International Electrotechnical Commission, *Shipborne DGPS and DGLONASS Maritime Radiobeacon Receiver Equipment, Technical Committee No. 80, Maritime navigation and radio communications equipment and systems.* IEC 61108-4: 2001, TC80/WG1 (DRAFT No 8), July 2000.

[7] Roberts, G., Last, J.D. & Poppe, D.C., "Designing radiobeacon differential satellite navigation systems using the Bangor coverage prediction model", *4th St. Petersburg International Conference on Integrated Navigation Systems,* St. Petersburg, Russia, 26-29 May 1997.

[8] Poppe, D. C., *Coverage and performance prediction of DGPS Systems Employing Radiobeacon Transmissions,* Ph.D. Thesis, University of Wales, Bangor, October 1995.

[9] Last, J.D. & Poppe, D.C., "A coverage prediction model for radio beacon differential satellite navigation systems", *Navigation (USA) - Journal of the Institute of Navigation,* Vol. 43, No. 4, pp451-467, Winter 1996-7.

[10] International Telecommunication Union (ITU), *Technical Characteristics of Differential Transmissions for Global Navigation Satellite Systems (GNSS) from Maritime Radio Beacons in the Frequency Band 285-325kHz (283.5-315kHz in Region 1),* Draft Revision of Recommendation M.823, ITU, Geneva, 1995.

[11] International Electrotechnical Commission, *Draft performance standards for shipborne DGPS and DGLONASS maritime radio beacon receiver equipment,* IEC Technical Committee No. 80, 1996.

[12] Baxter, M. and Last, J. D., "Designing a marine differential GPS service for the Arabian Gulf", *Satellite Positioning Systems Conf.,* Arab Institute of Navigation, Alexandria, Egypt, 12-13 December 1995, Paper 6.

[13] Turhan, B. E., *Optimisation of MF DGNSS, maritime and aeronautical radiobeacon coverage by frequency re-assignment,* Ph.D. Thesis, University of Wales, Bangor, November 1999.

[14] Last, J.D. & Turhan, B.E., "European radiobeacon DGNSS - Making the most of the frequency band", *Journal of the Royal Institute of Navigation,* 52, 2, pp176-188, May 1999.

[15] International Maritime Organisation, *Resolution A815 (19) World-Wide Radionavigation System,* November 1995.

[16] Last, J.D, Grant A.J. & Ward, N., "Radiobeacon DGNSS station selection strategies – can we do better?", *ION National Technical Meeting,* Long Beach, CA, USA, 22-24 January 2001

Understanding Radiobeacon DGNSS Standards, Post-SA

Alan Grant* and David Last, *University of Wales, Bangor, UK*
**E-mail: ajgrant@informatics.bangor.ac.uk*

BIOGRAPHIES

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institute of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and former Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer, and a Board Member of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

ABSTRACT

Marine radiobeacons are used by the maritime community world-wide as an efficient means of broadcasting differential GPS data to users at sea. In Europe and North America large numbers of these DGNSS beacons now serve not only coastal regions and waterways but also substantial inland areas. As a result, there is often overlapping coverage and a choice of stations. Choosing the best beacon ensures the highest quality of DGNSS service.

With many receivers, the user must select the station manually, but receives little guidance as to how to make that choice. Other receivers perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

Some time ago we proposed a third, novel, approach: the best station is the one with the highest signal-to-noise ratio (SNR) and hence the highest quality of data link performance. We show that this strategy was optimal for DGNSS with Selective Availability (SA) in operation.

But now that SA has been set to zero, the choice of strategy needs to be reconsidered. We show that spatial dilution and time-to-alarm are now the key factors. We examine them and conclude that the current international time-to-alarm standards are unclear and ambiguous. Despite that, we are able to propose a new "post-SA" beacon selection strategy: the best beacon is the one that gives the lowest spatial dilution of precision whilst meeting the time-to-alarm requirement.

A computer model, based on well-established techniques for DGNSS radiobeacon coverage analysis and system design, is used to compare the four strategies. The "best beacon" choices they make for the British Isles are mapped and compared. Then, the results of the post-SA strategy are presented for the entire European Maritime Area, with all beacons operating according to the new band-plan adopted last September. Finally, we show how to identify the best alternate beacon should the preferred station fail.

The paper identifies those regions in which receivers that employ the old *nearest beacon* or *strongest beacon* strategies fail to select the best beacon in a post-SA world.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the pseudorange errors. They transmit corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.
One of the oldest radio aids-to-navigation technologies, the marine radiobeacon, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, the user can receiver more than one DGNSS beacon in many areas [3].

With many receivers, the user must select a station manually, but there is little guidance as to how to make that choice. Other types of receiver perform the selection automatically, some choosing the nearest station, others the one that provides the strongest signal.

This paper considers the choice of best beacon, for both manual and automatic receivers. It compares the results of the *nearest beacon* and *strongest beacon* strategies that are commonly used at present. It then compares two novel approaches: a selection based on signal *quality* introduced recently, and then a strategy tailored to our new *post-SA* world.

INDIVIDUAL RADIOBEACON COVERAGE

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). Within the European Maritime Area (EMA) of the ITU Region 1 [4], a geographical point is deemed to lie within the coverage of a DGNSS beacon, if the beacon's field strength there is not less than 10μV/m (or a higher figure specified by the national administration) and the SNR not less than 7dB [4]. In addition, no interfering signal may exceed the protection ratios defined in [5].

Coverage prediction is described further in [6]. A widely-used tool for predicting coverage that takes into account skywave and groundwave propagation, own-skywave fading, and interference, is the Bangor Coverage Prediction Software. This suite of programs models the coverage area of single beacons or groups of beacons. If, however, we are to consider the choice of beacon at a location where more than one signal is available, we need data on all those beacons simultaneously. Achieving this has required the development of new software that employs a multi-layer array architecture [6].

This new software can be used to predict the coverage areas of single beacons, as previously. An example is Fig. 1 where the outer boundary is the limit of daytime, interference-free, coverage. But in addition, the new software can model the results of various strategies for selecting the best beacon, allowing us to compare them.

MODELLING BEACON SELECTION STRATEGIES

Currently two strategies for selecting the beacon to use are commonly employed in DGNSS receivers: the *nearest beacon* and the *strongest beacon* strategies.

When a receiver employs the *nearest beacon* strategy it ignores all attributes of the beacon's signal. Thus it will select a nearby weak station – possibly one whose signal has arrived over a land path of high attenuation - and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case the more distant beacon's signal would have a higher SNR than the nearest one. So choosing the nearest signal in this way could result in more data errors and so greater delays in receiving correction updates.

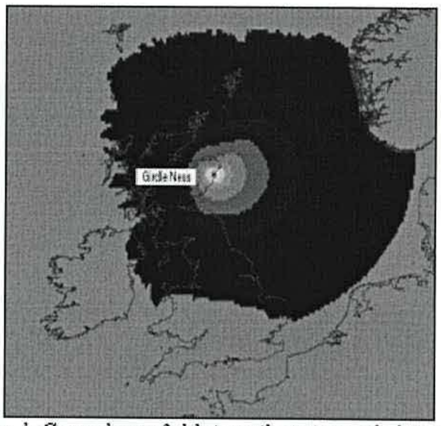

Fig. 1: Groundwave field strength contours of a beacon at Girdle Ness, Scotland. Outer boundary is daytime interference-free coverage.

In contrast, selecting the station using the alternative *strongest beacon* strategy would mean that the stronger, more distant one was chosen. However, this might result in greater position errors due to increased spatial dilution of precision.

We will first employ our software to map the choices of best beacon made by these two strategies, and then examine whether they generate significantly different choices. We will do so using the system of 16 beacons designed to serve the United Kingdom and Ireland. Note that the sets of British Isles and EMA beacons used in this paper, and the frequencies they employ, are taken from the new band-plan introduced in September 2001.

Modelling the *nearest beacon* strategy

The process starts by computing the coverage areas of each of the 16 beacons. Then, point-by-point throughout these areas, we identify the nearest beacon. When all points have been examined, we produce an output plot (Fig. 2), with different colours used to distinguish the area within which each beacon has been chosen.

Fig. 2 also distinguishes between the extent of coverage available by day (outer boundary) and at night (inner, lighter, region). The night-time coverage is less than the daytime because of fading due to skywave cancellation of the beacons' signals. This form of diagram is designed for navigators who must input the choice of beacon into their receivers manually. It tells them which beacon to use (by day or night), where on a voyage they should change beacon selection, and where they should cease to rely on coverage from the system.

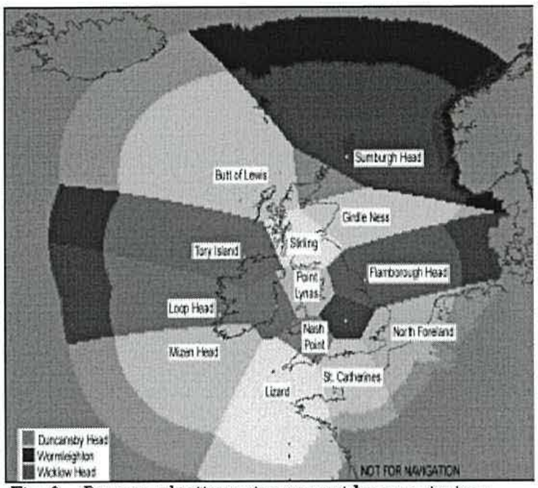

*Fig. 2 – Beacon selection using **nearest beacon strategy**, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.*

Since the selection is based solely on distance, the boundaries between adjacent areas are the straight lines along which pairs of neighbouring beacons are equidistant. It is interesting to compare the sizes of the coverage areas of the various stations: Sumburgh, for example, serves a much larger region than does Nash Point. This is partly explained by its greater nominal range, 370km as compared to 277km, but more so by the fact that Nash Point's neighbours are simply much closer to it than are Sumburgh's.

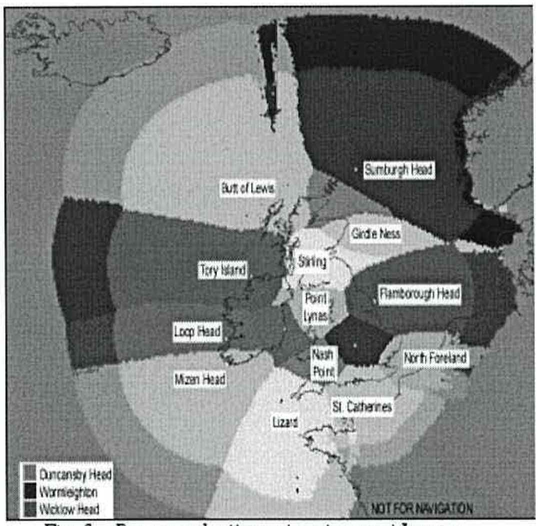

*Fig. 3 – Beacon selection using **strongest beacon strategy**, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.*

Modelling the *strongest beacon* strategy

The same process was then employed to model the *strongest beacon* strategy; this time the beacon with the strongest signal at each point was identified. The result is shown in Fig. 3.

The beacons this strategy chooses appear to be significantly different from those chosen by the *nearest beacon* strategy (Fig. 2). The yellow areas in Fig. 4 are the areas where the two strategies produce different results; they constitute 15% of the total daytime coverage.

To understand the reasons for the areas of difference, consider the large region west of Ireland that straddles the Tory Island/Loop Head boundary. Here the signal from Tory Island is the stronger, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head. But even where two stations of equal power compete, the *nearest beacon* strategy frequently selects the weaker signal. Consider the inland section of the yellow area that straddles the Duncansby Head/Girdle Ness boundary. Fig. 2 shows that Girdle Ness is the nearest beacon here. But its signal arrives via a land path of relatively high attenuation. The signal from the slightly more distant Duncansby Head station arrives over a sea path and is the stronger.

In this, and other fairly extensive regions, the *nearest beacon* strategy fails to select the station with the strongest signal. The consequences are a lower SNR, a higher message error rate, and greater message latency, than the *strongest beacon* would offer. With SA active, latency was the major constraint: the greater the latency, the greater the pseudo-range error that built up before the next correction was received, and so the greater the resulting position error.

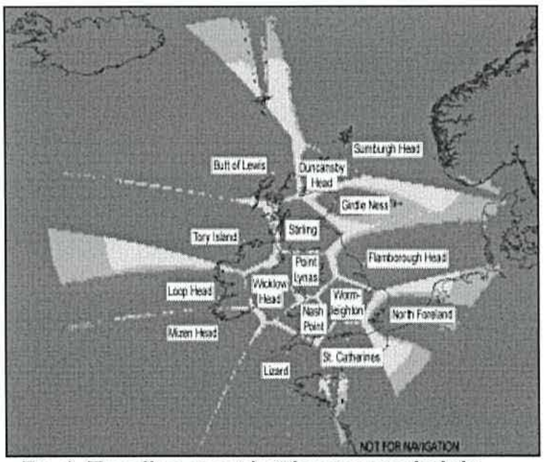

Fig. 4 - The yellow areas identify regions in which the two strategies select different beacons.

BEACON SELECTION BY SIGNAL QUALITY

The logical conclusion of the previous argument is that we should always choose the beacon whose signal has the highest signal-to-noise ratio. So far, the only *noise* taken into account has been atmospheric noise. Since its level at any time is essentially the same on all channels across the radiobeacon frequency band, choosing the *strongest beacon* automatically gives the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – the dominant factor for radiobeacon coverage in Europe at night [7]. One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength, but on a different frequency, might have much less interference, and so a higher SNR. Thus we should take into account in selecting our beacon not only atmospheric noise but also interference. And we should use as our measure of quality the overall SNR, that is, the ratio between a beacon's signal strength and either atmospheric noise or interference, whichever is the greater. That is our *quality strategy*.

Our software provides all the information we need to assess beacons' SNRs in this way: the groundwave and skywave strengths of the wanted beacon, the atmospheric noise level and the strengths of all interfering components on all channels. Thus we can compute the SNR of each beacon's signal at any point and so identify the best beacon there according to this *quality strategy*. Fig. 5 shows the results for the British Isles beacons.

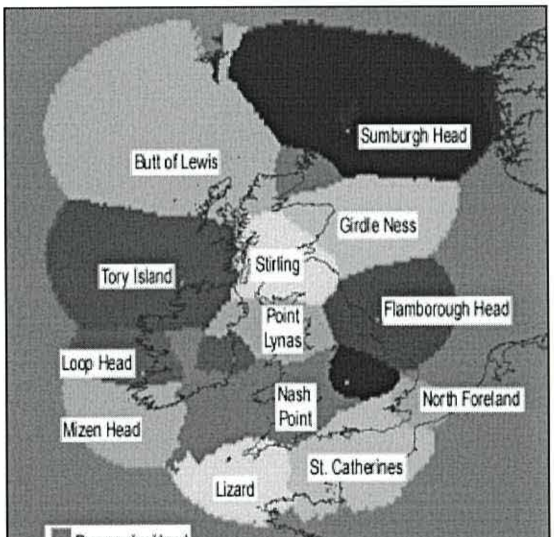

*Fig. 5. - Beacon selection using the **quality strategy** for the 16 beacons of the UK and Ireland, under night-time conditions with interference.*

This figure is plotted under worst-case conditions: at night, when interference capable of reducing coverage can be received via sky-wave propagation from other beacons up to 4200km away. In consequence, not only is night-time coverage smaller than by day, but the effect of interference on the choice of beacon is greatest.

In contrast, the *nearest beacon* strategy ignores interference. In the yellow areas of Fig. 6, which total 14% of the night-time service area of the system, the new *quality strategy* has chosen beacons of higher SNR than did the *nearest beacon* strategy. Clearly, the *nearest beacon* approach fails to provide the user with the highest quality signal over substantial and important areas.

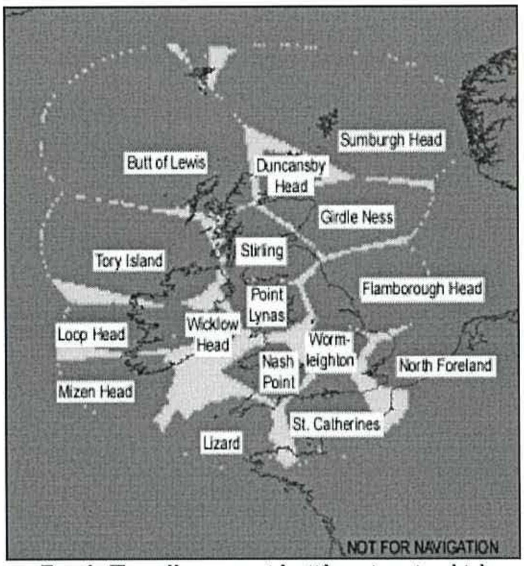

*Fig. 6 - The yellow areas identify regions in which different beacons are selected by **the nearest beacon and quality strategies**.*

THE ENDING OF SA

In May 2000 selective availability was set to zero. What effect does this have on beacon selection strategy? Now the dominant position error sources in GPS are ionospheric and tropospheric delays. Both types of error change much less rapidly than did the previously dominant SA. Therefore, correction messages remain valid for longer periods of time; indeed, they may be usable for tens, or even hundreds, of seconds. So the effect of latency on the reception of corrections is markedly reduced, and much lower beacon SNR values can be tolerated than before. Receiving the station with the highest SNR, or even the strongest one, would now appear to be much less important than before.

