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Optimisation of mf DGNSS, maritime and aeronautical radiobeacon coverage by frequency re-assignment

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OPTIMISATION OF MF DGNSS, MARITIME AND AERONAUTICAL RADIOBEACON COVERAGE BY FREQUENCY RE-ASSIGNMENT

A THESIS
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SUMMARY

Differential Global Navigation Satellite Systems (DGNSS) are based on the principle that the main sources of errors in satellite navigation are consistent over substantial geographical areas. These errors can be measured by employing reference receivers at fixed, known, locations. The correction messages they generate are broadcast, and used by mobile receivers in the region to adjust their own position measurements.

Currently one of the oldest aids-to-navigation technologies, that of marine radiobeacons, is being used to transmit correction signals. Such radiobeacon DGNSS installations are being planned and commissioned in many countries. However, the frequency band for the radiobeacon DGNSS service in Europe is crowded with marine and aeronautical beacons and, as a result, the coverage and performance of these transmitters are seriously degraded by interference.

This aim of this research is to minimise the effects of interference on the coverage of radiobeacons by frequency planning. In order to achieve our goal, methods of evaluating the interference are analysed and, where existing methods are not sufficient, better methods are developed. A suite of computer programs has been developed to analyse the performance of radiobeacons when interference is present, to help the system planner select the best frequency for a new radiobeacon and to re-plan the frequency allocations of all the radiobeacons in the European Maritime Area.

ABBREVIATIONS

AOF	Acceptable Occupied Frequency
C/A	Coarse/Acquisition
CCG	Canadian Coast Guard
DF	Direction Finding
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
DoD	(US) Department of Defence
DoT	(US) Department of Transport
EMA	European Maritime Area
ESA	European Space Agency
FDMA	Frequency-Division Multiple Access
FoM	Figure of Merit
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
GSD	Generalised Saturation Degree
HDOP	Horizontal Dilution of Precision
IALA	International Association of Maritime Aids-to-Navigation and Lighthouse Authorities (formerly: International Association of Lighthouse Authorities)
ICAO	International Civil Aviation Organisation
IFCA	Interference-Free Coverage Area
IMO	International Maritime Organisation
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radio
LF1	Largest degree first- one
LF2	Largest degree first- two
MB	Marine Radiobeacon
MEO	Medium Earth Orbit
MF	Medium Frequency
MOPS	Minimum Operational Performance Standards
MPA	Most Popular Algorithm
MSK	Minimum Shift Keying
MUA	Most Unpopular Algorithm
NDB	(Aeronautical) Non-directional Radiobeacon
NP	Non-deterministic Polynomial
PDOP	Position Dilution of Precision
PPS	Precise Positioning Service
PRC	Pseudorange Correction
PRN	Pseudorandom Noise
RF	Radio Frequency
RTCM	Radio Technical Commission for Maritime Services

S	Sequential
SA	Selective Availability
SAF	Smallest Acceptable Frequency
SAn	Simulated Annealing
SAOF	Smallest Acceptable Occupied Frequency
SIR	Signal-to-Interference Ratio
SL	Smallest degree last
SNR	Signal-to-Noise Ratio
SPS	Standard Positioning Service
TEC	Total Electron Content
TS	Tabu Search
USCG	United States Coast Guard
VDOP	Vertical Dilution of Precision
WGS 84	World Geodetic System 1984

LIST OF SYMBOLS

R_i	range from the *i*-th satellite
T_{ai}	time of arrival (*i*-th satellite)
T_{ti}	time of transmission (*i*-th satellite)
c	speed of light
B_{user}	user's GPS receiver's clock bias
ρ_i	pseudorange from the i-th satellite
e_i	1-σ pseudorange error
B_i	clock bias of the i-th satellite
Δ_ρ	pseudorange error
dB	decibel
dBμV/m	dB relative to 1 μV/m
Sky_{dB}	skywave field strength in dBμ
k	basic loss factor
G_V	antenna gain factor
p	slant propagation distance in km
Φ	geomagnetic latitude
G_S	sea gain
f_{kHz}	frequency in kHz
h	ionospheric height
α	geographic latitude
β	geographic longitude
l_d	base 10 logarithm of distance in km
Δ_{time}	differences in propagation time between skywave and groundwave
Δ_{path}	differences in path length between skywave and groundwave
d	distance in km
Gnd	groundwave field strength
Gnd_{dB}	groundwave field strength in dBμ
Sky	skywave field strength
SGR	skywave-to-groundwave field strength ratio
LF	low frequency
E_n	rms noise field strength
f_{MHz}	frequency in MHz
b_{Hz}	noise bandwidth in Hz
F_{am}	median noise level from world map
L_{AB}	distance between A and B
L_{XAB}	distance between X and the line between A and B
$\forall$	for all
P	probability
B	Boltzmann's constant
t	temperature
E_{new}	new configuration energy state
E_{old}	old configuration energy state
e_{vio}	number of violated constraints
e_{sum}	sum of the amounts by which each constraint is violated

f_{large}	largest frequency used
f_{small}	smallest frequency used
e_{order}	number of distinct frequencies used
l_{vio}	largest of the constraint violations

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Chapter 1

Introduction

The Global Positioning System is set to become the dominant navigation system world-wide; it provides continuous all-weather navigation information and time. With GPS in its present civilian version, the user can find his location within 100m, of the true position 95% of the time. This measurement can be made more accurate, with an error of 10m or less, 95% of the time, by utilising "differential" techniques. A differential GPS system computes the errors measured at a fixed, known, location and broadcasts them to users in the vicinity, who employ them to correct their own position fixes. Many different methods of conveying such correction information to the users are currently employed. For maritime use in coastal regions, however, one principal method has emerged: the data is carried as additional modulation on the radiobeacons traditionally used for direction finding.

Radiobeacons are attractive for this purpose since they have an existing, protected, frequency band and infrastructure. It has proved very cost-effective to use them to transmit additional differential corrections. However, to ensure good service quality, the factors affecting the signals of radiobeacons have had to be carefully analysed. The principal factors are the attenuation of the signal and the level of natural atmospheric noise and of interference from other transmitters in the frequency band.

The signal is normally received via both groundwave and skywave paths. The attenuation of the groundwave with range from the station depends on the type of terrain over which it travels; that of the skywave on range, latitude and temporal factors. Atmospheric noise and interference may corrupt the data and even render it unintelligible. Naturally-occurring atmospheric noise is a function of location, time and season. Interference, in contrast, is wholly man-made and in many areas, notably Europe, proves to be the principal factor limiting coverage. In these regions a large number of beacons are obliged to share a small number of frequencies. The process of planning the allocations of frequencies to beacons is a complex business, a compromise between the conflicting needs for maximum coverage and the minimisation of interference to other stations in the region.

Previous studies have shown that in the European Maritime Area (EMA) the main factor reducing total DGNSS radiobeacon coverage is interference. The goal of the research presented in this thesis is to find ways to minimise the mutual interference between DGNSS radiobeacons so that the maximum possible DGNSS radiobeacon coverage is obtained throughout the EMA. The technique employed has been to develop computer algorithms capable of evaluating and quantifying the interference between pairs of radiobeacons and then use the results to select the best frequency on which to operate each beacon. The resulting software should be capable of finding the best frequency for a new single radiobeacon, such that interference to and from other beacons is minimised. But more important is the objective that it should be capable of producing a complete re-assignment of the frequencies of all radiobeacons throughout the EMA in such a way as to minimise their mutual interference and so maximise their performance. That is the principal objective of the research to be described in this thesis.

1.1 Overview of the thesis

An introduction to GPS is given in Chapter 2. The sources of errors affecting position measurement are identified. An introduction to differential GPS (DGPS) is then followed by information on the maritime radiobeacon system; this deals with its use both for direction finding and for broadcasting differential GPS. Other Global Navigation Satellite Systems (GNSS), including GLONASS and Galileo, are also described in outline. Finally the problem to be tackled in this research is introduced and the European Maritime Area and its radiobeacon system described. Note that, although it is Differential GPS that the great majority of radiobeacons transmit, the term "Differential Global Navigation Satellite System (DGNSS)" will be used in this work, since that is now the term most generally employed.