On the other hand, as the separation between reference station and receiver increases, the dominant error source soon becomes spatial dilution of precision. This is not an error source itself, but is the result of the user and the reference station experiencing different ionospheric and tropospheric delays. So it would appear that a simple *nearest beacon* selection strategy is all that is now required.

But the situation is complicated by a third factor! Correction messages also carry alarms to warn the user of unhealthy satellites or failures of reference stations. Indeed, enhancement of integrity is now a much more important benefit of differential operation for many users than enhancement of accuracy. So it may not, in fact, be acceptable to choose a nearest beacon with minimal spatial dilution but low SNR, since this would result in increased message latency and, possibly, an excessive time-to-alarm.

TIME-TO-ALARM SPECIFICATIONS

Resolving this issue led us to study the time-to-alarm (TTA) specifications in the published radiobeacon DGNSS international and US national standards. Table 1 shows the requirements set by five authorities: the International Maritime Organisation (IMO); the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA); the International Electrotechnical Commission (IEC); the United States Coast Guard (USCG); and the US Federal Radionavigation Plan (FRP). The ambiguities in the statements and discrepancies between them, highlighted in the table using colours, are significant.

The first ambiguity (highlighted in blue) is as follows: IMO A.815 and IALA speak of a warning being "provided to users", and FRP states that "users will be notified", within the TTA. Does this mean that the user's receiver will *display* a warning within the TTA, as users might reasonably expect? Or does it mean simply that the reference station will *transmit* the warning, as some administrations appear to believe? The difference is very significant: it is the time the warning takes to pass through the transmission system and for the receiver to respond to it. This delay may be several seconds. Also, its magnitude depends in part on a latency determined by the SNR, and hence on the beacon selection strategy employed.

The USCG document appears to define TTA in both ways! In Chapter 4, the TTA lasts until "the user equipment suite/user is alarmed". But in the *Definitions* section, the TTA lasts until "the broadcast of the alarm".

As far as IMO is concerned, and IALA which bases its document on IMO, this ambiguity can be resolved by IMO A.860. This defines time-to-alarm as "the time elapsed between the occurrence of a failure in the system and its presentation on the bridge".

A second ambiguity (in green) is whether the "system malfunction" in IMO A815 means precisely the same as IALA's "system non-availability or discontinuity", or the IEC's "selected station is unhealthy, unmonitored, or signal quality is below threshold", or the USCG's "protection limit is exceeded", or the FRP's "out of tolerance condition". The IEC have yet another statement that applies to automatic receivers. These multiple ambiguities concern the causes of alarms only and so have no implications for the choice of beacon selection strategy. The resulting confusion could, however, be significant for administrations operating marine radiobeacons.

Authority	Statement regarding TTA
IMO (A.815) [8]	A warning of system malfunction should be provided to users within 10s.
IMO (A.860) [9]	Time to alarm is the time elapsed between the occurrence of a failure in the system and its presentation on the bridge. Time-to-alarm ≤10s
IALA [10]	A warning of system non-availability or discontinuity should be provided to users within 10s.
IEC [5]	While in manual mode and the manually selected station is unhealthy, unmonitored, or signal quality is below threshold, then an alarm shall be activated.
USCG [11]	[*Chapter 4*] (*Time-to-alarm is*) the time from when a protection limit is exceeded to when the user equipment suite/user is alarmed by the broadcast. (It shall be) less than 2s for 200bps transmission rates, 4s for 100bps transmission rates and 8s for 50bps transmission rates. [*Definitions*] Time-to-alarm: The maximum allowable time between the appearance of an error outside the protection limit at the integrity monitor and the broadcast of the alarm.
FRP [12]	Integrity of the Maritime DGPS service operated by the USCG is provided through an integrity monitor at each broadcast site. Each broadcast site is remotely monitored and controlled 24 hours a day from a DGPS control center. Users will be notified of an out-of-tolerance condition within 6s.

Table 1: Time-to-alarm definitions and specifications. Colours indicate discrepancies and ambiguities.

A major quantitative discrepancy is the time-to-alarm limit itself (in red). For 100bps transmission, IMO A.815 and A.860, and IALA, all specify 10s. The USCG specify 4s, the FRP 6s, while the IEC give no specification. Clearly, the USCG's 4s, from when the protection limit is exceeded to when the user's equipment, or the user, is alerted, is the most stringent of the TTAs and so demands the highest SNR.

Finally, only the USCG specify a maximum range (300 statute miles) at which a radiobeacon's signals should be used without warning.

We have chosen to interpret these confusing specifications as follows. We have assumed that the maximum TTA is that experienced by the receiver, in accordance with IMO A.860. This is the most conservative assumption – but also the common-sense one! It means that the TTA must include latency delays due to noise and interference. Secondly, for assessing beacon selection strategies and making coverage predictions in Europe, we have adopted the IMO/IALA 10s TTA requirement. Different values would be required for USCG systems that meet the FRP requirements. Finally, we decided to seek to minimise spatial dilution of precision.

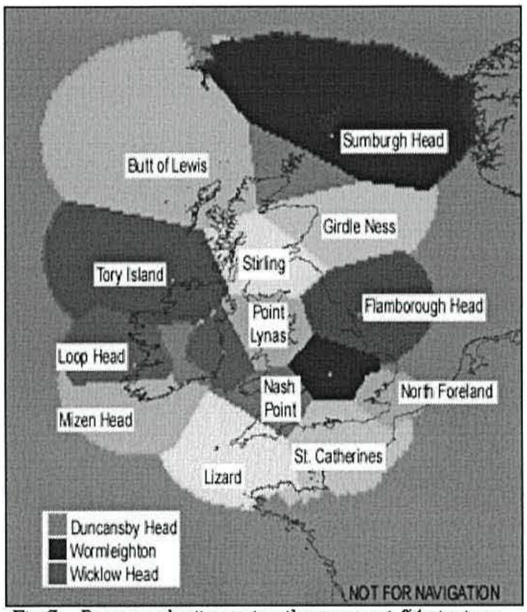

*Fig 7 – Beacon selection using the new **post-SA strategy** for the 16 beacons of the UK and Ireland, under night-time conditions with interference.*

BEACON SELECTION BY THE *POST-SA* STRATEGY

A satisfactory post-SA beacon selection strategy must embody these interpretations. A simple *nearest beacon* strategy would not guarantee that the TTA requirement was met. A quality strategy would not minimise spatial dilution. So we propose a post-SA strategy based on the following principle: the beacon to be selected is the nearest one that can meet the quality measure required for a 10s TTA.

Measurements relating the signal word error rate to SNR [13] have established that a signal of 7dB minimum *signal-to-noise or interference ratio*, will have sufficiently low latency to give a high probability of successful message reception within 10s. Indeed, this minimum SNR was included in the specification of beacons originally in order to ensure the 10s message updates required to achieve acceptably-low position errors when SA was in operation. So our post-SA strategy chooses to retain this minimum SNR.

The result of applying this strategy to the 16 British Isles beacons is shown in Fig. 7. This figure is again plotted under worst-case conditions: at night, with interference. The results are strongly influenced by the differences of interference levels on the various beacons' channels. For example, the coverage of North Foreland is reduced by skywave interference from a distant station in the Mediterranean region. As a result, St. Catherine's is selected as the best beacon to use when following some of the busy sea-lanes in the English Channel, even though North Foreland is the nearest beacon.

This point is clearly illustrated in Fig 8 in which the yellow areas are those where the *post-SA strategy* and the *nearest beacon* strategy give different results. Within these yellow regions the nearest beacon should not be used at night since its signal fails to meet the time-to-alarm criterion.

Our new post-SA strategy happily turns out to be very similar to one proposed by the IEC recently [5]. However, whereas the IEC take only the signal-to-*atmospheric* noise ratio into account, our strategy ensures that *interferers* also do not exceed the minimum protection ratios.

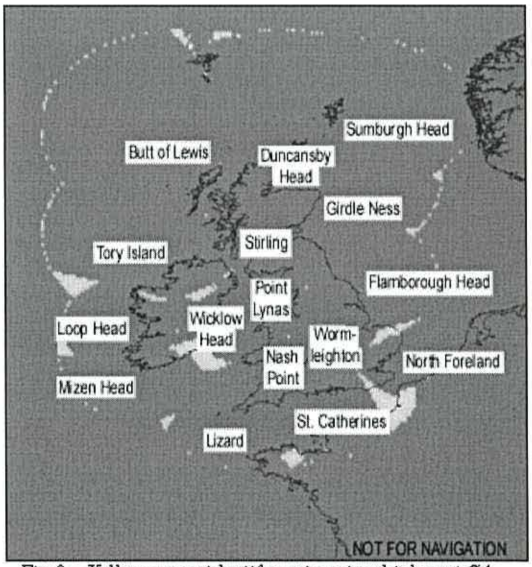

*Fig 8 – Yellow areas identify regions in which **post-SA** and **nearest beacon strategies** select different beacons.*

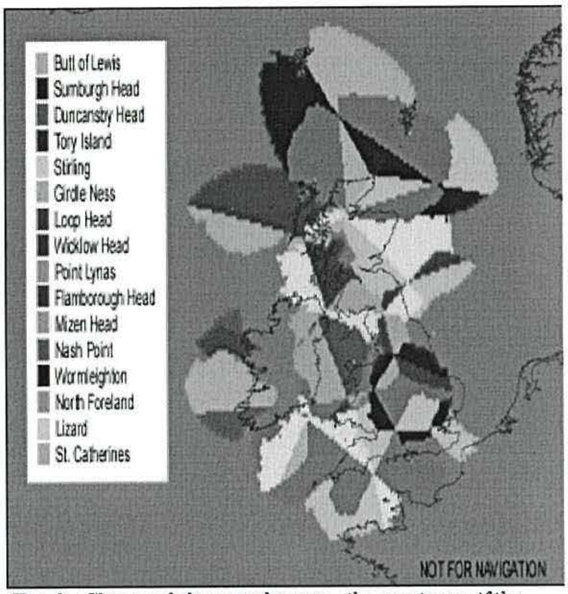

*Fig. 9 - Choice of alternate beacon - the one to use if the best beacon should be unavailable. The **post-SA strategy** has been employed.*

ALTERNATE BEACONS

This paper has presented strategies for identifying the best radiobeacon to use at any location. But, if that beacon should be unavailable because of a scheduled or unscheduled outage, it is far from obvious to the user which station to select as the alternate. Our new software also allows us to answer that question. We run the same process as for choosing the best beacon, but this time select the second best. The alternate beacon results from the *post-SA* strategy are presented in Fig. 9.

DATA IN TABULAR FORM

The maps shown in Figs. 2, 3, 5, 7 and 9 are in a format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. To allow "automatic" receivers to employ the same information, we have produced it in a tabular form that manufacturers can store within their receivers. Table 2 shows part of this data set: at each location, specified by latitude and longitude the best beacon (Primary) computed using the *post-SA strategy* and the alternate (Secondary),, are listed.

BEACON SELECTION ACROSS THE EMA

In Fig. 10 we show the result of applying the new *post-SA strategy* to identify the best beacon across the entire European Maritime Area (30-72°N, 30°W-55°E). The figure shows, for the first time, the combined coverage of all 158 differential GNSS radiobeacons in the EMA, identifying point-by-point the radiobeacon with the lowest spatial dilution whose signal meets the time-to-alarm criterion.

60 -	NASH_POINT	
61 -	WICKLOW_HEAD	
62 -	POINT_LYNAS	
:		
:		
Lat: 53.2 Lon -4.1	Primary- 62	Secondary- 61
Lat: 53.2 Lon -4.0	Primary- 62	Secondary- 61
Lat: 53.2 Lon -3.9	Primary- 62	Secondary- 61
Lat: 53.2 Lon -3.8	Primary- 62	Secondary- 61
Lat: 53.2 Lon -3.7	Primary- 62	Secondary- 61

*Table 2: Part of a tabulated data set for beacon selection, employing the **post-SA strategy**.*

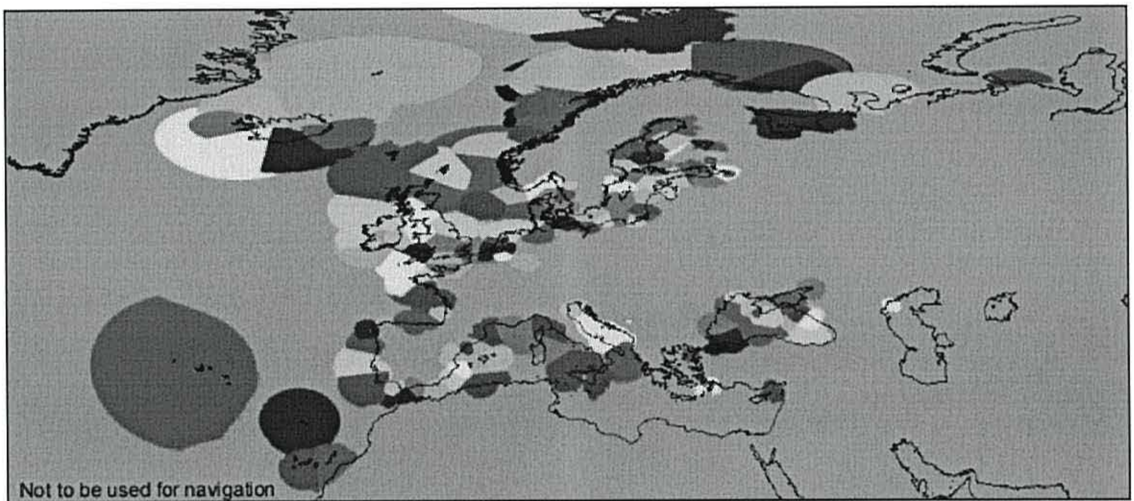

*Fig. 10 – Beacon selection using the new **post-SA strategy** for the whole European Maritime Area (daytime, with interference).*

CONCLUSIONS

The paper has compared competing strategies for selecting the radiobeacon to be used where more than one is available. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a *quality strategy* has been studied in which the best beacon is deemed to be the one with the highest ratio of signal-to-atmospheric noise, or interference.

With the ending of SA, however, the constraints on beacon selection have changed dramatically. We have proposed a new strategy in which the best beacon is the nearest one (ie with the least spatial dilution) whose signal quality meets the time-to-alarm requirements. Since there are multiple ambiguities in the TTA specifications of different international and national bodies, we have judged it most appropriate to interpret the requirement as being that the user is made aware of a fault within 10s of its occurring. Happily our new post-SA strategy turns out to very similar to one being considered by the IEC.

Our results are presented in a pictorial form designed to be convenient for users who are obliged to enter the choice of beacon into their receivers manually. We have shown diagrams for both the British Isles and, for the first time, the whole European Maritime Area. An example is also presented of the data in a tabular form that can be built into receivers at the time of manufacture. Both forms of presentation indicate not only the choice of best beacon, but also the alternate to be employed when the best station is unavailable.

Finally, we strongly recommend that steps be taken to eliminate the discrepancies between the specifications published by the various authorities, and the ambiguities within them.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data,* IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radiobeacons for the Broadcast of Differential GPS Data,* Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services,* Issue 7 – August 1999.
4. International Telecommunication Union, *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area,* Geneva, 1985.
5. International Electrotechnical Commission, *Shipborne DGPS and DGLONASS Maritime Radiobeacon Receiver Equipment,* Technical Committee No. 80, Maritime navigation and radio communications equipment and systems. IEC 61108-4: 2001, TC80/WG1 (DRAFT No 8), July 2000.
6. Last, J.D, Grant A. J. & Ward, N., *Radiobeacon DGNSS station selection strategies – can we do better?,* ION National Technical Meeting, Long Beach, CA, USA, 22-24 January 2001
7. Last, J.D. & Turhan, B.E., *European radiobeacon DGNSS - Making the most of the frequency band,* Journal of the Royal Institute of Navigation, 52, 2, pp176-188, May 1999
8. International Maritime Organisation, Resolution A.815 (19), *World-Wide Radionavigation System,* November 1995
9. International Maritime Organisation, Resolution A.860 (20), *Maritime policy for a future global navigation satellite system (GNSS),* November 1997
10. International Association of Marine Aids to Navigation and Lighthouse Authorities, *DRAFT revision of IMO resolution A.815(19),* Sub-Committee on Safety of Navigation, 31 March 2001
11. U.S. Department of Transportation United States Coast Guard, *Broadcast Standard for the USCG DGPS navigation service,* COMDTINST M16577.1, April 1993
12. U.S. Department of Transportation and U.S. Department of Defense, *1999 Federal Radionavigation Plan,* December 1999.
13. Poppe, D.C., *Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions,* Ph.D. Thesis, University of Wales, Bangor, October 1995.

Understanding and predicting the availabilities of radiobeacon DGNSS Systems

Alan Grant and David Last, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*

BIOGRAPHIES

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and former Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, a Chartered Engineer, and Vice-President of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

Dr Nick Ward is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in Radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

ABSTRACT

Marine radiobeacons are employed by the maritime community world-wide as an efficient means of broadcasting differential GNSS data to users at sea. Such DGNSS beacons also increasingly serve not only coastal regions and inland waterways but also substantial land areas of North America and Europe.

Recently, the International Maritime Organisation (IMO) has revised radionavigation service standards to reflect the signal availability requirements of DGNSS. In this paper we identify the many factors that need to be considered in calculating the level of availability, and appropriate methods for doing so.

We then propose a way of assessing availability, and embody its principles in a computer model. The model can calculate the availability of a single beacon or, as is more common, the service provided by a system of beacons with overlapping coverage. We show for the first time predictions of the availability and coverage of DGNSS systems in Europe. The new techniques presented in the paper provide a valuable tool for marine radiobeacon DGNSS systems planners and operating administrations.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the satellites' pseudorange errors. They transmit corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, marine radiobeacons, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, more than one DGNSS beacon can generally be received [3], which enhances signal availability for the user.

IMO resolutions stipulate the minimum signal availability that should be provided at critical, and other, locations. This paper considers these requirements together with other sources of availability specifications. We then take software designed to plot the coverage and performance of DGNSS radiobeacons [4] and extend it to map the availabilities of both individual beacons and groups of beacons.

The diagrams presented in this paper are examples of the use of this technique. The beacons employed in them are not necessarily those currently in operation.

DEFINITIONS OF AVAILABILITY

Availability is the percentage of time a signal at a location is usable. Being "usable" means meeting minimum criteria for coverage set out by the International Telecommunication Union (ITU) [5]. In

Europe these criteria are that the field strength must be not less than 10μV/m (or a higher figure specified by the national administration) and the signal-to-noise ratio (SNR) not less than 7dB. In addition, no interfering signal may exceed specified protection ratios that depend on its frequency separation from the beacon's signal.

Included in these criteria are both deterministic and stochastic elements. The deterministic elements are the strengths of the groundwave-propagated signals received from the reference station and possibly from interfering stations. Their strengths are constant and can be estimated using data from the ITU. The stochastic elements – those whose values exhibit random variations – are the strengths of the skywave components of the signals from the reference station and possible interfering stations, and also atmospheric noise. ITU data lets us predict both their mean values and the magnitudes of their variations at any time and place. For example, we customarily estimate the atmospheric noise level not exceeded 95% of the time [6].

The first task is to establish the signal availability requirement. We have reviewed the relevant current resolutions of the IMO [7,8], documents from the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA) [9,10] including their proposed changes to the IMO resolution A.815[11], the current US Federal Radionavigation Plan (FRP) [12] and United States Coast Guard (USCG) documentation, these are strictly only applicable within the US [13], and recent proposals for changes to the IMO documentation prepared by the European Maritime Radionavigation Forum (EMRF) [14]. Table 1 summarises the factors each document takes into account in determining availability. Thus, all sources include the availability of the reference station ("Ref Station") and most include the deterministic and stochastic factors listed above that describe the environment in which the receiver operates ("Environment"). No source, however, takes the availability of the user's receiver into account, nor the accuracy of the resulting position fix.

We decided to incorporate the reference station and environmental factors into our availability model so complying with the requirements of the most demanding sources.

The "Availability requirement" column shows the considerable variation in the requirements specified in these documents. IMO, USCG and EMRF set a single requirement, applicable everywhere. We chose to employ the IALA definition as its a development of the IMO requirements specified in resolution A.815(19). IALA not only include the 99.8% requirement for high risk areas but also include a lower 99.5% requirement for areas of single beacon coverage and lower risk. An amendment to the high risk requirement will be required when processing American radiobeacons, as their requirement is greater.

ESTIMATING A BEACON'S AVAILABILITY

Calculating availability in an environment in which a number of factors are stochastic is clearly a probabilistic process. However, although several of the documents cited give examples of such calculations, no example takes fully into account all deterministic and stochastic factors. We decided, therefore, to develop software to calculate availability values in accordance with our decisions to take reference station and environmental factors into account and to employ availability criteria of 99.8% and 99.5%.

Table 2 lists the various factors whose individual effects must be combined in determining the overall availability of the station. These factors are the availability of the reference station broadcast and the environment elements: own-skywave fading, atmospheric noise, ship's noise and skywave-borne interference. Each factor is estimated individually, then their combined effect calculated. The estimates of the environment factors are carried out point-by-point throughout an array of points centred on the reference station. This follows the practice of the widely-used Bangor coverage prediction model described in detail in [10].

Table 1

Document	Includes				Availability Requirement
	Ref Station	Environment	User's receiver	Position Accuracy	
IMO (860)	√	√	X	X	99.8% Everywhere
IALA (815)	√	X	X	X	99.8% Critical areas 99.5% All other areas
IALA (Guide)	√	√	X	X	None Specified
IALA (Draft Guide)	√	√	X	X	99.8% Critical areas 99.5% All other areas
FRP	√	√	X	X	99.9% Critical areas 99.7% All other areas
USCG	√	√	X	X	99.9% Everywhere
EMRF (App)	√	√	X	X	99.8% Everywhere

Comparison of signal availability definitions

The first stochastic factor is that of the reference station itself. IALA recommend calculating a "broadcast availability" from records of the station's *mean-time-between-failures* (MTBF) and *mean-time-to-repair* (MTTR) [10]. This broadcast availability is the percentage of time the reference station broadcasts a healthy signal. The method assumes that an unhealthy signal would be detected by the reference station's associated integrity monitor which would then switch off the transmission. The IALA target value, which we also employ in our calculations, is 99.5%.

Table 2

Event	Probability of event causing signal non-availability
Reference station broadcast	0.005
Own skywave fading	0.05
Atmospheric noise	0.05
Skywave interference	0.05

Factors that can cause non-availability of the signal. The probabilities shown are typical values, used in the example presented.

The first environment factor, strength of the reference station's signal, is not stochastic by day, but rather a fixed, deterministic, value. The signal travels by groundwave propagation. We calculate its strength at each array point by identifying the path over which the signal has arrived and taking its length and the electrical conductivity of the ground into account. At night, the signal also reaches the receiver as a skywave component. Its strength varies stochastically in a known fashion. The two components interact, giving a total signal the strength of which also varies (that is, the night-time signal fades) in a statistically-predictable fashion. We compute the field strength that is exceeded 95% of the time at the array point.

This 95% value, or the daytime field strength as appropriate, is then compared with the minimum field strength value specified by ITU [5]. By day, if the field strength at a point falls short, availability there is always zero. Own-skywave fading at night is the second of the stochastic factors listed in Table 2 whose probability of causing non-availability we need to know. We compute the probability of the field strength's failing to meet the ITU criterion, using Poppe's observation that the probability distribution of skywave strengths is close to Gaussian [15].

The third factor listed in Table 2 is atmospheric noise. This varies stochastically in the short term around a mean value that depends on the time of day, season of the year, location, and frequency. We calculate at each point in the array the atmospheric noise level at 300kHz not exceeded 95% of the time throughout the year. Using this noise value, and either the daytime or the night-time beacon field strength as appropriate, we then compute the signal-to-atmospheric noise ratio there. Finally, using curves from [6], we estimate the probability of the SNR's failing to meet the minimum value of 7dB and so causing the signal to become unavailable.

The remaining factor affecting availability is interference. In Europe, a large number of radiobeacons are packed into a relatively narrow frequency band. Despite careful frequency planning [16], the level of interference may cause the signal-to-interference ratio (SIR) to fall below 7dB, causing non-availability. By day, interference is received via groundwave propagation only and its value is deterministic. The software estimates the field strengths at the array point of all potential groundwave interferers. Taking their individual frequencies into account, it determines whether any of them causes the SIR limit to be breached. If so, availability at that array point is always zero. This happens in only a few, very small, areas. More commonly, strong interference is received at night via skywave propagation. We again estimate the strength of each potential interferer, computing the value not exceeded 95% of the time. Using this interference level and the night-time beacon field strength we compute the SIR. Finally, we estimate the probability of the SIR's failing to meet the minimum value of 7dB and so causing the signal to be unavailable. This is the fourth stochastic factor listed in Table 2.

We now compute the overall availability of the signal at each array point, taking into account these four factors. A programme of measurements has established that non-availability events due to these various phenomena are essentially independent and uncorrelated. Equation 1 thus states that the overall availability of the signal is the reciprocal of the product of the probabilities of the individual events that can cause non-availability.

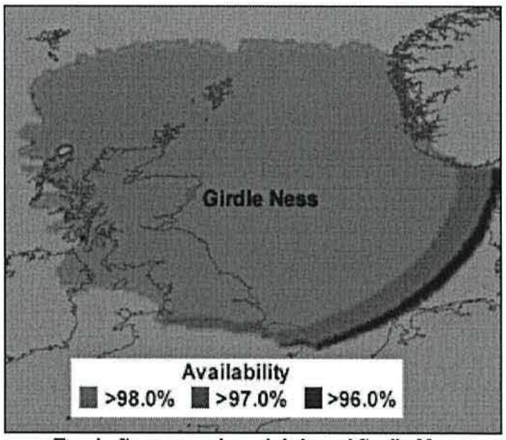

Fig. 1. Contours of availability of Girdle Ness radiobeacon by day.

$$\boxed{Signal\ availability = \prod_{i=1}^{N}(1 - P(event_i\ occurring))} \quad (1)$$

Consider the example values in the right-hand column of Table 2, each of which shows a typical probability that the corresponding event can occur, resulting in non-availability of the signal; for instance, the probability of the atmospheric SNR ratio falling below 7dB is 0.05%. Applying equation 1, we calculate that with these values the overall availability is 0.85, or 85%. This figure is for a position at the extreme boundary of coverage where the field strength has fallen to 20dBµV/m. However, many administrations measure availability at the nominal range where the field strength is either 34 or 37.5 dBµV/m. At this range the availability will, of course, be much greater.

Fig. 1 has been plotted using this method. The reference station is at Girdle Ness on the north-east coast of Scotland. Daytime conditions are assumed; thus, own-skywave fading and skywave-borne interference are assumed to be zero. The colours are contours of overall availability values, assuming a broadcast station availability of 99.5% and computing the effects of atmospheric noise and ground-wave interference. As would be expected, the availability figures are highest close to the beacon where the SNR and SIR values are greatest. The outer boundary of the plot is the coverage limit [5], that is, the area within which the reference station field strength exceeds the ITU minimum, the atmospheric SNR and interference SIR values both exceed 7dB, and no groundwave interferer breaches a protection ratio.

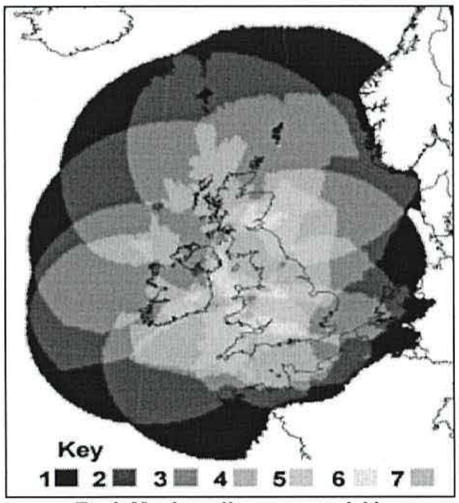

Fig 2. Number of beacons available

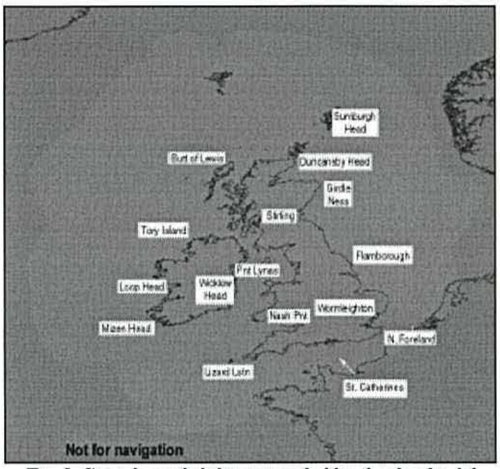

Fig 3. Signal availability provided by day by the 16 beacons planned for the UK and Ireland. Light blue = 99.8% critical areas requirement is met.

AVAILABILITY WITH MULTIPLE BEACONS

Over large geographical areas, multiple beacon signals that meet the coverage criteria can be received. Fig. 2 shows the number of such beacons point-by-point across the combined coverage of the system of 16 beacons planned for the United Kingdom and Ireland. Because of redundancy they afford, multiple stations provide much greater availabilities than can a single station, which is in any case limited to 99.5% by the availability of its own broadcast signal. At each location we calculate the availability of the service provided by a system of beacons by estimating their individual availabilities and computing the probability that they will all fail simultaneously. The reciprocal (equation 2) is the availability of the multi-beacon system at this location.

In creating Fig. 3 we have computed this availability at each point and compared it with the two standards: 99.8% (in critical areas) and 99.5% (other areas). The lighter blue regions are those in which the calculated availability exceeds 99.8%.

AVAILABILITY OF BEACONS ACROSS THE EUROPEAN MARITIME AREA

The new software has been employed to model for the first time the combined availability of the service from

$$\boxed{Combined\ availability = \prod_{i=1}^{N}(1 - signal\ availability\ from\ beacon_i)} \quad (2)$$

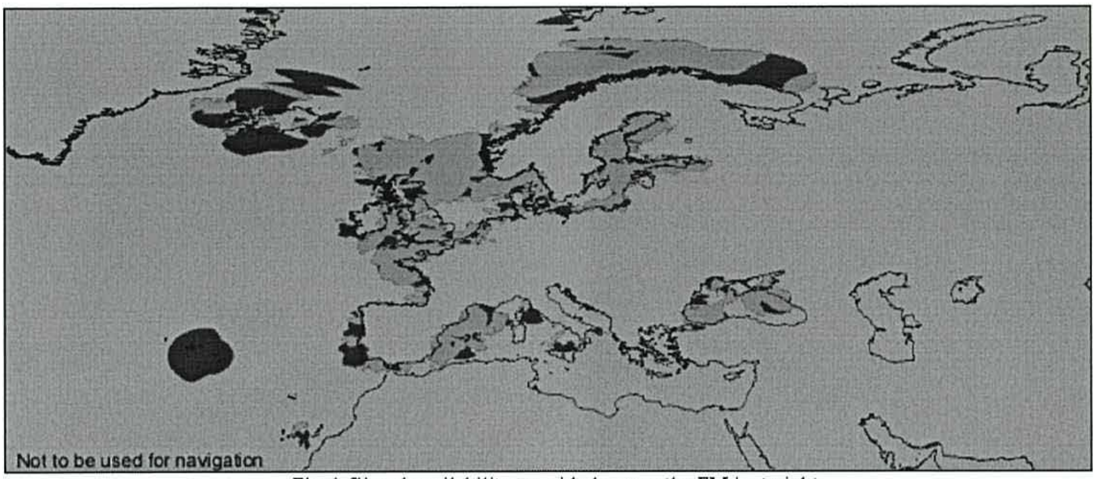

Fig 4. Signal availability provided across the EMA at night.
Light blue = 99.8% critical areas requirement is met, Dark blue = 99.5% other areas requirement is met.

the 158 DGNSS radiobeacons either currently installed, or listed in the current frequency plan, across the European Maritime Area (EMA) of the ITU.

In Fig. 4 the colours represent the 99.8% and 99.5% standards as before. The plot is for night-time conditions, when both unwanted fading of the beacons and skywave-borne interference are at their greatest. Note that this lower 99.5% availability can never be achieved by a single beacon when environmental factors are taken into account in addition to the beacon's own 99.5% availability. Thus at least two beacons are required to reach 99.5% availability. Fig. 5 shows the corresponding plots under the more beign daytime conditions.

The highest availability value anywhere is greater than 99.99999%. It is achieved during daytime in an area of the North Sea at which 23 beacons simultaneously provide coverage! The availability specifications are set over a two year period. Across the EMA we calculated the average percentage of time which is day, to be approximately 43% and night to be approximately 57%. These percentages were then used to calculate the overall availability for the year. The result of which is shown in figure 6.