Chapter 3 then discusses the natural and man-made factors that affect the coverage of radiobeacons, starting with how the field strength is attenuated as a function of range from the transmitter. The two modes of propagation, groundwave and skywave, are explained, together with the fading of signals associated with skywave propagation. Atmospheric noise is also discussed and techniques for evaluating its magnitude given. A coverage prediction model incorporating all these factors is introduced. After the natural factors, the effect of interference on the coverage is given and the performance of a number of European radiobeacons is shown by way of example.

Chapter 4 explains how to maximise the coverage of a single radiobeacon. Different methods of evaluating the interference between pairs of radiobeacons are analysed and a new method proposed. Then, a novel program for selecting the best frequency for a single new beacon is developed and demonstrated. The use of this programme is shown to offer considerable benefits in terms of enhanced coverage.

Chapter 5 introduces and discusses the most important result of this research: a new algorithm developed by the candidate for re-assigning the frequencies of all the radiobeacons of the EMA. Ways of handling the various constraints of frequency assignment are explained. These constraints include: co-channel and adjacent-channel interference; the need to retain the current frequencies of certain transmitters; and the assignment of adjacent channels to co-sited pairs of transmitters. The new algorithm is proposed for packing a population of stations into the minimum number of channels. The results of various test runs are presented and analysed.

Chapter 6 compares the results of the new frequency-assignment algorithm with alternative types of algorithm taken from other areas of research. The whole class of such algorithms is described on the basis of an extensive literature review. The performance of the new algorithm is then measured against that of the best of the others using a series of benchmarks. The new algorithm is shown to compare very favourably.

Chapter 7 summarises the major conclusions of this research and proposes further work in this area.

The list of publications co-authored by the candidate describing this research, together with a selection of those publications, is presented at the end of the thesis.

1.2 Contributions

The major contributions claimed for the research presented in this thesis are as follows:

- Analysis of the loss of coverage of radiobeacons in the EMA due to interference.
- Analysis and quantification of the loss of potential coverage under the current frequency plan.
- Identification of deficiencies in the existing methods of frequency planning for radiobeacons.
- Assembly of a new ground conductivity databases for regions of Africa, Asia and Europe
- Assembly of an expanded atmospheric noise database for the EMA.
- Development and implementation of an improved method of evaluating the interference between pairs of radiobeacons.
- Development of a frequency selection program for individual new radiobeacons.
- Development and implementation of a new method for solving limited-spectrum frequency assignment problems.
- Development of a new method for representing interference between members of groups of radiobeacons.
- Development and implementation of a novel technique for frequency assignment using the minimum number of channels.
- Comparison of this method with other frequency assignment algorithms, both deterministic and random.
- Computation of a new band plan for the future radiobeacons of the European Maritime Area.

Chapter 2

Radiobeacon Differential GPS

2.1 Introduction to GPS

GPS is a satellite system designed to provide high-accuracy navigation for civilian and military users on a world-wide basis. It is operated by the United States Department of Defence (DoD), and controlled by them in collaboration with the United States Department of Transport (DoT) [1].

The GPS constellation consists nominally of 24 satellites, each in a circular orbit at 20,200km with a period of 11h 58min. These 24 satellites are in 6 orbital planes, 4 satellites per plane, at an inclination of 55° to the equator (Fig. 2.1) [2]. GPS gives users two different levels of service: the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). Civilian users can generally employ only the SPS, which is intentionally degraded to give positions within 100m of the true two-dimensional position 95% of the time. That is, if a circle with a static receiver in a true position at the centre and radius of 100m is drawn, 95% of the measured positions should lie within the circle. This is expressed as "100m, 2drms" where the second part is the abbreviation for the distance root mean squared (rms) error in the latitude-longitude plane [3,4]. This degradation of accuracy, known as Selective Availability (SA), was introduced for military and political reasons since the US government did not want to allow to unauthorised users positioning of the accuracy GPS turned out to deliver [5-7]. Because of this SA, the user's measured GPS position wanders randomly around the true position. In contrast, an authorised user of the PPS has a positioning accuracy of no more than 22m, 2drms [1,8]. SPS GPS is now widely utilised by civilian users; major classes of applications are listed in Table 2.1 [9].

Figure 2.1: *The GPS constellation, with its 24 satellites in 6 orbital planes, after [2].*

Application Area	Application
Marine Navigation	Oceanic Coastal Harbour Approach Inland Waterways Off-shore Surveying
Aviation	Non-precision Approach and Landing Domestic en Route Oceanic en Route Terminal Approach Remote Access Helicopter Applications Crop Spraying Attitude Determination Collision Avoidance
Land Navigation	Vehicle Tracking Fleet Management Schedule Improvement Law Enforcement
Static Positioning and Timing	Surveying Aids to Navigation Synchronisation Offshore Research Exploration Agriculture Geographical Information Systems
Search and Rescue	Position Reporting and Monitoring Rendezvous Co-ordinated Search Collision Avoidance
Space	Attitude Determination Launch In-flight / Orbit Re-entry / Landing

Table 2.1: *Examples of civilian GPS applications [9].*

	SPS (C/A code)	PPS
Frequency	1575.42 MHz (L1)	1227.6 MHz (L2)
Chip rate	1.023 Mbps	10.23 Mbps

Table 2.2: *Frequencies and modulation rates of SPS and PPS PRN codes [10,11].*

Table 2.2 gives the frequencies and modulation rates of SPS and PPS navigational information broadcast on the two GPS frequencies [10,11]. GPS is a code division multiple access system; that is, all satellites transmit their messages on the same two carrier frequencies, each modulating the carrier with a different pseudorandom noise (PRN) code to produce a spread-spectrum signal. The PPS service utilises the longer-PRN "precise code (P-code)", which modulates both L1 and L2 frequencies The P-code is further encrypted to provide additional protection against jamming or spoofing; it is then known as the Y-code.

Both carriers are also modulated at 50bps by a navigational message which conveys the satellite clock, ephemeris, and other data, repeating itself every 30s. A full message, including almanac data, takes 12.5min to transmit.

2.1.1 GLONASS

The Russians also operate a satellite system, called GLONASS, which is similar to GPS and controlled by the Russian Federation Ministry of Defence. The most obvious difference between the two systems is that GLONASS uses frequency-division multiple access (FDMA) transmissions [12]. That is, all GLONASS satellites use the same PRN code, but their carrier frequencies are different; however, antipodal pairs of satellites share a frequency. GLONASS has equivalents to both SPS and PPS, but no SA. World-wide, the term *Global Navigation Satellite System (GNSS)* is now being used to refer to systems such as GPS and GLONASS and their would-be successors [13].

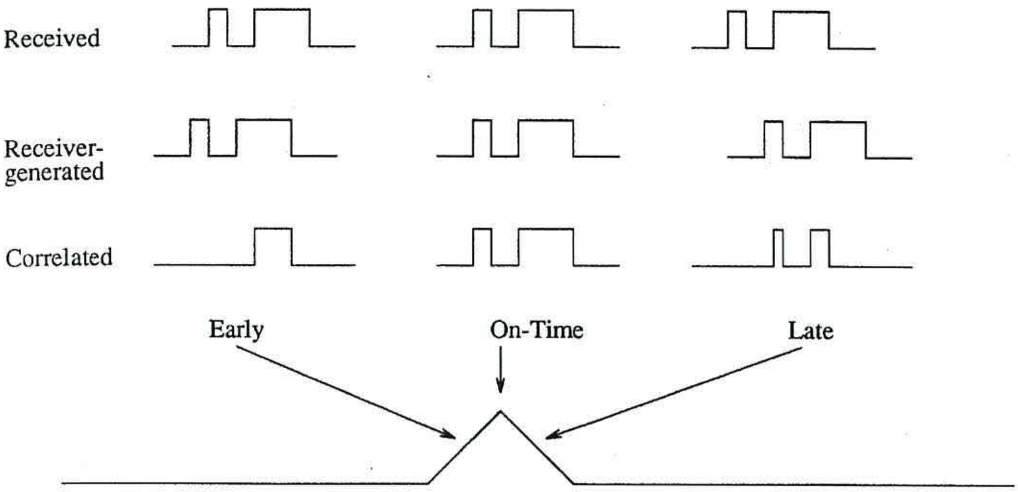

Figure 2. 2: *The output of a receiver correlator showing the relative alignment of received and receiver-generated codes [15,16].*

2.1.2 A civilian system: Galileo

Both GPS and GLONASS are controlled by the military authorities of single nations. The European Union decided that there are problems for civilians if they are to depend on systems controlled by foreign militaries. In addition although both services are currently free of charge there is no guarantee that this situation will continue. With the prediction that the GNSS market will come to be worth more than £20B, Europe has decided to have a GNSS service of its own; this is to be named *Galileo* [14].