CONCLUSIONS

We have examined the definitions of the availability of radiobeacon DGNSS stations in various authoritative sources. While there are differences between them in respect of both the factors claimed to affect availability and the probability values to be used to define a service area, it is possible to establish a sensible set of standards.

Fig 5. Signal availability provided across the EMA by day.
Light blue = 99.8% critical areas requirement is met.

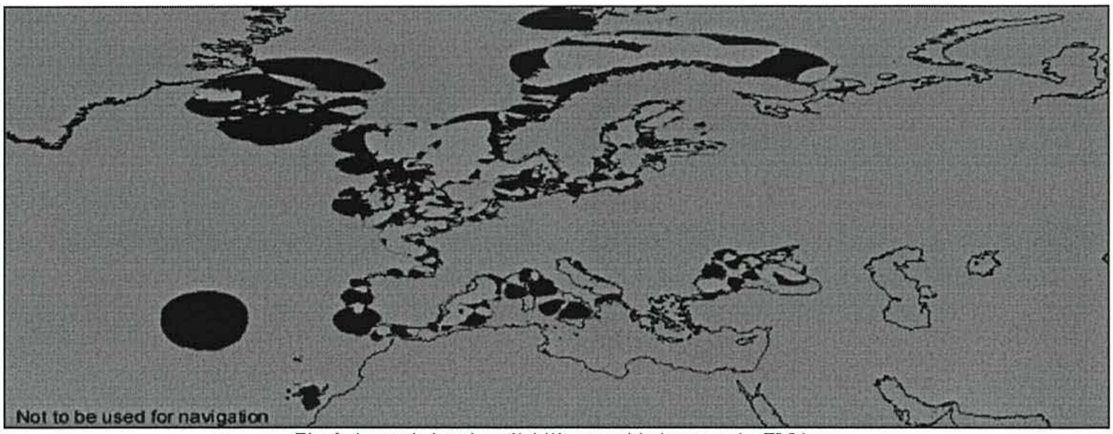

Fig 6. Annual signal availability provided across the EMA.
Light blue = 99.8% critical areas requirement is met, Dark blue = 99.5% other areas requirement is met.

We then consider how to handle the various deterministic and stochastic elements that together determine availability. These include the availability of the reference station broadcast, which is a function of its mean-time-to-fail and mean-time-to-repair. They also include the environmental factors specific to the receiver's location: the strength of the reference station signal, its own-skywave fading at night, atmospheric noise and interference received via both groundwave and skywave paths.

Each of these factors is considered individually, using techniques taken from the Bangor coverage prediction model. A method for combining their individual contributions to give the non-availability of the signal is then presented.

A novel software package has been developed which embodies these techniques. It allows the signal availabilities of both single stations, and systems of stations, to be calculated and plotted for the first time. The availability values can also be compared with international standards. The results are presented in a pictorial form designed to allow administrations when planning networks to see clearly where their DGNSS services meet international requirements.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data*, IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radiobeacons for the Broadcast of Differential GPS Data*, Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services*, Issue 7 – August 1999.
4. Last, J.D, Grant A.J. & Ward, N., *Radiobeacon DGNSS Station Selection Strategies – Can We Do Better?*, ION National Technical Meeting, Long Beach, CA, USA, 22-24 January 2001
5. International Telecommunication Union, *Final Acts of the Regional Administrative Conference for the planning of the Maritime Radionavigation Service (Radio-beacons) in the European Maritime Area*, Geneva, 1985.
6. International Telecommunication Union, *Radio Noise*, ITU-R P.372-7, 2001.
7. International Maritime Organisation, Resolution A.815 (19), *World-Wide Radionavigation System*, November 1995
8. International Maritime Organisation, Resolution A.860 (20), *Maritime Policy for a Future Global Navigation Satellite System (GNSS)*, November 1997.
9. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Guidelines for the performance and monitoring of a DGNSS service in the Band 283.5 - 325 kHz'*, March 1999
10. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), 'Draft Recommendation on the performance and monitoring of DGNSS services in the frequency band 283.5 – 325KHz', June 2001
11. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Draft Revision of IMO Resolution A815(19)'* Nav 47/../.., 31st March 2001.
12. United States Department of Defense & Department of Transportation, *Federal Radionavigation Plan* 1999.

13. United States Coast Guard, *'Broadcast Standards for the USCG DGPS Navigation Service'*, COMDTINST M16577.1 April 1993.
14. European Maritime Radionavigation Forum, *'Adoption of revised "Applications and User Requirements"'*, DOC EMRF 6/9/1, July 2001.
15. Poppe, D.C., *Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions*, Ph.D. Thesis, University of Wales, Bangor, October 1995.
16. Last, J.D. & Turhan, B.E., *European radiobeacon DGNSS - Making the most of the frequency band,* Journal of the Royal Institute of Navigation, 52, 2, pp176-188, May 1999

Marine Radiobeacon DGNSS Service - Predicting Availability and Continuity

Alan Grant and David Last, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*

BIOGRAPHIES

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Institute of Navigation, the Royal Institute of Navigation, the Institute of Electrical and Electronic Engineers and the Institution of Electrical Engineers.

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and former Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, a Chartered Engineer, and Vice-President of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

Dr Nick Ward is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in Radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

ABSTRACT

The maritime radiobeacon differential GNSS service in Europe has expanded very rapidly in the last two years. In September 2001, a new frequency plan was brought into effect across the whole of the European Maritime Area (EMA). This has resulted in reduced levels of interference and enhanced coverage. There are now 162 maritime differential beacons positioned so that, as far as possible, all critical coastal locations are served by at least two stations.

Recently, maritime administrations agreed specifications for the levels of availability and continuity the service should provide. These values depend on whether the location is oceanic, coastal, a harbour approach, or an inland waterway. However, although there have long been software tools for computing the coverage of radiobeacon differential systems, there has been no such tool that administrations could employ to predict availability or continuity. This paper addresses that shortcoming. It describes a novel approach to these key parameters that takes into account beacon availability figures and combines them with propagation factors including groundwave signal attenuation, interference, and skywave fading at night.

We then propose a novel way of assessing availability and continuity, and embody these principles in a computer model. The resulting software tool maps the availability and continuity of the service enjoyed by users. It accommodates both individual beacons and networks of beacons in a way that allows administrations to see whether their systems meet the standards. Availability and continuity maps produced by the new programs are presented in the paper.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the satellites' pseudorange errors. They transmit corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, marine radiobeacons, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, more than one DGNSS beacon can generally be received [3], which enhances signal availability and continuity for the user.

IMO resolutions stipulate the minimum signal availability and continuity that should be provided at critical, and less critical, locations. This paper considers these requirements together with other sources of availability and continuity specifications. We then take software designed to plot the coverage and performance of DGNSS radiobeacons [4] and extend it to map the locations where both individual beacons and groups of beacons meet these service standards. The diagrams presented in this paper are examples of the use of this technique. The beacons employed in them are not necessarily those currently in operation.

DEFINITIONS OF AVAILABILITY

Availability is the percentage of time a signal at a location is usable. Being "usable" means meeting minimum criteria for coverage set out by the International Telecommunication Union (ITU) [5]. In Europe, these criteria are that the field strength must be not less than 20dBμV/m (or a higher figure specified by the national administration) and the signal-to-noise ratio (SNR) not less than 7dB. In addition, no interfering signal may exceed specified protection ratios that depend on its frequency separation from the beacon's signal.

Included in these criteria are both deterministic and stochastic elements. The deterministic elements are the strengths of the groundwave-propagated signals received from the reference station, and possibly from interfering stations too. Their strengths are constant and can be estimated using data from the ITU. The stochastic elements – those whose values exhibit random variations – are the strengths of the skywave components of the signals from the reference station and possible interfering stations, and also atmospheric noise. ITU data lets us predict both their mean values and the magnitudes of their variations at any time and place. For example, we customarily estimate the atmospheric noise level not exceeded 95% of the time [6].

The first task is to establish the signal availability requirement. We have reviewed the following documents: the relevant current resolution of the IMO [7]; a proposal from the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA) to amend IMO A.815 (19) [8]; the current US Federal Radionavigation Plan (FRP) [9] and United States Coast Guard (USCG) documentation [10] (both only strictly applicable within the US. Table 1 summarises the factors each document takes into account in determining availability. Thus, all sources include the availability of the reference station ("Ref Station"). Most also include the deterministic and stochastic factors listed above that characterise the environment in which the receiver operates ("Environment").

These factors are not always identified explicitly. Rather, the documents make it clear that the availability specifications they propose apply across the whole area of the beacon's coverage. So they must include regions adjacent to the coverage boundary, where the field strength and signal-to-noise ratio are at their lowest.

We decided to incorporate the reference station and environmental factors into our availability model thus complying with the requirements of the most demanding specifications.

The "Availability Requirement" column shows the variation in the numerical requirements in these documents. Both the IMO and FRP set two standards applicable for high and low risk areas, whereas the USCG set a single value, applicable everywhere. We chose to employ the IMO definition, as a world body. They not only include the 99.8% requirement for high risk areas, but also a lower 99.5% requirement for areas of single beacon coverage and lower risk. An amendment to the high-risk requirement will be required when processing US radiobeacons, as the US specification is tighter.

Table 1

Document	Includes		Availability Requirement
	Ref Station	Environment	
IMO A.915(22)	√	√	99.8% Critical areas 99.5% All other areas
IALA (815)	√	X	99.8% Critical areas 99.5% All other areas
FRP	√	√	99.9% Critical areas 99.7% All other areas
USCG	√	√	99.9% Everywhere

Comparison of signal availability definitions

ESTIMATING BEACONS' AVAILABILITIES

Calculating the availability in an environment in which a number of factors are stochastic is clearly a probabilistic process. However, although several of the documents cited give examples of such calculations, none of those examples takes fully into account all deterministic and stochastic factors. We decided, therefore, to develop software to calculate availability values in accordance with our decisions to take reference station and environmental factors into account and to employ availability criteria of 99.8% and 99.5%.

The stochastic events with which we are concerned are the beacon's own periods off-air, a rise in atmospheric noise or skywave-borne interference, and self-fading. The other, deterministic, events have already been taken into account when coverage was predicted; they do not affect availability.

Clearly, we require a statistical approach to modelling the effects of multiple stochastic elements. Poppe [11] has shown that skywave field strength has a Gaussian probability distribution. She provides data from which the mean and standard deviation values of the skywave components of both the wanted beacon and interfering signals can be calculated. Similarly, the mean and standard deviation of the atmospheric noise can be obtained from the ITU noise data [6]. Atmospheric noise, however, has a two-sided distribution. Both sides closely fit Gaussian distributions but with different standard deviations. However, only one side of the distribution is involved when excessive noise causes loss of availability, so we can treat noise as having a single Gaussian distribution.

Poppe calculated the effect of self-fading on the resulting field strength of the beacon. She developed a technique of calculating this effect for a given ratio between skywave and groundwave signal strengths. Nominally the 95% fading curve is employed when predicting coverage. However, by calculating the difference in the fading between the 95%-ile curve and the 50%-ile curve (Δfade), the standard deviation can be calculated. By assuming a Gaussian distribution the following equation applies:

$$\sigma = \frac{\Delta fade}{1.65} \tag{1}$$

where σ is the standard deviation, *Δfade* is the difference between the 95% and 50% curves and *1.65* is the constant for obtaining the standard deviation of a Gaussian distribution.

By using the mean and standard deviation values of both the wanted beacon's skywave signal and the atmospheric noise, the probability of the SNR's exceeding the 7dB threshold can be calculated. In the same way, we can compute the probability of the SIR's exceeding its protection ratio, from knowledge of the mean and standard deviation of the strongest interferer's skywave signal. In this new method, a new distribution 'b' is generated from both means and standard deviations. The probability of this new distribution exceeding the relevant SNR or SIR floor is then calculated by:

$$Pr(b \geq c) = 1 - \Phi\left(\frac{c - (\mu_s - \mu_n)}{\sqrt{\sigma_s^2 + \sigma_n^2}}\right) \tag{2}$$

where c is the SIR or SNR floor, μ_s is the mean of the beacon's signal, μ_n is the mean of the noise signal (atmospheric noise or interference), σ_s is the standard deviation of the beacon's signal, σ_n is the standard deviation of the noise signal (atmospheric noise or interference) and Φ is the standard normal cumulative distribution function, given by:

$$\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{\frac{-t^2}{2}} dt . \tag{3}$$

Using this equation at each location, the probabilities of exceeding the SNR and SIR floors are calculated, along with the beacon's availability. The actual beacon availability is recorded by system administrators. In this paper an example figure of 99.5% will be employed. These three probabilities are then combined using:

$$\text{Avail}_{\text{signal}} = \prod_{i=1}^{n} (1 - P(\text{event}_i \text{ occurring})) \tag{4}$$

which results in a single availability figure at each location. In locations where more than one beacon provides coverage simultaneously the choice of beacons will result in greatly enhanced availability. We have demonstrated by means of a measurement programme that the various failure mechanisms are essentially uncorrelated. The final availability figure at such locations is therefore:

$$Availability = \prod_{i=1}^{n} (1 - \text{Avail}_{\text{signal}_i}) \tag{5}$$

'TWO YEARS' STANDARDS

The specifications require availability to be measured over a two-year period. The IALA example figure for availability from [8], makes no distinction between day and night operation. However, we have made the assumption that scheduled maintenance is carried out by day only; that reflects reality. Thus, although the overall beacon availability remains at 99.5%, the daytime value falls to 99.19% while the night-time value rises to 99.71%.

Fig. 1: Daytime service availability provided by the 16 beacons of the United Kingdom and Ireland. Light blue = 99.8%, Dark blue = 99.5%

Fig. 1 shows the daytime availability provided by the 16 beacons of the United Kingdom and Ireland, using these assumptions. The light blue regions show that the higher requirement of 99.8% over two years has been met; this is the case in all coastal regions. Fig. 2 shows the corresponding night-time plot. The radiobeacons' coverage areas are reduced by self-fading, interference, and an increase in atmospheric noise.

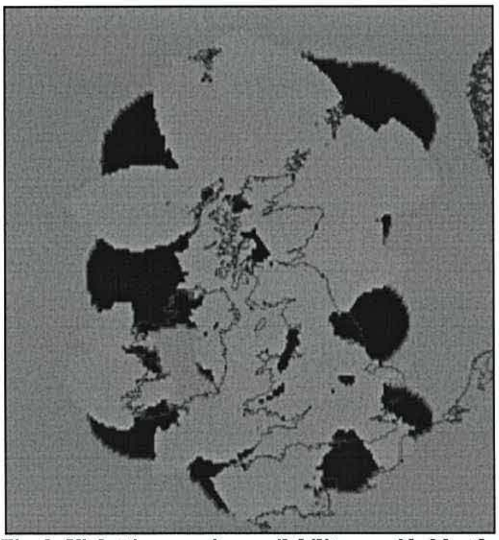

Fig. 2: Night-time service availability provided by the 16 beacons of the United Kingdom and Ireland. Light blue = 99.8%, Dark blue = 99.5%

Again areas coloured light blue are provided with a service which is available 99.8% of the time. In those coloured dark blue, the lower 99.5% requirement has been met. The majority of coastal regions still enjoy the higher 99.8% availability. Most other regions get the lower 99.5% requirement.

Now we combine these two plots into a single availability plot. Across the EMA, we estimated that the average percentage of the two-year period when daytime radio conditions apply is 43%; night-time conditions apply for 57%. We combine the day and night figures in accordance with these weightings to create the 2-year availability results for the 16 beacons of the United Kingdom and Ireland.

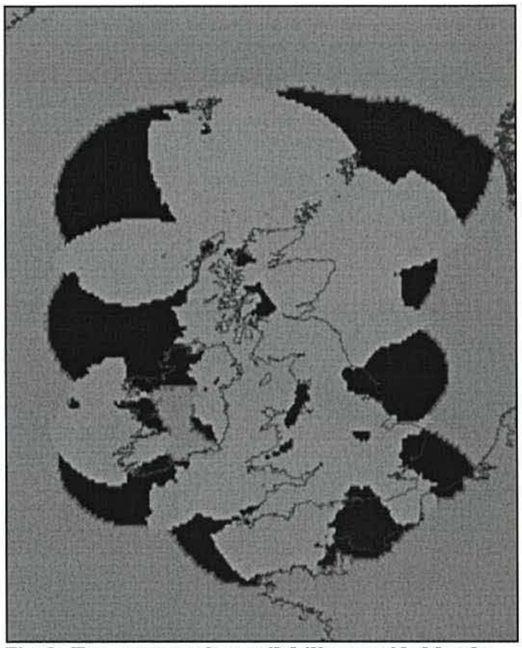

Fig. 3: Two-year service availability provided by the 16 beacons of the United Kingdom and Ireland. Light blue = 99.8%, Dark blue = 99.5%

Fig. 3 shows the result: much to the delight of the system administrators, the majority of the coastal regions are provided with a service that meets the 99.8%, 2-year, standard. Most other regions are provided with a service that meet the lower 99.5% standard. Where this standard does not appear to be met, it is achieved once additional beacons on the continent are taken into account.