2.1.3 Range and Pseudorange

Both GPS and GLONASS make use of the measured distance between a transmitter and a receiver. Evaluating the range depends on precise measurement of the propagation time, the time it takes the signal to travel from the satellite to the receiver. Propagation time can be evaluated by subtracting the time-of-transmission from the time-of-arrival.

The time-of-arrival of a received signal is measured by correlating it with a copy of the corresponding C/A code generated by the receiver, the signal consists of chips as shown in Fig. 2.2 [15,16]. The receiver-generated copy is shifted in time until it is aligned with that of the received signal, when the correlation between the two peaks.

Using this time shift of the correlation peak, the receiver establishes the time-of-arrival of the signal with respect to the its own clock. The time-of-transmission of the chips of the signal, relative to the satellite's atomic clock, is then evaluated by computing it from the information in the received navigational message.

Since the signal travels with a speed very close to the speed of light, the range from the satellite being received (we will call this "the *i*-th satellite"), R_i, is given by:

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

where T_{ai} and T_{ti} represent the times of arrival and transmission of the signal, and *c* is the speed of light.

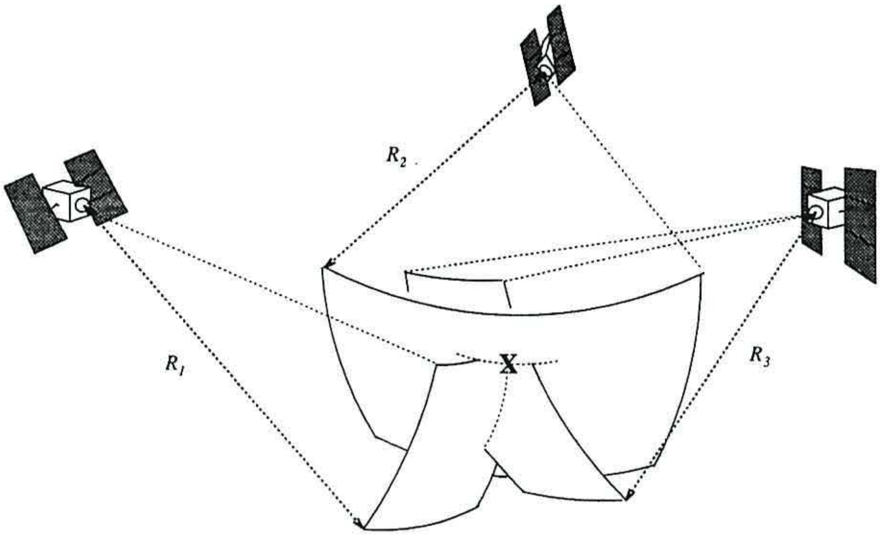

Figure 2. 3: *The receiver lies at the intersection of three spheres with ranges R_1, R_2, R_3..*

The propagation time could be measured precisely if a very accurate (and hence very expensive) atomic clock, synchronised to the satellites' atomic clocks, were used in the receiver. Instead, the receiver uses a less-accurate and much cheaper clock with an unknown clock error or bias, B_{user}. Because of this error, the range measurements must be considered as "*pseudoranges*" from the satellites. A pseudorange, ρ_i, from the i-th satellite may be written as:

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

The receiver determines its position (Fig.2.3) as the point of intersection of the three spheres, with radii R_1, R_2 and R_3, centred on the three satellites from which it measures its ranges. These errors will be examined in more detail in section 2.2.

2.1.4 The satellites' orbits

Since the GPS constellation consists of Medium Earth Orbit (MEO) satellites, which are not synchronised with the earth, the transmitters do not have fixed locations, unlike terrestrial radionavigation transmitters. Thus, for the range information to be useful, the position of each satellite has to be sent as a set of parameters that define its orbit [11,17]. This *ephemeris data* enables the receiver to evaluate the position of the satellite at the moment of transmission. Both the satellites' and the receivers' positions are represented in an earth-fixed, earth-centred, reference frame, the World Geodetic System 1984 (WGS 84) for GPS; similarly the PE 90 system is used for GLONASS. Transformations between the reference frames exist.

In order to compute its own position (in latitude, longitude and altitude) plus time, the receiver solves four equations derived from four simultaneous pseudorange measurements:

$$\boldsymbol{e_1}.\boldsymbol{R}_{user}-B_{user} = \boldsymbol{e_1}.\boldsymbol{R_1} - \rho_1 - B_1, \qquad (2.3)$$

$$\boldsymbol{e_2}.\boldsymbol{R}_{user}-B_{user} = \boldsymbol{e_2}.\boldsymbol{R_2} - \rho_2 - B_2, \qquad (2.4)$$

$$\boldsymbol{e_3}.\boldsymbol{R}_{user}-B_{user} = \boldsymbol{e_3}.\boldsymbol{R_3} - \rho_3 - B_3, \qquad (2.5)$$

$$\boldsymbol{e_4}.\boldsymbol{R}_{user}-B_{user} = \boldsymbol{e_4}.\boldsymbol{R_4} - \rho_4 - B_4, \qquad (2.6)$$

where ρ_i, R_I, e_I, and B_i are the known variables corresponding to the range, satellite position co-ordinates vector, co-ordinate transformation vector and clock bias in meters of the i-th satellite. The unknowns calculated are the position, R_{user} [x y z], and receiver clock bias B_{user}. Note that bold variables are vector quantities. In the special case that altitude is known *a priori* (or the user is only interested in two-dimensional positioning), only three simultaneous pseudoranges from three satellites are needed to calculate the three unknowns: latitude, longitude and time.

2.2 Sources of error in GPS positioning

Since the differential systems with which this thesis is concerned are designed *inter alia* to minimise position errors, it is appropriate to study the principal sources of error in normal GPS position measurements (Table 2.3); errors encountered when operating in the DGPS mode, local area only, will be introduced in section 2.4. The error sources will now be considered individually.

Error Source	**Expected range measurement error (m rms)**		
	PPS	**SPS**	**DGPS**
Selective Availability	0	< 66	0
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	< 66	2 – 6
Resulting 95% position error			
Horizontally	4.5 – 12	100	3 – 9
Vertically	7.5 – 20	150	5 – 15

Table 2. 3: *GPS positioning errors when operating in PPS, SPS and DGPS modes. For DGPS operation, a distance of 90 km between the receiver and the reference station is assumed [7,16,18].*

2.2.1 Selective Availability

The main source of error is Selective Availability, which degrades the system's accuracy to 100m, 2drms. Selective Availability uses two techniques to reduce the accuracy of GPS position measurements: ephemeris manipulation and satellite clock dither. In ephemeris manipulation intentional errors are introduced into the broadcast orbital parameters which affect the measured position co-ordinates. Clock dither is a time-varying de-synchronisation of the satellite's clock with respect to GPS time. The SA error at any moment is different for each satellite and the DoD sets its magnitude and rate of change.

2.2.2 Ephemeris error

Apart from the intentional SA error introduced into the ephemeris data, there is a natural uncertainty in determining the orbital location of the satellite since the orbital parameters are changing constantly. The error with which a satellite's position is known is normally of the order of a few metres, but can be as high as 20-30m if an error occurs in the ground control segment of the GPS system. Also, the ephemeris information transmitted by the satellites has been supplied by the GPS ground monitoring sites and is inevitably out-of-date. Post-processed measurements of the precise orbits are available with delays of typically 48h; thus they are of use for surveying purposes but not for real-time navigation [17,18].