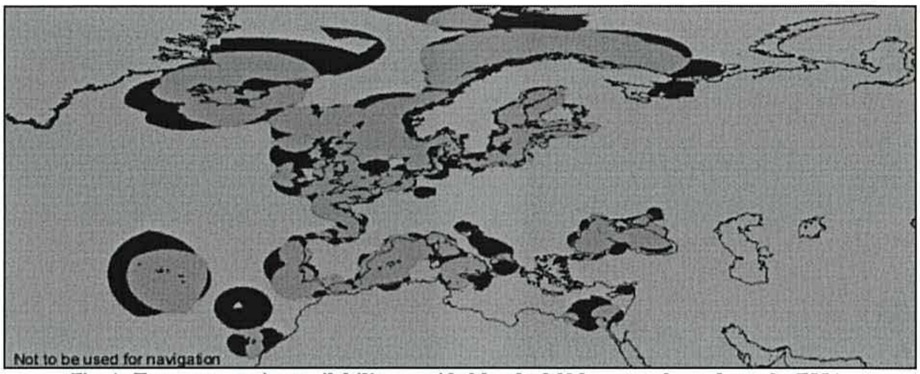

Fig. 4: Two-year service availability provided by the 162 beacons throughout the EMA. Light blue = 99.8%, Dark blue = 99.5%

The model was now employed to calculate two-year availability for the service provided by the full 162 beacons of the European Maritime Area (Fig. 4). Again, the majority of coastal areas are provided with a service available 99.8% of the time. This includes the important coastal areas of the North Sea, the English Channel and the north coast of the Mediterranean Sea. The majority of the remaining coastal regions are provided with a service that meets the lower 99.5% requirement.

DEFINITIONS OF CONTINUITY

The authorities who specify availability standards also set standards for continuity, summarised in Table 2. Again, there are substantial variations!

IMO [7], and IALA's proposed revision of IMO resolution A.815(19) [8], set a 99.97% requirement for high-risk areas, and a lower 99.85% requirement for areas of lower risk and single beacon coverage. The FRP standard for continuity (they call it *reliability*) is that the *number of outages per site will be less than 500 in one million hours of operation* [9]. As a continuity requirement this is vague, since there is no indication as to the minimum duration of an outage. Similarly, the USCG specify the reliability of the system in terms of a number of manoeuvres of different durations, and the corresponding numbers of outages allowed per million hours. But, again, no indication is given to what constitutes an outage.

In our judgement it is appropriate to employ the 99.97% and 99.85% IMO values: they are world values, rather than US national ones. IMO also make it clear that they calculate continuity over three hours, as opposed to "1 year" or "1 million hours". Since continuity is to do with providing guidance for the whole of a manoeuvre such as port entry and docking, this 3-hour definition appears appropriate, given that such manoeuvres typically take three hours or less [12] A 'realistic' figure according to [8].

As with availability, only the stochastic factors affect continuity: beacon service, atmospheric noise, self-fading and skywave-borne interference.

Document	Continuity Requirement	Calculation Period
IMO A.915 (22)	≤99.97% High risk areas ≤99.85% All other areas	3 hours
IALA (815)	≤99.97% High risk areas ≤99.85% All other areas	3 hours
FRP	The number of outages per site will be less than 500 in one million hours of operation	
USCG	Manoeuvre Category (seconds)	Reliability (Outages/Mhr)
	<140	2000
	140 to 280	1000
	280 to 560	50

Table 2: Continuity specifications and periods

BEACON CONTINUITY

The beacon's continuity can be calculated in accordance with a method given in the IALA guidelines [13]. The continuity is calculated using:

$$continuity = 1 - \left(\frac{CTI}{MTBF} \right) \tag{6}$$

where *CTI* is the continuity time interval (three hours in this case) and *MTBF* is the mean time between failures, in hours. When calculating beacon continuity, it is assumed that there are no scheduled outages for the duration of the manoeuvre. This assumption is based on the fact that scheduled outages are announced in advance. Thus, no manoeuvre that depends critically on the system should be commenced if the system is forecast to be unavailable for any part of the duration of the manoeuvre. Continuity failure occurs where a manoeuvre has been commenced and then cannot be completed because the system fails.

Using the example from [8] and assuming the lowest beacon availability of 99.5%, the corresponding MTBF calculated would be approximately 1946 hrs. This number would be the same under both day and night conditions. From this we calculate a beacon continuity of 99.85%:

As with availability, the probability of a failure due to a rise in atmospheric noise, self-fading or skywave interference decreases the closer the receiver is to the beacon. Continuity behaves in the same way: close to the beacon, the beacon's continuity dominates.

ATMOSPHERIC NOISE

Calculating the effect of atmospheric noise on continuity is considerably more difficult than calculating the effect of the beacon's continuity. Since atmospheric noise is stochastic and difficult to predict, even knowing the standard deviation and mean value does not suffice. They tell us the percentage of the time that atmospheric noise will cause non-availability, but they give us no information as to the distribution in time of those failures. We do not know the MTBF, for instance. Thus we cannot directly use this information to compute the effect of atmospheric noise on continuity. We need to develop a different approach.

Atmospheric noise consists of two parts: random spikes of relatively high intensity, and continuous background noise of lower intensity. The high-intensity random spikes are what predominately disrupt the service. To calculate their effect on continuity, one needs a measure of the mean time between these spikes and thus of the relationship between MTBF of the message and SNR. To measure these factors with a high level of confidence would require data to be measured over a long period. No such set of data appears ever to have been recorded. However, indirect evidence is available from Poppe's research [11]. Poppe studied atmospheric noise extensively and recorded the variation of word error rate (WER) with SNR, as shown in Fig. 5.

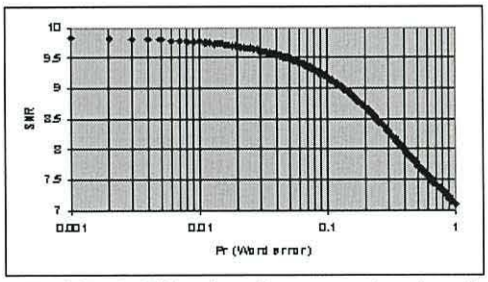

Fig. 5: Probability of word error as a function of SNR.

Poppe recorded this data in a quiet location using a transmitter (with negligible propagation effects) and a conventional differential beacon receiver. Noise was off-air atmospheric noise. Her measurements show that an SNR of 7dB, the ITU threshold, corresponds to a fairly high probability of word error. However, we see that by 9dB errors are rare. Thus Poppe's results appear accurate enough to give us a good estimate of the effects of atmospheric noise on continuity.

We use Poppe's word error rate (WER) results to calculate the probability of the service's becoming unavailable due to noise. This can be done knowing the number of words in each message. The probability of a message being received is given by:

$$\Pr(success) = \left[1 - \Pr(word\ error)\right]^{W} \qquad (7)$$

where, W is the number of words (7 in the case of a Type 9-3 message), and Pr means probability. Fig. 6 plots this probability of message success against the signal-to-noise ratio. An SNR of 8.5dB appears to result in only 1 message in 10 being received successfully.

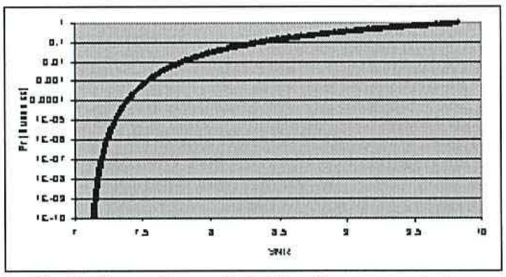

Fig. 6: Shows the probability of a message being successful as a function of SNR.

Since Selective Availability (SA) was set to zero, spatial decorrelation has become the dominant source of error in GPS. This error is caused by atmospheric delays, which vary very slowly in time. The minimum frequency of RTCM messages is now set by the desire to meet the time-to-alarm requirement of 10s [14]. Since each Type 9-3 message takes 2.1s to transmit, missing four or more consecutive messages would constitute a failure. The probability of four successive messages failing can be calculated using the results from Fig. 6 and the following equation:

$$\Pr(failure) = (1 - \Pr(success))^{4} \qquad (8)$$

Fig. 7 plots, against signal-to-noise ratio, the probability of failing successfully to receive any one of four consecutive messages. Clearly, this graph shows that in areas where the SNR is greater than 9dB, the probability of failure is extremely small. There is only 2dB difference between this 9dB and the ITU minimum SNR of 7dB.

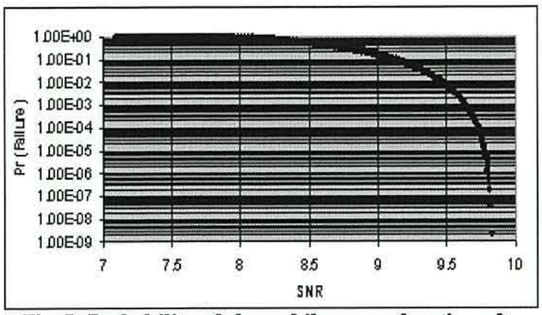

Fig. 7: Probability of alarm failure as a function of SNR.

This method lets us calculate the probability of a short-term unavailability of the service due to a rise in atmospheric noise. This probability is used directly in the calculation of continuity to represent the probability of atmospheric noise disrupting the service.

SKYWAVE INTERFERENCE

Like atmospheric noise, skywave interference is stochastic and can affect the continuity of the signal. Again simple measures of statistical distribution are meaningless in this context of continuity, since we need to know the time between failures. As with atmospheric noise, no long-term data records are available from which we can compute an MTBF or its dependence on SNR. Such measurements would in practice be difficult to make in the radiobeacon band since it would be essential to separate the skywave interfering signal from all other unwanted skywave signals and from atmospheric noise.

The approach we will take is to assume that, for a given SNR, the probability of an error due to "noise" being skywave interference is the same as if the noise were atmospheric noise. We then use the same continuity/SNR relationship as for atmospheric noise (Fig. 7). Again, since there is a rapid change of error rate over just a small number of dB of SNR, this approximation is unlikely to result in significant errors.

In the case of SIR, however, the lowest value that should ever be encountered within the coverage area is 15dB, the edge-of-coverage limit. Thus, while there will undoubtedly be a finite probability of message failure due to skywave interference, it will be extremely small, and insignificant in comparison with the other two factors studied. The result of our analysis, therefore, has been to demonstrate that we do not need to take skywave interference into account in computing continuity.

SELF-FADING

Self-fading, due to the interaction between the deterministic groundwave signal and the stochastic skywave signal, gives a stochastic result. We are again interested in the frequency between occasions when it disrupts the service. Again, the necessary large volume of experimental data to establish the relationship accurately is not available.

We have adopted the following method of taking into account the effect of signal fading on continuity. When calculating the SNR and SIR values used to determine the continuity figure, we employ a reduced beacon field strength due to fading. The value used at each point is the strength exceeded 95% of the time [11]. This 95%-ile figure is, of course, the same one used to establish the outer edge of the beacon's coverage.

Fig. 8: Daytime 3-hour service continuity for the 16 beacons of the UK and Ireland.

Fig. 9: Night-time 3-hour service continuity for the 16 beacons of the UK and Ireland.

Light blue = 99.97% (critical areas requirement met), Dark blue = 99.85% (other areas requirement met).

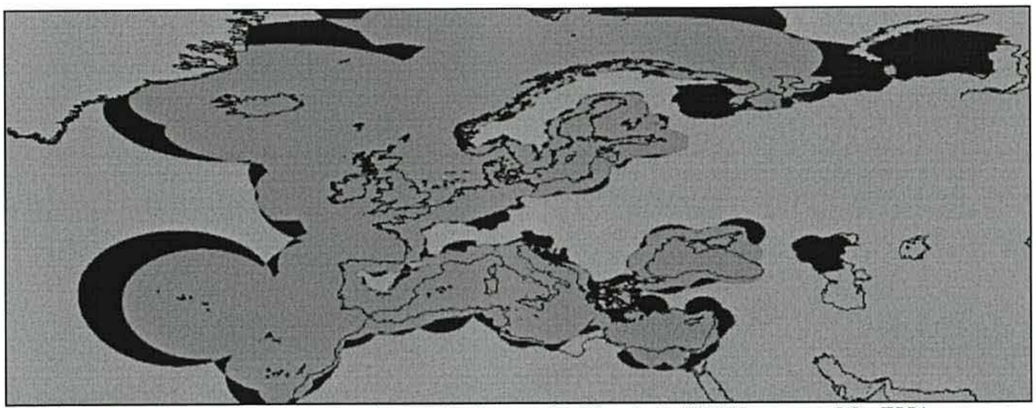

**Fig. 10: Daytime 3-hour service continuity provided by the DGNSS beacons of the EMA.
Light blue = 99.97% (critical areas requirement met),
Dark blue = 99.85% (other areas requirement met).**

CONTINUITY RESULTS

Figures 8 and 9 show the results for the 16 beacons of the United Kingdom and Ireland, for daytime and night-time respectively. The conventions are the same as for availability: light blue shows where the beacons provide the higher level of service continuity (99.97%) and dark blue the lower requirement (99.85%). Meeting the higher standard requires more than one beacon to provide coverage simultaneously. Just a single beacon is sufficient to meet the lower standard.

Fig. 8 shows that, as with availability, meeting the higher continuity requirement by day is not a problem. In all coastal and inland locations multiple beacons provide coverage simultaneously and the 99.97% requirement is met easily.

By night, in contrast, with the reduction of beacons' coverage areas due to self-fading and the rise in skywave interference and atmospheric noise, we see substantial reductions in the areas in which both standards are met. By night, fewer coastal areas are provided with a service that meets the 99.97% continuity standard, but in all other coastal regions the lower 99.85% is achieved.

Figs. 10 and 11 show the daytime and night-time continuity results, respectively, for the whole EMA.

Again, by day, all coastal regions meet the higher 99.97% continuity requirement. Fig. 11 shows the now familiar night-time reduction. But in most coastal regions the 99.97% standard is achieved, with the other areas getting the lower-standard service.

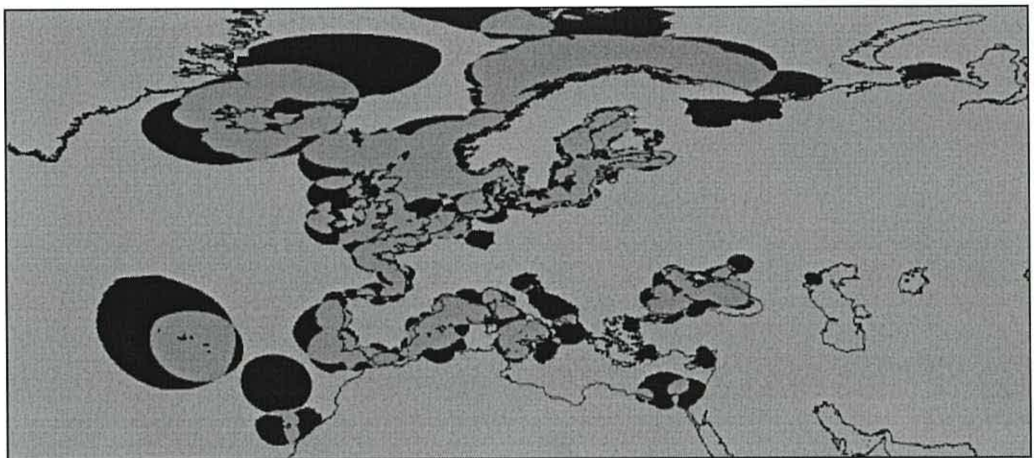

**Fig. 11: Night-time 3-hour service continuity provided by the many beacons of the EMA.
Light blue = 99.97% (critical areas requirement met),
Dark blue = 99.85% (other areas requirement met).**

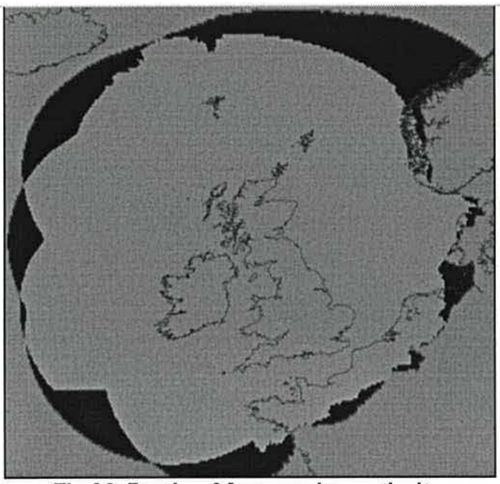

Fig. 12: Daytime 3-hour service continuity.
Light blue = 99.97% (critical areas requirement met), Dark blue = 99.85% (other areas requirement met).

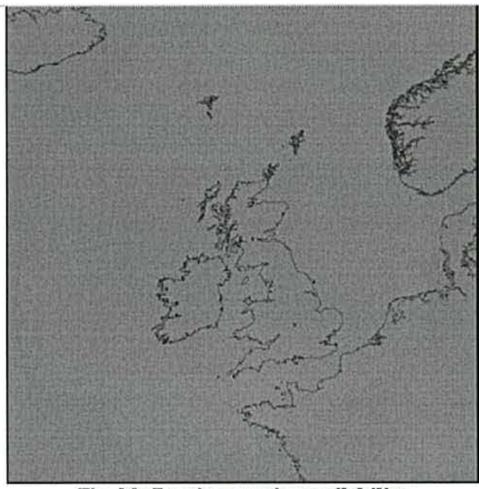

Fig. 13: Daytime service availability.
Light blue = 99.8% (critical areas requirement met), Dark blue = 99.5% (other areas requirement met).

Fig. 14: Daytime service meets coverage, availability and continuity requirements.

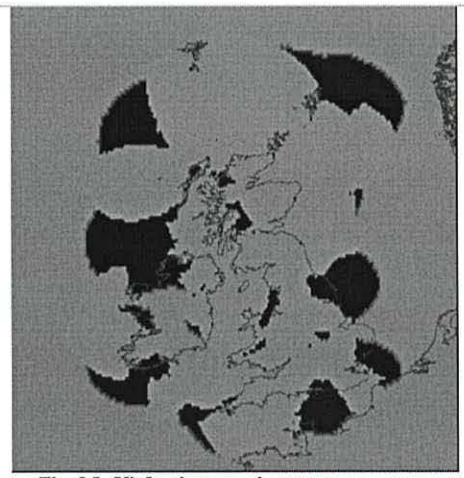

Fig. 15: Night-time service meets coverage, availability and continuity requirements.

Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%.
Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

SERVICE STANDARDS

The set of service standards we have calculated at each location includes the coverage criteria, the availability standards and the continuity standards. For a service to be satisfactory, all these must be met. Taking the 16 beacons of the United Kingdom and Ireland, let us first compare the new continuity results (Fig. 12) with the availability results computed earlier (Fig. 13). It is clear that the service meets the continuity requirements in areas where it fails to meet the availability requirements. In such areas the service is available for 3-hour periods of time, but is not available 99.5% of the time over two years. We conclude that the availability criterion is the more stringent one.

We are now in a position to examine all service criteria and plot the regions in which the service meets all three standards: coverage, availability and continuity. Fig. 14 shows the results by day for the 16 beacons of the United Kingdom and Ireland and Fig. 15 shows the equivalent night-time results.

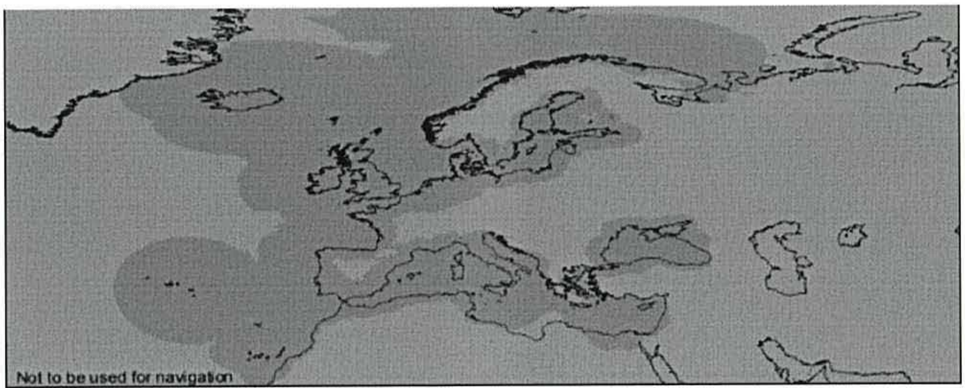

Fig. 16: Daytime service meets coverage, availability and continuity requirements. Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%. Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

Fig. 17: Night-time service meets coverage, availability and continuity requirements. Light blue = regions where availability exceeds 99.8% and continuity exceeds 99.97%. Dark blue = regions where availability exceeds 99.5% and continuity exceeds 99.85%

Because the availability requirements are more stringent than the continuity ones, Figs. 14 and 15 are identical to the corresponding day and night availability plots. Figs. 16 and 17 show the equivalent plots for the DGNSS beacons of the EMA.

Fig. 16 shows, with the figures used which include the IALA example values in the case of the beacon, by day all of coastal regions of the EMA are provided with a service which meets the higher standards for coverage, availability and continuity. By night (Fig. 17), when coverage areas are reduced, the majority of the coastal regions are still provided with a service which meets the more stringent requirements. In those regions where these conditions are not met, the service nevertheless meets the requirements for areas of low-risk and single beacon coverage.

CONCLUSIONS

This paper has demonstrated the processes involved in predicting the availability and continuity of a maritime radiobeacon DGNSS service. It has shown that predicting availability is a complex process involving many elements. A novel method is described and employed for the first time, that statistically combines the means and standard deviations from these stochastic elements to calculate the availability of not only each beacon, but the overall service availability provided at each location by multiple beacons. Data regarding the statistical distributions of atmospheric noise and skywave interference were obtained from referenced material, whilst the statistical data for the self-fading was derived by greatly expanding the work of Poppe.

Then, for the first time continuity has been examined. We see that the same events that affect availability, affect continuity. Each of these events has been examined. Without knowing, or being able to calculate, an MTBF for each signal-to-noise ratio, it is impossible to calculate precisely their effects on continuity. But an alternative approach has been pioneered, based on the work of

Poppe. Her research has shown us the dependence of word error rate (WER) on signal-to-noise ratio. From this we have developed a way of estimating the probability, for a particular SNR, of missing a message. We then define a failure as failing to receive four consecutive messages. Using this method we calculated the probability of such a failure as a function of SNR, and hence the effect of that failure on continuity. This is done for atmospheric noise and the process repeated for skywave interference. However, the latter is shown to have a negligible effect on continuity. The effect of self-fading is taken into account when calculating the night-time field strength for use in the appropriate SNR and SIR ratios. In this way continuity values are estimated and compared with the international standards.

For the first time, it is now possible for administrations, service providers and other bodies, to plot where the marine radiobeacon DGNSS service meets all the standards: coverage, availability and continuity. The results show where the beacons should provide a safe and reliable service.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland. The authors would also like to thank Dr L. Kuncheva and Mr C. Whitaker for their assistance and guidance.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data,* IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radiobeacons for the Broadcast of Differential GPS Data,* Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services,* Issue 7 – August 1999.
4. Last, J.D, Grant A.J. & Ward, N., *Radiobeacon DGNSS Station Selection Strategies – Can We Do Better?,* ION National Technical Meeting, Long Beach, CA, USA, 22-24 January 2001
5. International Telecommunication Union, *Technical Characteristics of Differential Transmissions for Global Navigation Satellite Systems from Maritime Radio Beacons in the Frequency Band 283.5-315 kHZ in Region 1 and 285-325 kHz in Regions 2 and 3,* ITU-R M.823-2, 1997.
6. International Telecommunication Union, *Radio Noise,* ITU-R P.372-7, 1999.
7. International Maritime Organisation, Resolution A.915 (22), *Revised Maritime Policy for a Future Global Navigation Satellite System (GNSS),* November 2001
8. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Draft Revision of IMO Resolution A815(19)'* Nav 47/../.., 31st March 2001.
9. United States Department of Defense & Department of Transportation, *Federal Radionavigation Plan* 2001.
10. United States Coast Guard, *'Broadcast Standards for the USCG DGPS Navigation Service',* COMDTINST M16577.1 April 1993.
11. Poppe, D.C., *'Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions',* Ph.D. Thesis, University of Wales, Bangor, October 1995.
12. IALA Radionavigation Committee, *'Draft. Note to the IALA council on Availability and Reliability for Modification of IMO Resolution A815(19)',* RNAV 14/5/7, September 2000.
13. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Guidelines for the performance and monitoring of a DGNSS service in the Band 283.5 - 325 kHz',* March 1999
14. Grant A. and Last D., *'Understanding Radiobeacon DGNSS Standards – Post-SA',* RIN NAV'01, November 2001.

Enhanced accuracy by regional operation of Europe's new radiobeacon differential system

David Last, Alan Grant and Alwyn Williams, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*

BIOGRAPHIES

Professor David Last has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and former Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, a Chartered Engineer, and Vice-President of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

Alan Grant received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

Alwyn Williams received the degree of MEng (Hons) from University of Wales, Bangor in 2000. He is currently studying for a PhD at Bangor. He is a member of the Royal Institute of Navigation, the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

Dr Nick Ward is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

ABSTRACT

The maritime radiobeacon differential GNSS service in Europe has expanded very rapidly in the last two years. In September 2001, a new frequency plan was brought into effect across the whole of the European Maritime Area (EMA). This resulted in reduced levels of interference and enhanced coverage. There are now 162 maritime differential beacons positioned so that, as far as possible, all critical coastal locations are served by at least two stations.

Along many coastlines, inevitably, three or more beacons can now be received simultaneously. Indeed, by day when coverage is greatest, more than 20 signals are available at some locations. This provides an opportunity to make use of multiple transmissions. With the ending of Selective Availability, spatial dilution of position has come to dominate the accuracy of radiobeacon differential fixes. We have proposed using these multiple sources of pseudorange corrections in a Regional Area Augmentation System (RAAS) to minimise spatial dilution. The approach would be similar to that demonstrated successfully on a larger scale with Loran-C in the Eurofix system.

The paper presents the results of measurements made simultaneously on groups of radiobeacon stations under various receiving conditions. It demonstrates the degree to which RAAS processing of the results enhances position accuracy. In this work, the results from several receivers were combined. The same effect could be achieved with a multi-channel receiver, or by combining the data at a central point and re-broadcasting the result.

Using recently-developed mapping techniques, the paper then analyses the availability of multiple beacon signals across the EMA and maps the areas in which enhanced performance is expected to be available using this new RAAS mode of operation by day and by night.

INTRODUCTION

Differential Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be corrected by using reference stations at known locations to measure the satellites' pseudorange errors. They transmit corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, that of marine radiobeacons, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In

Europe and North America, the recent expansion of the numbers of beacons in this system has ensured that, at most locations, at least one DGNSS beacon can generally be received [3]. Frequently there is a choice from several. It is customary to use the nearest beacon that provides a signal meeting the appropriate standards, with the second-nearest acting as an alternate.

This paper questions whether that is the best policy. A user who can receive several beacons simultaneously has access to corrections from a number of geographically-separated reference stations. Working satellite-by-satellite, it should be possible to compute a best set of corrections for the user's actual location. This is analogous to the use of a wide-area augmentation system (WAAS), and very similar to the use of a regional area augmentation system (RAAS), such as Eurofix [4]. We explore in this paper the question of whether corrections computed using a number of radiobeacon stations can be more accurate than those from the alternate beacon - or even corrections from the nearest beacon.

COVERAGES OF BEACONS

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and differential radiobeacons (DGNSS). The area within which the signal of any of these services provides satisfactory coverage is determined by minimum standards laid down by the International Telecommunication Union (ITU), the International Civil Aviation Organisation (ICAO), the International Association of Lighthouse Authorities (IALA) or, in the US, the US Coast Guard [5-9]. Within the European Maritime Area (EMA) of the ITU Region 1 [5], the field strength and signal-to-atmospheric noise ratio of each service must exceed the minima shown in Table 1 [7,8]. The signal-to-interference ratio (SIR) must exceed the appropriate protection ratio in Table 2; these values are derived from the minimum performance standards for receivers [10]. Thus, for a geographical point to be deemed to lie within the coverage of a DGNSS beacon, the beacon's field strength there must be not less than 10µV/m (20dBµV/m), or a higher figure specified by the national administration. The SNR must be not less than 7dB. Finally, no interfering signal may exceed the protection ratios shown in Table 2.

In computing the coverage area of a beacon, we estimate the level of its signal point-by-point throughout an array centred on the station. By day, this strength depends on the radiated power of the station, its distance and the nature of the propagation path. At night, signal components are also received from the beacon via ionospheric propagation. The intensity of these skywave components depends on range, latitude, time of day and season of the year. Skywave will interfere with the groundwave, causing fading. We customarily compute the signal level from the beacon that can be guaranteed for at least 95% of the time at night. This value is weaker than that of the daytime groundwave.

Table 1

	Units	Marine (MB)		Aero (NDB)	DGNSS
Min. Field Strength	µV/m	N of 43°N	50	70	10
		S of 43°N	75		
	dB µV/m	N of 43°N	34	37	20
		S of 43°N	38		
Min. SNR	dB		15	15	7

Minimum field strength and SNR for MB, NDB and DGNSS services in the European Maritime Area of ITU Region I [3,8,11].

Table 2

Wanted signal:	**Marine (MB)**	**Aero (NDB)**	**DGNSS**	
Interfering signal:	**Any**	**Any**	**MB or NDB**	**DGNSS**
Separation (kHz)				
0	15	15	15	15
0.5	-39	15	-25	-22
1	-60	9	-45	-36
1.5	-60	2	-50	-42
2	-60	-5	-55	-47
2.5	-	-12.5	-	-
3	-	-20	-	-

Protection ratios (dB) for minimising interference between interfering and wanted beacons of various types [8,11].

The intensity of the atmospheric noise is also estimated at each array point; it varies in a random fashion, its mean value over an interval being a function of geographical location, time of day, and season of the year. The values of the wanted signal and the atmospheric noise determine whether or not the point lies within the 'interference-free' coverage of the station.

It is customary to compute the daytime and night-time coverages separately. Daytime coverage is determined by the groundwave signal strength, and night-time coverage by the weaker 95%-ile of the fading signal.

At each point we also estimate the level of any interference from stations on the same frequency as the beacon, or on adjacent frequencies. Interference may be received via either a groundwave or a skywave propagation path, or both. We assess whether the strength of the interference relative to that of the wanted beacon exceeds the protection ratio in Table 2, taking into account both the transmission types of the two stations and their frequency difference. With skywave interference, we use the signal level not exceeded more than 5% of the time. The coverage of the beacon is then that part of the interference-free coverage within which no protection ratio is infringed. These techniques are employed in the widely-used Bangor Coverage Prediction Software for DGNSS Beacons [12-14].

GROWTH OF DGNSS IN EUROPE

By 1998, many European administrations had either closed, or were planning to close, their maritime DF services and were introducing new, or additional, DGNSS beacons. This provided an opportunity for designing a completely new frequency plan for the radiobeacon band in Europe. The object was to reduce the very high levels of skywave-borne interference between beacons that share channels, and so maximise range and performance. Without this reorganisation it was clear that this interference – already at unacceptable levels - would increase significantly, since most of the new DGNSS beacons would be of substantially higher power than the old marine beacons they replaced.

In order to co-ordinate this reorganisation, IALA first requested each administration in the EMA to submit details of its future requirements. The result was a list of 427 beacons in total. It contained a massive increase in the number of DGNSS beacons, from the previous 62 to 154, and an equally dramatic cut in marine beacons, from 226 to just 77. The new band-plan would need to pack these 427 stations into the 64 available channels. But among these stations were also 196 aeronautical NDBs, which had to be left on their existing frequencies. So, too, would 26 MBs located in countries whose administrations had not responded to IALA's request. The new band-plan would have to accommodate all these stations.

The tool developed for the unique task of fitting these many stations into these few frequencies in such a way as to minimise mutual interference, was a set of Optimisation Software [15,16]. This employed the groundwave and skywave modelling techniques of the Bangor Coverage Prediction Software to estimate the potential for interference between each beacon and every other beacon. It took into account both groundwave and skywave propagation, and in both directions. The software then employed a novel algorithm to find the allocation of beacons to channels that minimised mutual interference, a task that was mathematically NP (Non-deterministic Polynomial)-Complete.

This process was successful. When tested on the population of the band before re-organisation, it produced a dramatic reduction in the level of interference. Whereas previously certain stations had lost 90% of their coverage to interference, with the reorganised band-plan no station lost more than 6%. The software was accepted by IALA and used to generate the new band-plan, which was first published for comment by administrations, and then implemented. Across Europe, beacons changed to their new frequency allocations on 18 & 19 September 2001.