2.2.3 Satellite Clock Bias

Since the receiver clock bias, B_{user}, and its rate can be isolated as an unknown in the navigation solution to equations 2.3-2.6, its magnitude does not affect the position co-ordinates. Further, receivers do not need to carry very accurate clocks. However B_{user} is found by assuming that all satellites' clocks are perfectly synchronised. Unfortunately this not the case, in spite of the use of atomic clocks in the satellites. Satellite clock bias values can be of the order of tens of nanoseconds. To allow receivers to remove these errors, the satellites broadcast values estimated by ground stations as 'clock corrections'. These enable the receiver to correct the time-of transmission to within 5-10ns of true GPS time. Each remaining nanosecond of satellite clock error causes a pseudorange error, Δ_ρ:

$$\Delta_\rho = c.10^{-9} = 0.3\ m. \tag{2.7}$$

Thus a typical satellite clock bias of 5-10ns results in a position error of 1.5-3 m [18].

2.2.4 Additional Signal Delay

The velocity of the signal from a GPS satellite is a little lower when propagating through the ionosphere or troposphere than in free space. This may result in a positive pseudo-range measurement error. Corrections may be applied as follows [19,20,21].

The ionospheric signal delay may be estimated from the Total Electron Content (TEC) along the propagation path. At the L_1 frequency, typical delays are tens of nanoseconds; maximum values may be as great as 200ns. The delay is strongly frequency-dependent, being inversely proportional to the frequency squared. PPS users, with their access to both frequencies, can measure this delay by comparing the times-of arrival of signals at the two frequencies. SPS users, with only a single frequency, must employ ionospheric models that allow the delay due to the ionosphere can be estimated and so rectified. Such models can reduce the effects by typically 50% [22,23]. If no compensation is applied, ionospheric delay may introduce errors of 3-30m. The model generally reduces the error to 1.5-15m.

Tropospheric delays are essentially frequency-independent and apply equally to SPS and PPS users. One correction model relates delay to the angle of the satellite above the horizon viewed from the user's location; the value is typically a few meters for satellites above 5°; for satellites below 5° positioning errors of tens of meters have been measured [24]. Employing tropospheric models can correct 90% of the error. In addition and most users limit the minimum angle to 5°, or even 10°.

2.2.5 Multipath propagation

Further pseudorange errors are experienced when the signal reaching the receiver has arrived via reflection from nearby objects. Such multipath propagation is frequency-independent and can affect PPS and SPS users similarly, introducing errors of tens of nanoseconds. It is possible to reduce the effect of multipath by signal processing techniques in the receiver, such as Kalman filtering of the pseudoranges [25], by using antennas with left-hand circular polarisation (to match the polarisation of the signals but not that of the reflections) and by careful antenna site selection.

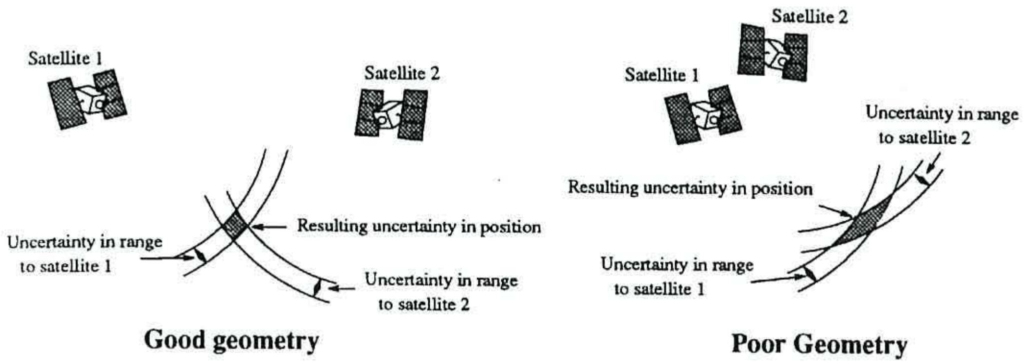

Figure 2. 4: *For the same degree of uncertainty in pseudorange measurements, the accuracy decreases considerably when the satellites are close to one another, as shown in the 'poor geometry' case, after [27].*

2.2.6 Satellite Geometry

As with many navigation systems, the geometrical distribution of GPS transmitters has a considerable effect on the system's accuracy. Poor satellite geometry can dramatically increase the effects of small uncertainties in pseudorange measurements, corresponding to Geometrical Dilution of Precision (GDOP). Fig. 2.4 shows the effect of GDOP for a two-dimensional case. For same level of error, if the satellites are close to each other (the "Poor geometry" case), the area of uncertainty is much larger than where the satellites are distant from each other ("Good geometry"). A good GPS geometry would be obtained if three of the satellites were spaced around the horizon and a fourth was directly overhead.

GDOP consists of two components: the Position Dilution of Precision (PDOP) and the Time Dilution of Precision (TDOP). A higher DOP means a higher degree of uncertainty in the result. Users with a clear sky in all directions can usually select from a greater number of visible satellites, choosing the four that give the lowest DOP; they would expect to achieve PDOPs of less than 6 under normal conditions. PDOP can also be considered to consist of two parts: Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP). Under normal conditions users enjoy HDOPs of less than 2 [1,11,26].

2.3 The need for DGPS

GPS users' real-time navigation accuracy requirements change dramatically depending on the application. For the SPS users, GPS generally provides 100m 2drms accuracy world-wide. Table 2.4 [9,28-30] lists the precision required for the various tasks that increasingly employ GPS.

Users require a cost-effective way to improve real-time GPS accuracy to a few meters. This can be achieved by using differential techniques: errors in the pseudoranges are measured at a reference station and communicated to the user who employs them to correct his own measurement errors.

In addition, users engaged in safety-critical and mission-critical tasks need assurance that the system is working correctly [31,32] and to be sure that system errors are flagged promptly [9, 33]. Because such integrity is not built into the GPS system, it can take hours before the system reports that the satellites are faulty. However, reference stations can detect that satellites are healthy by checking their pseudoranges. In case of an unhealthy satellite, the differential system can then warn the user and disable the usage of a faulty signal.

Application	**Accuracy (2 drms)**	**Is SPS enough?**
Intelligent Vehicle Highway Systems		
Navigation	5 – 20 m	No
Mayday/ Incident Alert	5 – 30 m	No
Fleet Management	25 – 1500 m	Some
Automated Stop Announcement	5 – 30 m	No
Vehicle Command and Control	30 – 50 m	No
Collision Avoidance	1 m	No
Accident Data Collection	30 m	No
Infrastructure Management	10 m	No
Railroad Traffic Management		
Train Position Tracking	10 – 30 m	No
Train Control	1 m	No
Automated Road Vehicle Warning at Crossing	1 m	No
Marine Transportation		
Harbour / Harbour Approach	8 – 20 m	No
Harbour Research Exploration	1 – 3 m	No
Coastal	460 m	Yes
Ocean	3700 – 7400 m	Yes
Air Transportation		
En Route Oceanic	23 km	Yes
En Route Domestic	1000 m	Yes
Terminal	500 m	Yes
Approach / Landing: Non-precision	100 m	Yes
Approach / Landing: Precision Cat. I – III	H: 17.1 – 4.1 m V: 4.1 – 0.6 m	No
Non –Transportation		
Search and Rescue	10 m	No
Aerial Crop Dusting	10 m	No
Aerial Surveillance	1 – 5 m	No
Emergency Management	8 – 10 m	No

Table 2.4: *For numerous applications, including many safety-critical civilian ones, the positioning accuracy of SPS is inadequate [9,28-30].*

2.4 Introduction to DGPS

Differential operation of GPS greatly reduces many of the errors discussed above, including the dominant one, SA. The principle is that such errors are well correlated at locations in the same area and so the relative locations of two receivers can be evaluated with high accuracy. Thus, if the location of one of the receivers is known precisely, the location of the other can be determined accurately.