A CHANGING RADIOBEACON DGNSS SERVICE

Since the reorganisation, a number of administrations have added further DGNSS beacons. The current population of the band is 461 stations: 162 DGNSS beacons, 143 MBs and 146 aeronautical NDBs [17]. The locations of all these stations are shown in Fig. 1.

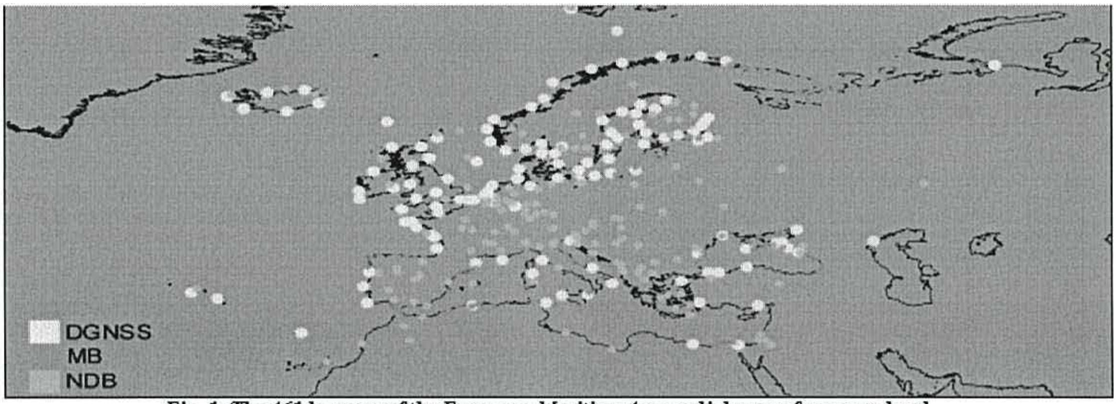

Fig. 1: The 461 beacons of the European Maritime Area radiobeacon frequency band

The development of this large number of new stations has fundamentally changed the nature of the DGNSS service in Europe. In most coastal locations, and over large inland areas, several beacons can now be received simultaneously. This has raised the question for users: which is the best beacon to use. The present authors have developed a further software model that answers this question [18,19]. At all locations across the EMA, it identifies the best beacon, and also the best alternate should that beacon not be available. We have shown that, in general, the best beacon at any location is the nearest beacon that meets international standards: specifically, that has a sufficiently-high signal-to-atmospheric noise ratio, and signal-to-interference ratio, to meet the time-to-alarm requirement. Identifying this beacon is a complex matter that requires analysis point-by-point. The software designed for this process employs a more advanced architecture than that for determining coverage. It is capable of giving access to the groundwave and skywave field strengths of all beacons simultaneously, since this is necessary for identifying the best beacon.

In this paper, however, we question whether using the best beacon guarantees the most accurate position fix. The reason for choosing the *nearest* beacon (provided it meets the time-to-alarm requirements) is that the accuracy of radiobeacon DGNSS fixes is now dominated by spatial dilution of precision of the corrections. The degree of dilution increases with the distance of the receiver from the reference station. This dominance of spatial dilution is in marked contrast to the traditional situation: in the days of selective availability (which was a major factor driving the growth of the radiobeacon DGNSS system) it paid to use the beacon with the highest SNR and SIR, thus minimising the error rate of the messages and so the latency (ie delay) of the corrections. In that way, the effects of the rapidly-changing errors due to SA were minimised by differential operation, and the accuracy of the fixes thus maximised.

But, if we truly wish to minimise spatial dilution of precision could we not do better than using the nearest station - or the next nearest, if the nearest is unavailable? If, as a result of the growth in the numbers of stations, we now have access to multiple sets of correction data, could we not compute the best set of data for the receiver's actual location? After all, that is essentially what happens in a wide-area augmentation system such as WAAS [20] or EGNOS [21]. It is also the basis of Eurofix [4]; as with radiobeacon DGNSS, Eurofix employs a series of independent Local Area Augmentation (LAAS) reference stations, each co-sited with its own transmitter - a Loran station. The Eurofix user receives a number of these stations simultaneously and computes the corrections at his location using these multiple sets of data. In Eurofix, this is called a RAAS – a Regional Area Augmentation System [4].

Let us explore whether we can turn our radiobeacon DGNSS LAAS system into something better? And even if users would not have sufficient stations everywhere, where could we expect improved accuracy from doing so? We also sought to know whether there are snags, such as clock bias differences between the stations, that would prevent this idea succeeding?

We decided first to identify the areas in which users enjoy the benefits of multiple stations; that could be done using our new-architecture software. Then we would try out the idea using off-air signals. We would attempt to answer the questions: is the concept feasible; is it worthwhile; and, if so, where will it work?

NEW SOFTWARE ARCHITECTURE

The Bangor Coverage Prediction Software was designed to identify the coverage area of a single beacon. By computing the coverage of each member of a group of beacons in turn, it can also generate their combined coverage. But if we are to consider the use of multiple beacons at a point where more than one signal is available, we require simultaneous access to data on all those beacons at that point. Achieving that goal required the development of a new and different software architecture that will now be described briefly.

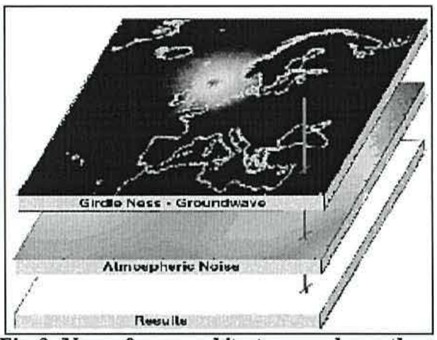

***Fig. 2:** New software architecture employs a three-dimensional array. This simple example has just three layers. They hold the groundwave strength of a single beacon, the atmospheric noise, and (in the results layer) coverage computed using the first two.*

The factors that determine the coverage of a beacon have been identified as the field strengths of: the beacon's groundwave and skywave, atmospheric noise, and the groundwave and skywave components of all potential interferers. The groundwave and skywave field strength distributions of each beacon are first pre-computed at every point in a very large array, spaced by 0.1° of latitude by 0.1° longitude. This array covers an area exceeding that of the European Maritime Area (EMA).

The array structure (Fig. 2) is three-dimensional. The computed groundwave distribution of each beacon is stored in a single level (the top level in this figure). Since there are hundreds of beacons in the EMA, the structure must be capable of accommodating hundreds of such levels. The skywave distributions are stored in a further such set of levels. The atmospheric noise distribution across the area is contained in a single additional level (the middle one in this figure).

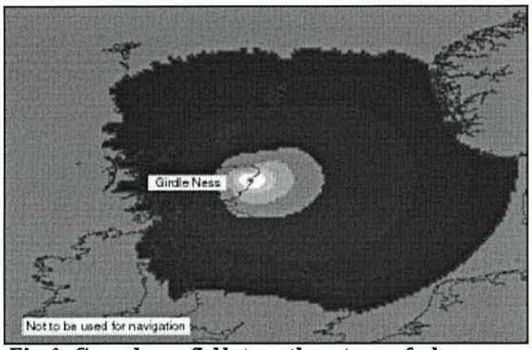

Fig. 3: Groundwave field strength contours of a beacon at Girdle Ness, Scotland. The outer boundary is the limit of daytime interference-free coverage computed using data from top two layers in Fig. 2.

We can choose to extract and plot the data from a single layer - as in Fig. 3, which shows contours of the groundwave field strength of a beacon, taken from the top layer in Fig. 2.

Likewise, by accessing point-by-point the groundwave, skywave, atmospheric noise and interference relevant to a single beacon, we can plot its coverage. For example, the top two layers in the figure contain sufficient data for producing a plot of the simple interference-free groundwave coverage. In Fig. 3, the region within the outer boundary of the contour plot is that coverage. At all points within it, both the field strength (top layer) and signal-to-atmospheric noise ratio (top and second layers) meet the international standards.

This three-dimensional, multi-layer, structure is the tool we need to help us identify the number of beacons that provide coverage simultaneously at any point.

SERVICE FROM MULTIPLE BEACONS

We ran the software analysing at each location in the array, and for each beacon, whether all criteria for coverage were met. That is: whether the field strength exceeded its minimum, including taking fading into account at night; whether the signal-to-atmospheric noise was adequate; and whether all signal-to-interference ratios exceeded their appropriate protection ratios. This latter check involved analysing the groundwave signals from every other beacon, plus at night the skywaves too. In this way, we established beacon-by-beacon whether the array point lay within the beacon's service area. Finally, we totted up how many beacons provided service simultaneously at that point.

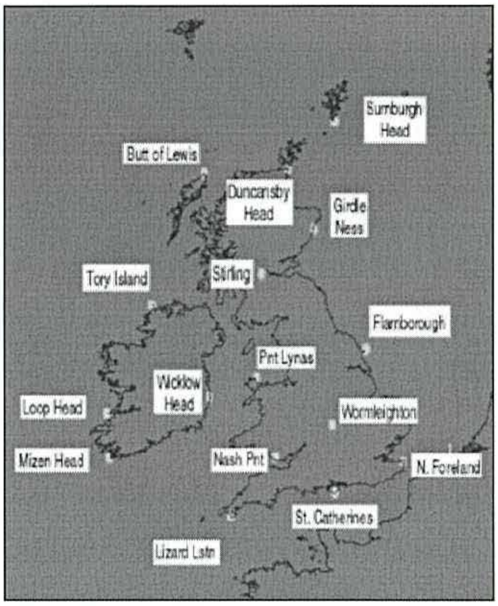

Fig. 4: The 16 DGNSS beacons that serve the British Isles (Duncansby Head and Wicklow Head are planned but not implemented)

This computation was first carried out using just the system of 16 beacons designed by the General Lighthouse Authorities (GLAs) to serve the United Kingdom and Ireland (Fig. 4). Of these beacons, 14 are now on air and two are yet to be installed. The result of the computation is shown in Fig. 5. The number of beacons simultaneously available varies from just one, in regions close to the edge of coverage, to 7. A large proportion of the critical coastal areas, and of the land areas, are served by at least three beacons. Whilst not all beacons are available everywhere all the time, we have shown recently that availability levels of individual beacons generally exceeds 99.5% [22]. Thus, there is a very high probability in practice of these numbers of beacons' signals being available simultaneously.

We now extended the analysis to the whole of the European Maritime Area, with its 162 DGNSS beacons. Fig. 6 shows the result by day when, in many areas, there are large numbers of beacons with overlapping coverage. The greatest concentration - in the North Sea - is 23! By night, of course, many fewer signals that meet the minimum standards are available because of fading of the beacons' signals, and an increase in skywave-borne interference from distant co-channel stations. Nevertheless, there are still many areas with simultaneous coverage from multiple beacons.

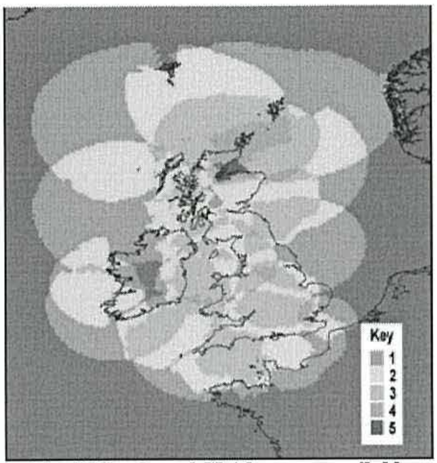

Fig. 5: Number of GLA beacons available simultaneously (worst case, at night), including stations at Wicklow and Duncansby Head that are planned but not implemented

These analyses have shown that over large areas of the EMA at least three signals are available with a quality that will ensure a high availability of correction messages. We will now employ the signals at one such location to explore the degree to which the use of these multiple signals is both possible and advantageous.

TEST RESULTS

Tests were carried out at our laboratories in Bangor, North Wales (N53°13, W004°08). The nearest DGNSS station is Point Lynas, at just 23km range. By day, Bangor lies within the coverage of 7 stations: Point Lynas (primary), Nash Point (alternate), Flamborough Head, Lizard, Tory Island, Stirling and Wormleighton (Fig. 4). At night, only Point Lynas meets all coverage criteria. The strongest of the other beacons just fails to meet the 95% skywave-borne interference criterion. As we will see, this does not prevent these other beacons being used in a regional area augmentation system.

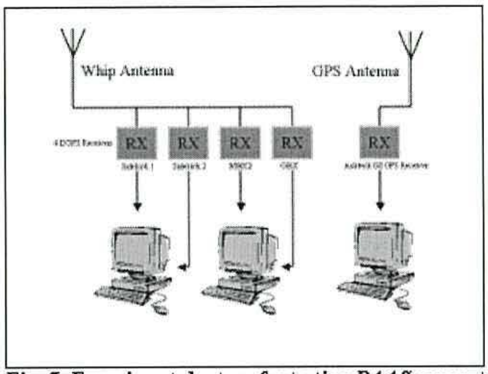

Fig. 7: Experimental set-up for testing RAAS concept

We set up the equipment shown in Fig. 7: four DGNSS radiobeacon receivers (two Cambridge Engineering Sidekick receivers, a CSI MBX2, and a CSI GBX). We also installed an Ashtech G8 GPS receiver. We allocated one beacon receiver to the nearby station of Point Lynas and the others to Wormleighton, Stirling and Loop Head (Fig. 4). Each of these stations is equipped with Trimble 4000MSK Reference Station equipment and transmits Type 9-3 messages at a data rate of 100 bps. We recorded the RTCM data from the beacon receivers, and the full data output stream of the GPS receiver, for 24 hours. The tests were conducted in August 2002.

The RTCM data sets from the four beacon receivers were converted to text format. The results, in the form of pseudo-range corrections (PRCs) and range rates (RRs) were entered into a Microsoft Excel spreadsheet for processing. Since the reference stations are not synchronised in such a way that they broadcast the PRCs of a given satellite simultaneously, we first processed the data so as to enable us to compare PRC values that were as close to simultaneous as possible. The time-skews were less than 10s. Post-SA, PRCs vary very slowly; our measured average range rate was only 0.027m/s; thus, the errors resulting from using PRCs that were not precisely simultaneous should have been less than 0.3m, even with the maximum time-skew.

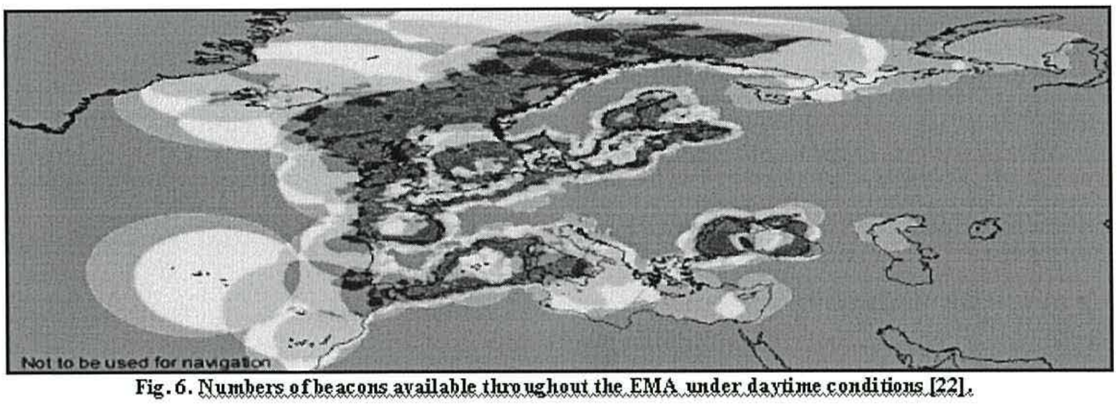

Fig. 6. Numbers of beacons available throughout the EMA under daytime conditions [22].

We were concerned about clock bias differences between the reference stations. A clock bias error results in an equal shift of all PRCs from the station. They are of little significance when radiobeacon DGNSS is used in its conventional way, with all corrections being taken from a single station, since the result is a small error in the time output of the navigation solution, not in the position. In the same way, when we come to combine PRCs from multiple stations, clock bias errors should not matter provided we use the same proportions of each station's PRC for all satellites. But such bias errors could mask the small differences in PRCs between stations that we wish to investigate in this study.

To estimate the magnitudes of any such clock bias components, we first computed for each station the average of all PRCs, for all satellites, over the 24 hours. The reasoning was that, with stations located relatively close together like these, the effects of location on these averages should be very small and differences between averages would be due principally to clock bias discrepancies.

Table 3

Station	PRC average	Distance from Point Lynas (km)	Weighting factor
Wormleighton	-11.08	219	0.45
Stirling	-10.90	336	0.29
Loop Head	-11.14	385	0.26
Point Lynas	-10.92		

Table 3 lists the "PRC average" values of the first set of stations investigated. Happily, each of these four average values lay within 0.13m of the overall mean value (-11.01m). These are negligible differences; we concluded that we could safely proceed with comparing the PRCs between these stations.