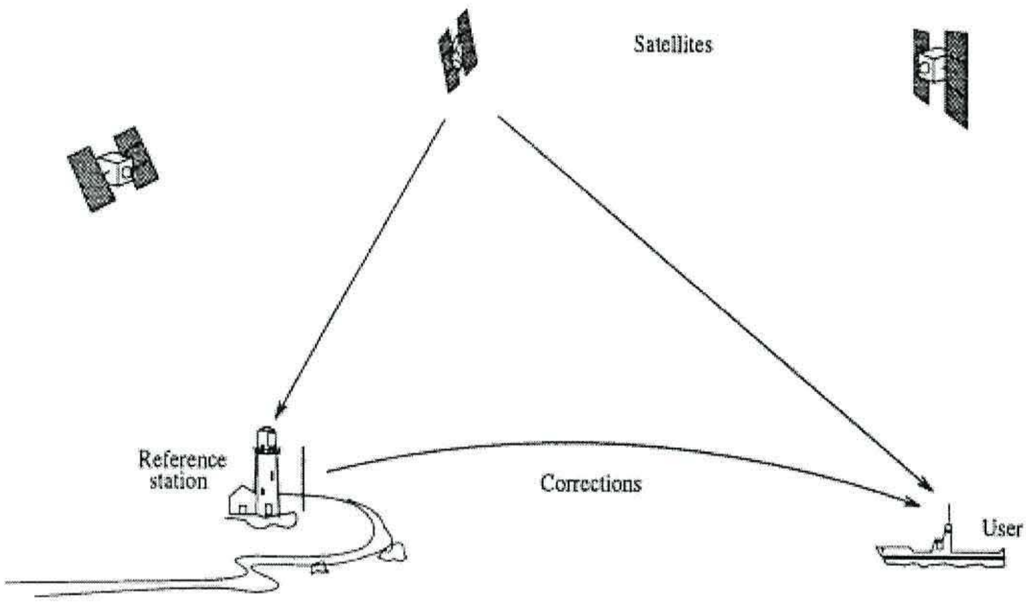

Figure 2. 5: *The reference site and the user receive signals transmitted from the same satellites. Corrections are calculated at the reference station and broadcast to the user to allow him to correct his pseudorange errors [5,34].*

Fig 2.5 shows a typical marine DGPS system [5,34]. The reference station and the user employ signals from the same GPS satellites. The reference station, which is situated at a known, surveyed, position, compares each measured pseudorange with the pseudorange it calculates from knowledge of its location and the satellite's ephemeris. The difference is the pseudorange correction (PRC) for the satellites at that time. The reference station tracks all the satellites it has in view, and calculates their PRCs. It then sends these PRCs through a data link to the user's receiver where they are added to the measured pseudoranges to correct the pseudorange errors. The user then employs all the satellites above the masking angle to calculate a position.

Timely reception of PRCs largely neutralises positioning errors due to SA, both the satellite ephemeris and the clock dither components. It also reduces the ionospheric and tropospheric delay errors to an extent that depends on the separation between the reference station and the user, specifically to the degree to which the TEC of the ionosphere is the same for both. DGPS cannot reduce multipath errors or receiver-dependent errors; on the contrary; any multipath errors at the reference station will be included in the PRCs and so affect the user's measured position. The errors in the case of DGPS are shown in Table 2.3; it can be seen that DGPS can offer a positioning accuracy better than either SPS and PPS. Differential GLONASS operates in just the same fashion as DGPS.

2.5 Radiobeacons

Radiobeacons are radio stations installed at lighthouses, or on light vessels, on which ships can take direction-finding (DF) bearings. In one mode of DF operation the ship uses a beacon as a leading mark and steers towards it, the navigator correcting the course from time to time by reference to successive radio bearings (Fig. 2.6) [35]. The radio bearing corresponds directly to the Great Circle course, and if repeated consistent radio bearings are followed, the shortest course to the beacon will be steered. The ship's position may also be fixed by radio cross-bearings, using two or more radiobeacons (Fig. 2.6). Radio direction finding is not much used nowadays; however, the radiobeacon transmitters are being widely used instead to broadcast differential GPS data to mariners.

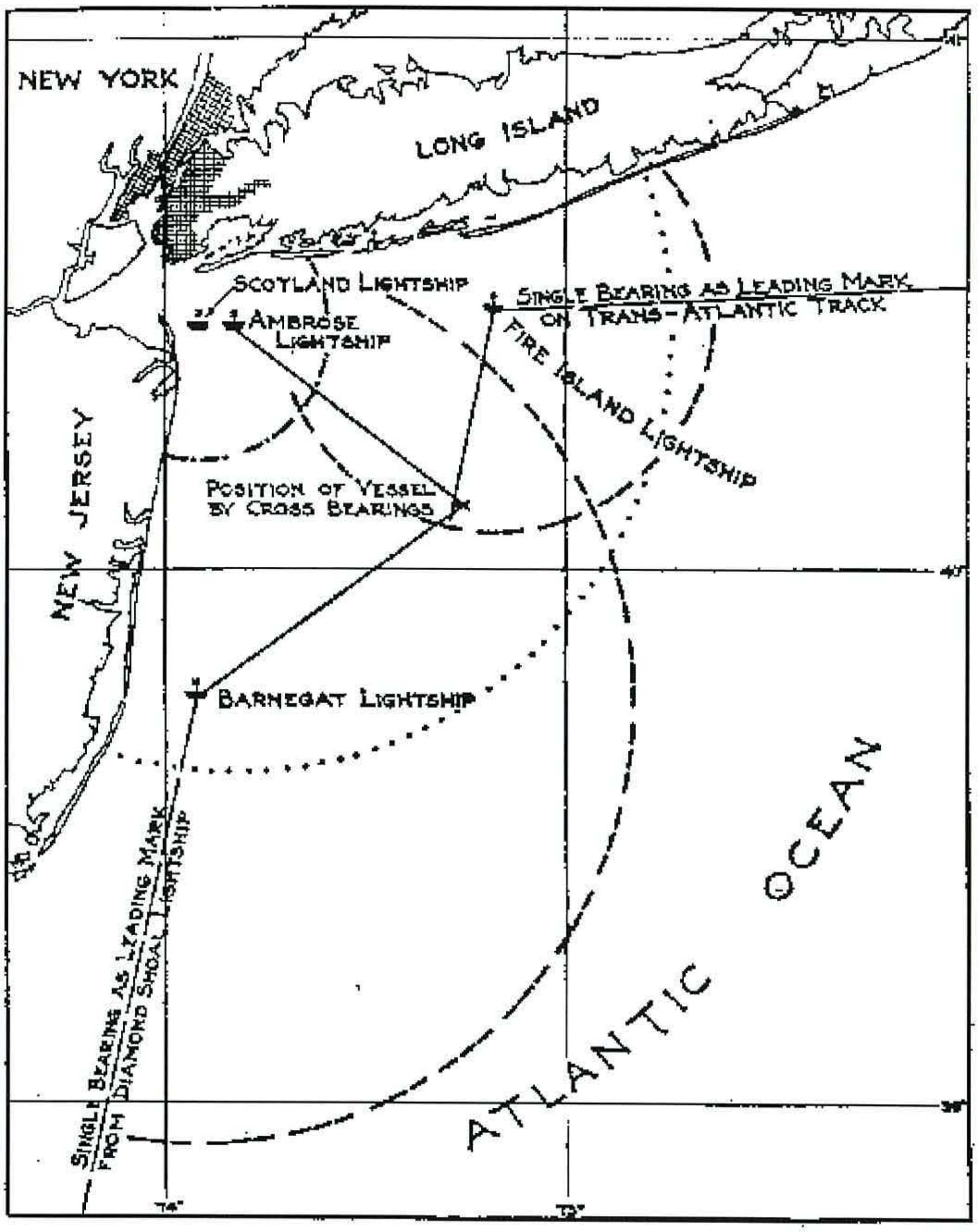

Figure 2. 6: *A radiobeacon can be used as a leading mark for a vessel to steer towards for a non-precision approach. Alternatively, cross-bearings from two or more radiobeacons may be taken to give a position by triangulation [35].*

2.5.1 DGPS Radiobeacons as datalinks

For the broadcasting of differential GNSS data, the Radio Technical Commission for Maritime Services, Special Committee No. 104 (RTCM SC-104), has issued recommendations concerning the message format [18,36]. Data can be sent in this RTCM104 format using any RF link, or any other medium that offers reliable communication with a data rate of at least 50 bps [37]. This minimum data rate is set by the rate of SA clock dither, which dominates the rate at which pseudorange corrections should be updated. If broadcast and received continuously, 50 bps data rate should result in a differential GPS position accuracy of approximately 5m 95% of the time.

When RTCM data messages are broadcast via a radiobeacon, its carrier is modulated using Minimum Shift Keying (MSK). This modulation has been shown not to interfere with the use of the beacon for direction-finding. MSK is also a narrow-band technique, which minimises the bandwidth of the transmitted signal. The corresponding receiver bandwidth can also be narrow, thus minimising received noise power and so maximising signal-to-noise ratio (SNR). The radiobeacon DGNSS system is approved by the International Association of Lighthouse Authorities (IALA) [38] and by the International Telecommunication Union (ITU) [13]. It is employed by many national and international organisations including the General Lighthouse Authorities of British Isles (GLAs), the United States Coast Guard (USCG) and the Canadian Coast Guard (CCG) [5,39,40].

Radiobeacons are very suitable for transmitting DGNSS corrections since they are installed at surveyed locations, easily equipped with the necessary infrastructure to broadcast the correction data, and a band of the frequency spectrum has been allocated for their transmissions. Also, their ranges are of the order of hundreds of kilometres at most; over such distances the errors of the users are well correlated with those at the reference stations. As a result, pressing them into service proved much more straightforward than pioneering a new service. Many countries already had radiobeacons systems and the cost of adapting them was much lower than that of building a new infrastructure. Equipment for receiving the MSK transmissions was relatively easy to develop and it is now widely available. [41,42].

IALA is the main international body for setting radiobeacon standards, co-ordinating frequency planning and specifying correction standards for both GPS and GLONASS; it is especially influential in Europe. IALA collaborates with the United Nations Organisation's International Maritime Organisation (IMO) and with the International Telecommunication Union - Radio (ITU-R). We will see in

Chapters 4 and 5 that the work of these organisations influences (and hopefully will be influenced by) the research in this thesis.

2.5.2 Radiobeacons in the EMA

Radiobeacon DGNSS installations are being planned and commissioned in many countries [44,45]. In the European Maritime Area (30°N to 72°N 30°W to 55°W), such stations are operated in the frequency band 283.5-315 kHz. This band is split into 64 channels spaced at 500 Hz, which are currently occupied by more than 400 DGNSS and marine beacons and with a number of aeronautical beacons whose service shares the allocation [46]. Fig. 2.7 shows the extent of the EMA and the locations of the radiobeacons currently operating in it within the frequency band 283.5-315 kHz .

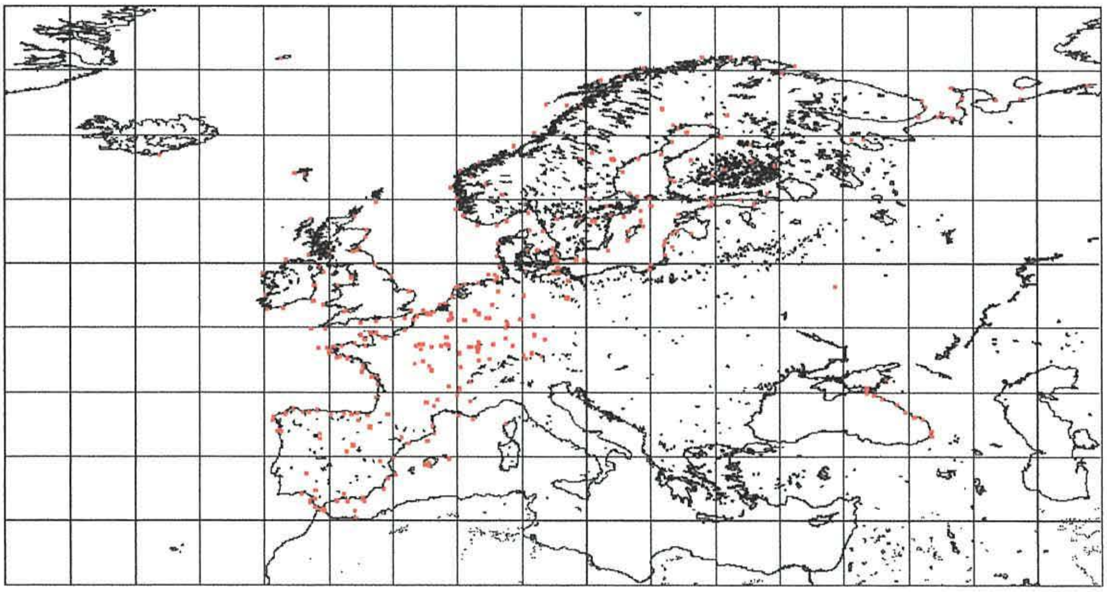

Figure 2.7: *The European Maritime Area of ITU Region 1 and the radiobeacons operating in the frequency band allocated for DGNSS radiobeacons.*

2.6 Conclusions

GPS is now used for a wide range of positioning applications, in either stand-alone form (providing typically 100 m accuracy), or as DGPS with an accuracy in the order of few metres. Using differential reference stations, many errors can be corrected and the integrity that GPS itself lacks may be built into the system.

Marine radiobeacons, with which this research is concerned, is a very efficient way of transmitting these correction signals. DGNSS radiobeacons are now being installed throughout the EMA.

Chapter 3

Performance of Radiobeacons

3.1 Introduction

In Chapter 2 we have seen that stand-alone GNSS is not sufficient for many applications. These applications require an augmentation to GNSS, which can make the system more accurate and also inform the user if the satellites fail to operate properly. One possible augmentation is to use the maritime radiobeacons.

The new data transmission imposed on this old system, however, is very different from its traditional transmissions. The question therefore is to evaluate the performance of radiobeacons in their new task. A coverage prediction model developed by Poppe and Last [27] will be introduced in this chapter. It takes into account various factors that affect the signal transmitted from the radiobeacons, including attenuation, different modes of propagation and their interactions, and the effects of atmospheric noise. Finally the performance of a number of radiobeacons in the EMA, analysed using the model, will be illustrated. Much of the research to be described in this thesis is based on Poppe's work, which it extends greatly.

3.2 Coverage prediction

The area in which the signal transmitted from a radio transmitter achieves a minimum standard is the coverage area of that service. In the case of radio navigation, this minimum standard is the required accuracy and availability. For radiobeacons this availability and accuracy can be affected by a number of factors and evaluating the coverage area can be very complex. The rates of attenuation of the signal are different for different propagation modes [47]. Signals refracted back from the ionosphere can travel much further than the intended range of the beacon [48]. At the frequencies at which the radiobeacons operate, non-Gaussian atmospheric noise has a considerable effect [49]. Furthermore, fading and interference can seriously undermine service quality [27,50]. Many system planners, however, do not take these effects into account and represent coverages simply as circles centred on the beacons' sites, their radii representing their nominal ranges (Fig. 3.1) [51].