We first looked at the discrepancies between the PRCs for a given satellite measured at Point Lynas, and those from each of the other three stations: Stirling, Wormleighton and Loop Head (let us call those the "outstations"). We asked: how much error would there be in the PRCs if a user at Point Lynas employed corrections from each of these outstations? We first computed, satellite-by-satellite the correlation coefficients of each outstation's PRCs with those at Point Lynas. These correlation values ranged from 0.852 for Satellite 10 at Wormleighton, to 0.990 for Satellites 11 and 20 there. We then averaged the correlation coefficients for each station across all satellites. The results are shown in Table 4 in the column headed "Correlation coefficient". The average correlation coefficient was 0.963 at both Wormleighton and Stirling, and a lower 0.940 at more distant Loop Head.

We now calculated a set of PRCs for Point Lynas by interpolating between the PRCs at the three outstations. This RAAS interpolation was weighted by the reciprocals of the ranges from the outstations, so favouring the nearest. Table 3 shows these ranges and the weighting factors: Wormleighton 0.45, Stirling 0.29 and Loop Head 0.26. The "interpolated PRCs" for Point Lynas were then compared, satellite-by-satellite, with the PRCs actually recorded there. The correlation, 0.982 (Table 4), was much better than that at any of the individual outstations; the degree of de-correlation was between 30% and 49% of that at the outstations. It appears, therefore, that RAAS interpolation offers a significant benefit.

Table 4

Station	Correlation coefficient	PRC difference (m)
Wormleighton	0.963	1.05
Stirling	0.963	1.06
Loop Head	0.940	1.40
Interpolated	**0.982**	**0.66**

Computing the correlation coefficients in this way measures the agreement between the variations in the PRCs. We separately assessed the situation by examining the discrepancies between the actual PRC values. We computed the average of the modulus of the errors between each outstation PRC and the corresponding PRC at Point Lynas. The results, averaged across all satellites, are in the columns of Table 4 headed "PRC difference". These average discrepancies vary from 1.05m at Wormleighton to 1.40m at Loop Head. When we then compared the interpolated PRCs for Point Lynas with the values measured there, the average difference fell to 0.66m; this error is between 47% and 63% of those for the individual outstations. Again, we see a marked improvement.

We conclude that, in this case, a user would obtain PRC values much closer to the correct ones by interpolating the PRCs from these three outstations than by simply using the PRCs from any one of them, even Wormleighton the recommended night-time alternate.

The complete test was now repeated using Wormleighton with Tory Island (358km) and Mizen Head (417km). The two new stations are a little further away than Stirling and Loop Head. There was a larger discrepancy between clock bias values, with maximum differences of approximately 0.5m. But, again, the interpolated PRCs for Point Lynas proved much closer to the PRCs actually measured there than did the PRCs from any individual outstation. In other words, the results confirmed those from the first group of stations.

Finally, using this second group of beacons, we also checked the position results at Bangor over a total of 24h. Table 5 shows the 2-d and 3-d errors with respect to an antenna position established by long-term code-differential GPS measurements. Using corrections from the nearby station, Point Lynas, reduced the 2-d mean error from 5.3m to 2.5m. Corrections from the individual outstations also reduce the error, but by less. But interpolating their PRCs gave 2.6m, a value within 0.1m of that of Lynas itself. The 3-d results followed the same pattern. We conclude that interpolating the PRCs from these three outstations, even including one as distant as 417km, gives results almost indistinguishable from those provided by the local beacon.

Table 5

Station	Distance from Bangor (km)	Mean error (m)	
		2-d	3-d
No differential		5.3	15.2
Wormleighton	219	2.6	2.7
Tory Island	358	3.4	3.5
Mizen Head	417	4.9	5.0
Lynas	23	2.5	2.5
Lynas interpolated		2.6	2.7

WHERE RAAS PAYS OFF

Our analysis of these test results suggests that it pays to use a RAAS solution, rather than any of the possible alternate beacons, where three beacons contribute to that solution and the receiver lies within the triangle they form. Interpolating between three beacons in this way takes into account the gradients of the PRCs, of course.

But if the receiver were to lie outside the triangle, we would still have knowledge of those gradients and it would be reasonable to apply them, at least in regions close to the triangle. Then, a different way of calculating the PRCs at the receiver would then be required, since the process would be one of extrapolation, not interpolation. This option has not so far been explored.

Similarly, if only two beacons were available, the gradient in one direction would be known. This should also provide a limited benefit. It would be interesting to explore where, and for how far, a two-beacon solution would provide more accurate PRCs than either beacon alone.

But even if extrapolation and the use of two beacons are excluded, we can employ our computer model to identify those areas in which the receiver lies within a triangle of beacons each of which meets the full coverage criteria. In such regions, it should pay to use a RAAS solution. Fig. 8 shows the area in which these fairly conservative criteria are met by day when the British Isles beacons are used. Fig. 9 shows the (much smaller) area at night. The equivalent results for the entire EMA are presented in Figs. 10 and 11.

FURTHER BENEFITS OF RAAS OPERATION

There are fundamental differences between a three-beacon RAAS solution and the traditional single-beacon LAAS approach. We have seen that RAAS should be more accurate then LAAS in many cases. But, with the ending of SA, the key reason for using radiobeacon DGNSS is not its greater accuracy but the enhancement of integrity it provides [18,21]. And, of course, a receiver that can take advantage of multiple beacons will enjoy at least as great an integrity benefit as a traditional single-beacon receiver. Indeed, provided the receiver marks a satellite as unhealthy as soon as it is flagged by any of the reference stations being received, the degree of integrity improvement afforded by differential operation will actually be increased.

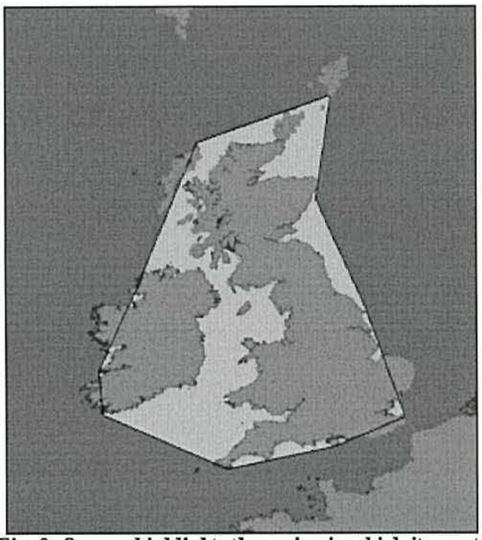

Fig. 8: Orange highlights the region in which it pays to use RAAS: ie we are within a triangle of three stations, each of which meets full coverage criteria by day.

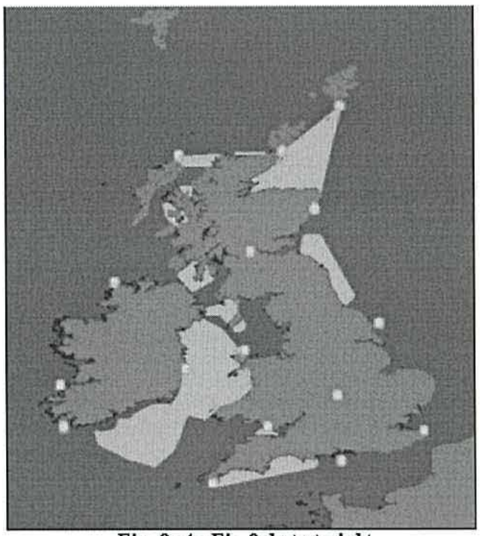

Fig. 9: As Fig.8, but at night

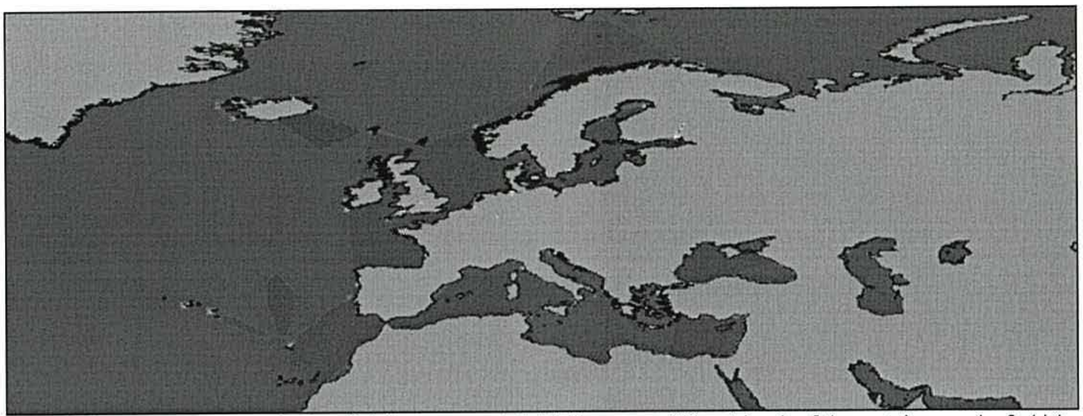

Fig. 10: Red highlights the region in which it pays to use RAAS: ie we are within a triangle of three stations, each of which meets full coverage criteria by day.

A further benefit of RAAS operation is that it should extend the area over which high-quality differential reception is available. We have seen that, with the ending of SA, the need for rapid updates of PRCs has gone. In principle, delays of many tens of seconds between PRC updates would lead to little degradation of position accuracy. Thus, we could make use of weaker signals from more distant radiobeacons. The 24-hour test data analysed above actually employed two groups of three beacons outside the area in which their coverage at night fully meets the international standards. Yet these beacons clearly provided accuracy benefits. The factor that requires us to continue to employ tight specifications in stating the coverage of radiobeacons post-SA is the time-to-alarm [18]. Indeed, we show in another paper in this session that no easing of standards can be permitted if this specification is to be met [21]. But if the receiver now has access to multiple beacons, the probability of receiving an alarm message will be greatly enhanced, and that is likely to extend substantially the area within which the TTA specification can be met.

In that case, multiple beacon operation – even employing beacons outside the standard coverage limits - is likely to provide both accuracy and integrity benefits.

It remains to explore this aspect of multiple beacon operation fully. We would also wish to investigate the degree to which even better results than those demonstrated above could be achieved by the use of other algorithms than simple weighted interpolation. We envisage exploring at the same time the dependence of accuracy on the geometry of the outstations, including the use of extrapolation to areas outside the region bounded by the outstations.

That done, we will be in a position to set formal criteria to be met if a RAAS solution is to be better than a LAAS one. We will then go on to prepare coverage plots according to those criteria; we anticipate that these will be more extensive than the plots presented above, especially at night.

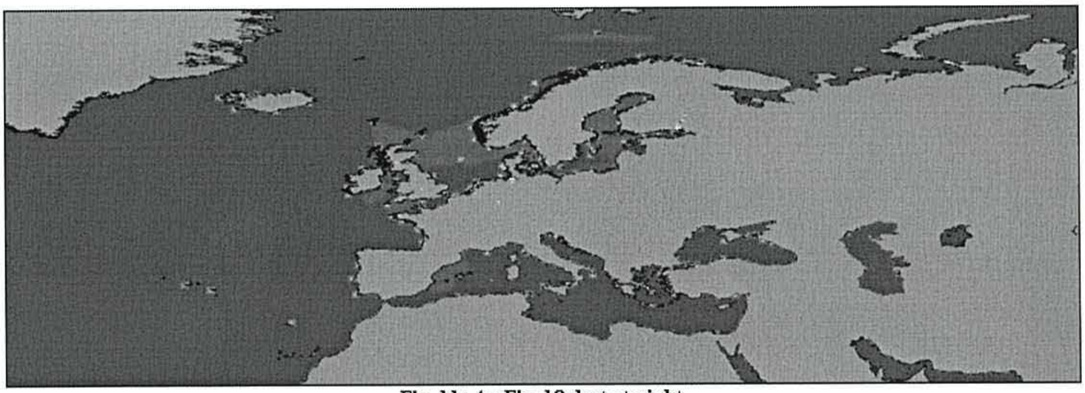

Fig. 11: As Fig. 10, but at night

CONCLUSIONS

This paper has presented a preliminary exploration of the benefits of receiving multiple beacons from a radiobeacon DGNSS network. It has shown that the feasibility of doing so is now commonplace, especially by day, given the recent substantial increases in the numbers and ranges of European beacon systems. We have demonstrated that PRCs calculated by interpolating the values from three stations at ranges of approximately 200-400 km from the receiver are more accurate than the PRCs from any single such outstation. Thus, when a local station fails, interpolation is a better option than the use of a simple alternate.

We go on to argue that the benefits of a RAAS solution over a conventional LAAS one include not only higher accuracy but also a greater degree of integrity. We propose exploring whether these benefits are available, at least in part, outside the area within which the PRCs of three stations can be interpolated. Indeed, we show good reason to believe that RAAS operation could even extend the use of the radiobeacon service beyond its present boundaries.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland. They wish to thank Alison Bryant for the contribution she made as part of her final-year student project, and Mathieu Lebihan of the École Polytechnique de l'Université de Nantes, France, for the work he did whilst visiting Bangor.

REFERENCES

1. Enge, P.K. and Olsen, K.E., *Medium Frequency Broadcast of Differential GPS Data,* IEEE Transactions on Aerospace and Electronic Systems, Vol.26, No. 4, July 1990, pp. 607-617.
2. Enge, P.K. and Ruane, M.F., *Marine Radiobeacons for the Broadcast of Differential GPS Data,* Record of the IEEE Position, Location and Navigation Symposium, Las Vegas, NV, November 1986.
3. International Association of Lighthouse Authorities, *List of Radionavigation services,* Issue 7 – August 1999.
4. Offermans, G.W.A, Helwig, A.W.S. & Van Willigen, D., *Eurofix system and its developments,* Royal Institute of Navigation NAV98, London, 1998
5. International Maritime Organisation, Resolution A.815 (19), *World-Wide Radionavigation System,* November 1995
6. International Maritime Organisation, Resolution A.860 (20), *Maritime Policy for a Future Global Navigation Satellite System (GNSS),* November 1997
7. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Recommendation on the performance and monitoring of a DGNSS service in the Band 283.5 - 325kHz',* Rec.121, June 2001
8. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), 'Draft Recommendation on the performance and monitoring of DGNSS services in the frequency band 283.5 – 325KHz', June 2001
9. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), *'Draft Revision of IMO Resolution A815(19)'* Nav 47/../.. 31st March 2001.
10. United States Department of Defense & Department of Transportation, *Federal Radionavigation Plan* 2001.
11. United States Coast Guard, *'Broadcast Standards for the USCG DGPS Navigation Service',* COMDTINST M16577.1 April 1993.
12. Poppe, D.C., *Coverage and Performance Prediction of DGPS Systems Employing Radiobeacon Transmissions,* Ph.D. Thesis, University of Wales, Bangor, October 1995.
13. Last, J.D. & Poppe, D.C., *A coverage prediction model for radio beacon differential satellite navigation systems,* Navigation (USA) - Journal of the Institute of Navigation, **43**, 4, pp451-467, Winter 1996-1997
14. Last, J.D. & Turhan, B.E., *European radiobeacon DGNSS - Making the most of the frequency band,* Journal of the Royal Institute of Navigation, 52, 2, pp176-188, May 1999
15. Last, J.D., Turhan, B.E. & Ward, N., *IALA's new European DGNSS radiobeacon plan,* International Association of Institutes of Navigation/ Institute of Navigation (USA), IAIN/ION 25th Anniversary World Congress, pp.329-335, San Diego, CA, 26-28 June 2000
16. International Association of and Lighthouse Marine Aids to Navigation Authorities (IALA), Frequency Plan *fplan46,* 2002
17. Last, J.D, Grant A.J. & Ward, N., *Radiobeacon DGNSS Station Selection Strategies – Can We Do Better?,* ION National Technical Meeting, Long Beach, CA, USA, 22-24 January 2001
18. Grant, A., Last, J.D. & Ward, N., *Quality criteria for the maritime DGNSS system in a world without SA,* GNSS2001 Conference, Seville, Spain, 8-11 May 2001
19. United States Department of Defense & Department of Transportation, *Federal Radionavigation Plan* 2001
20. http://www.esa.int/export/esaSA/GGGE3A50NDC_navigation_0.html
21. Last, J.D., Grant, A. & Ward, N, *Radiobeacon DGNSS service – predicting availability and continuity,* ION GPS 2002
22. Last, J.D., Grant, A. & Ward, N., 'Understanding and predicting the availabilities of radiobeacon DGNSS systems' National Technical Meeting 2002, Institute of Navigation (USA), San Diego, CA, 28-30 Jan, 2002