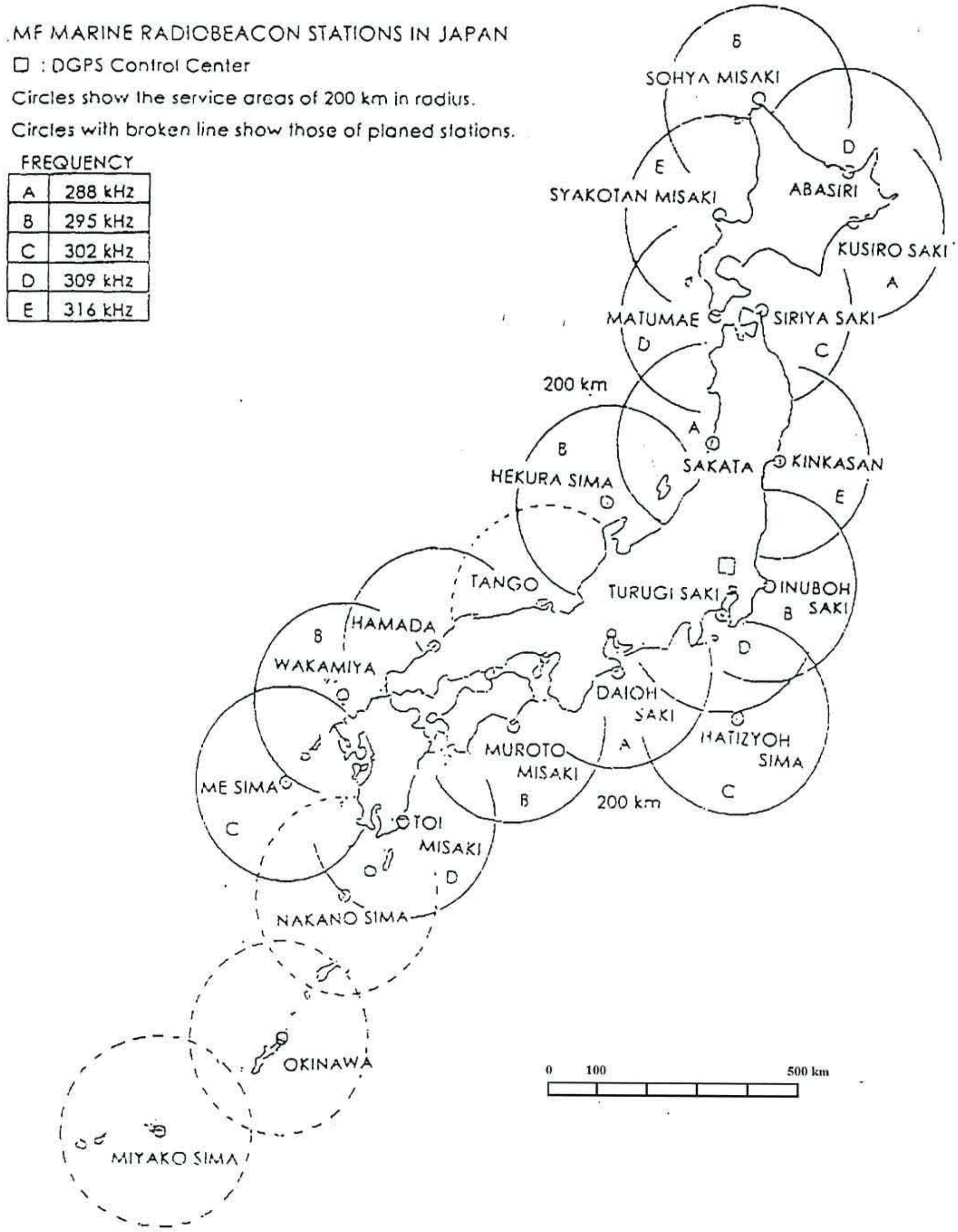

Figure 3. 1: *Planning of a radiobeacon DGPS system with coverages represented simply by circles centred on the beacons, their radii representing nominal ranges [51].*

3.2.1 Bangor coverage prediction model

In recent years a great deal of work has gone into developing techniques for predicting the coverages of radiobeacon DGNSS stations, principally at Bangor. The coverage prediction model developed at Bangor by Poppe and Last [27,52] is based on the concept that the coverage of a radiobeacon is the area within which the wanted field strength and signal-to-atmospheric noise ratio (SNR) are higher than internationally agreed minima and the wanted signal is not degraded by interference to more than a specified degree.

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) and, in the US, the national administration [13,37,38,53]. Within the European Maritime Area of ITU Region I, the field strength and atmospheric signal-to-noise ratio (SNR) of each service must exceed the minima shown in Table 3.1 [9,10]. The signal-to-interference ratio (SIR) for the wanted signal must exceed any interfering signal in Table 3.2 [13,37,53]. As an example, Table 3.1 shows that at all points within the coverage of a DGNSS radiobeacon, the field strength must exceed 10μV/m (20dBμV/m) and the SNR 7dB.

The powers of MB and DGP transmitters are conventionally expressed by their nominal ranges; that is, the ranges over sea-water at which their field strengths have fallen to these minimum values. In the case of DGNSS beacons the same convention is maintained; however the nominal ranges are those at which the signals have fallen to the MB minima rather than the actual ranges for the DGNSS transmissions.

The figures in Table 3.2 are the ratios of the wanted signal's field strength to that of any interfering signal. For example, a DGNSS receiver must be capable of correct operation when subject to an interfering MB or NDB on the first adjacent channel (0.5kHz separation) up to 25dB stronger than the wanted signal.

	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 [13,37,53].*

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 3.2: *Protection ratios (in dB) that specify the minimum ability of a receiver to reject interference [after 13,37,53].*

The model predicts the coverage of a DGNSS station by working one-by-one through an array of geographical points centred on the station, computing at each point the field strength of the wanted signal, the atmospheric noise and the interference. By reference to the above tables it then determines whether the point lies within coverage or not.

The model recognises that the signal from a DGNSS station is normally received principally by means of groundwave propagation. The strength of the groundwave component depends on the range of the receiver from the transmitter and on the nature of the propagation path. Attenuation is greater over land than it is over sea [47].

During night-time a skywave component of the signal appears that has travelled via the ionosphere. This may interfere with the groundwave signal, resulting in fading. There is a finite probability that the total signal strength available to the receiver will be much less than the normal steady groundwave signal. Skywave intensity and fading depend on range, latitude, time of day and season of the year [27,48,50]. The model takes all these factors into account and estimates the signal level that can be guaranteed for 95% of the time at night.

The signal-to-atmospheric noise ratio is estimated from the strength of the wanted signal and that of the atmospheric noise. The intensity of the noise varies in a random fashion, its mean value over any interval being a function of geographical location, time of day and season of the year [49].

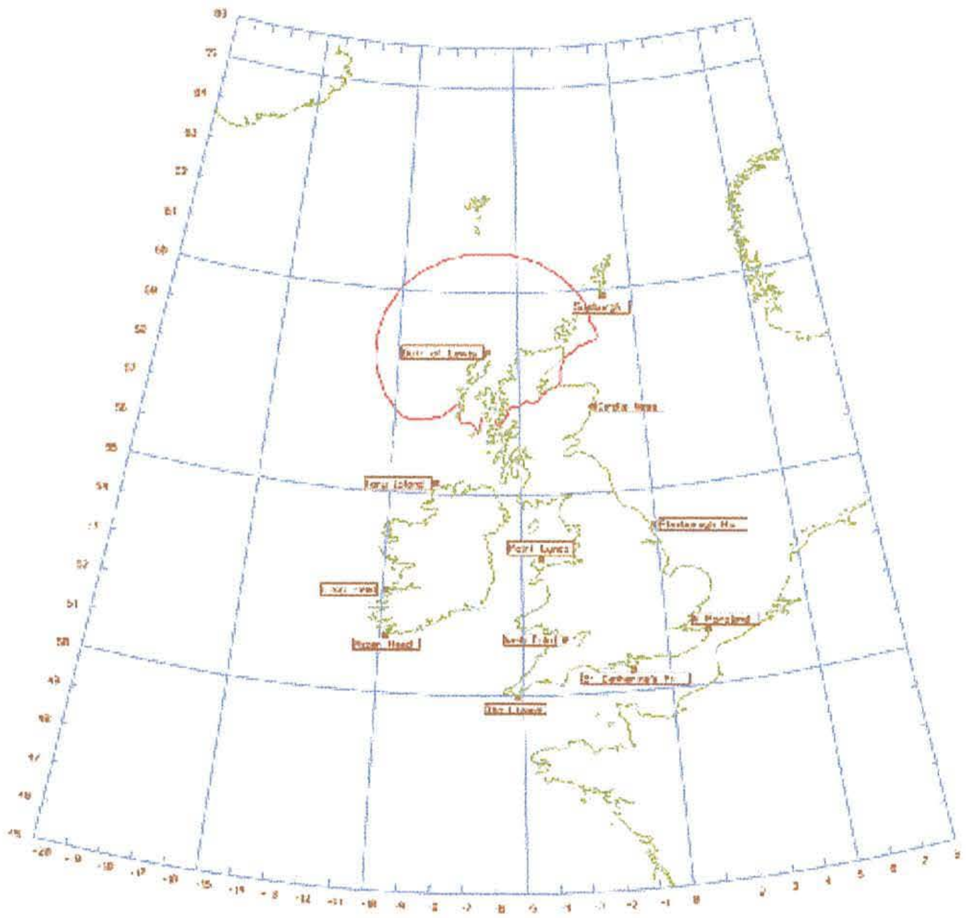

Figure 3.2: *The coverage of the DGNSS radiobeacon at Butt of Lewis predicted by the Bangor Coverage Prediction Model, after [54].*

The model also estimates the level of interference received from other stations at each point in the array. The Minimum Performance Standards (MOPS) for radiobeacon DGNSS receivers set limits (Table 3.2 above) to the signal-to-interference (SIR) for co-channel transmissions and those up to 6 channels either side

[53]. The model estimates the levels of interference received from every other beacon that is a potential interferer, via both groundwave and skywave propagation, and compares the result with these standards. Fig. 3.2 shows an example of a coverage area predicted by this model in which, at every point, the minimum field strength, SNR and SIR conditions are met.

We will now consider individually in more detail each of the factors taken into account by this model.

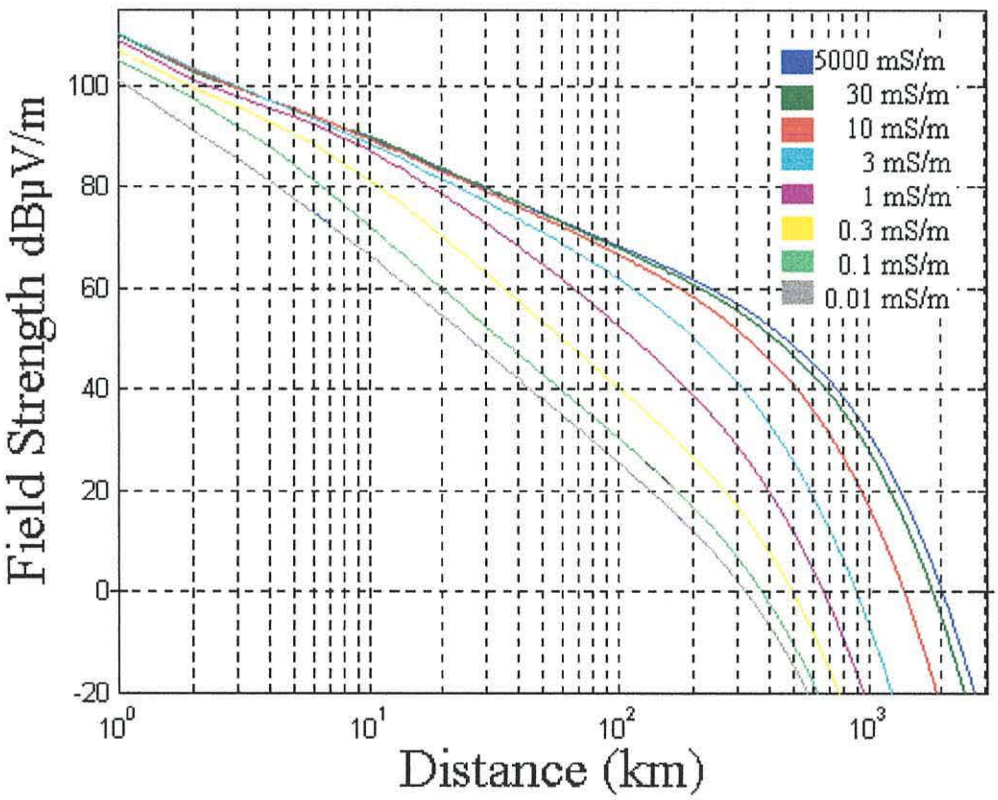

Figure 3. 3: *Groundwave field strength in dBµV/m curves for a 1 kW radiobeacon operating at 300 kHz [47]. The individual curves of the family correspond to different path conductivity values in milli-Siemens per metre (mS/m).*

3.2.2 Groundwave Propagation

The groundwave field strength of a radiobeacon's signal received at any point depends on its transmission power and on the attenuation of the path between the radiobeacon and the receiver. The attenuation can be evaluated using standard ITU curves of groundwave attenuation versus distance [47]. These curves (Fig. 3.3) plot the attenuation of the field strength of the groundwave signal with respect to distance over different types of terrain. They are produced for a wide range of frequencies; the curves in Fig. 3.3 represent propagation at 300kHz, the centre of the radiobeacon frequency band. The individual curves of the family correspond to 8 standard ground conductivity values employed by ITU. It can be seen that ground conductivity is a very powerful factor, the attenuation over the poorest land path being some 40dB greater at 100km than that over seawater.

Poppe has shown that, given that the frequency band for maritime radiobeacons in the EMA is relatively narrow (283.5-315.0 kHz), these 300 kHz curves may be employed at all frequencies in the band, the error at the band edges being less than 1dB [27].

3.2.2.1 Millington's Method

In general, propagation paths consist of sections that have different conductivities. For such inhomogeneous paths, ITU recommend the use of Millington's method, a technique for estimating the total attenuation of a mixed conductivity path [55]. A detailed explanation of Millington's method is given in Appendix A.

3.2.2.2 Ground Conductivity

It is clear that calculation of groundwave attenuation (and hence of groundwave field strength) requires information about the electrical conductivity of the paths involved. The ground conductivity for most of the EMA has been studied by Last, Searle and Farnsworth [56]. Using data from the ITU World Atlas of Ground Conductivities [47] and other sources, they created a digitised map, the Bangor Ground Conductivity Database, with a resolution of 0.1° of latitude by 0.1° of longitude. A section of this database is illustrated in Fig. 3.4. In assembling the database, ground conductivity values are assigned to the nearest of the 8 standard ITU values further described in Table 3.3. Areas of exceptionally low conductivity can be seen in Scandinavia, where there is glacial ice. Most of Britain has well-conducting soil.

The use of Millington's method and the Bangor Ground Conductivity Database are illustrated in Fig. 3.5. This shows groundwave field strength contours surrounding the DGPS radiobeacon at Girdle Ness, near Aberdeen. Note how rapidly the field strength is attenuated when the signal reaches the poorly-conducting land of Scandinavia, and the much greater ranges achieved over the sea path towards Denmark than over the Scottish Highlands [57].

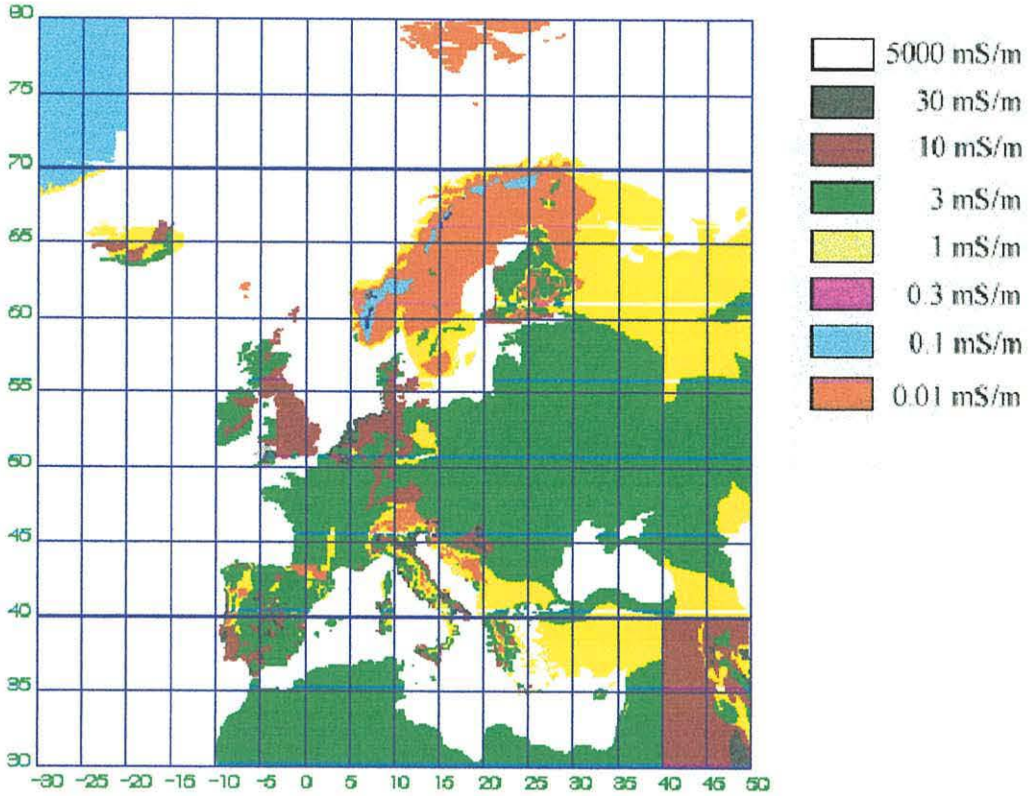

Figure 3. 4: *The part of the Bangor Ground Conductivity Database that covers the European Maritime Area. The colours represent the 8 standard ground conductivity values employed by the ITU.*

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 3.3: *The 8 standard ground conductivity values employed by ITU with the types of terrain they represent and the penetration depths of 300 kHz signals [47].*

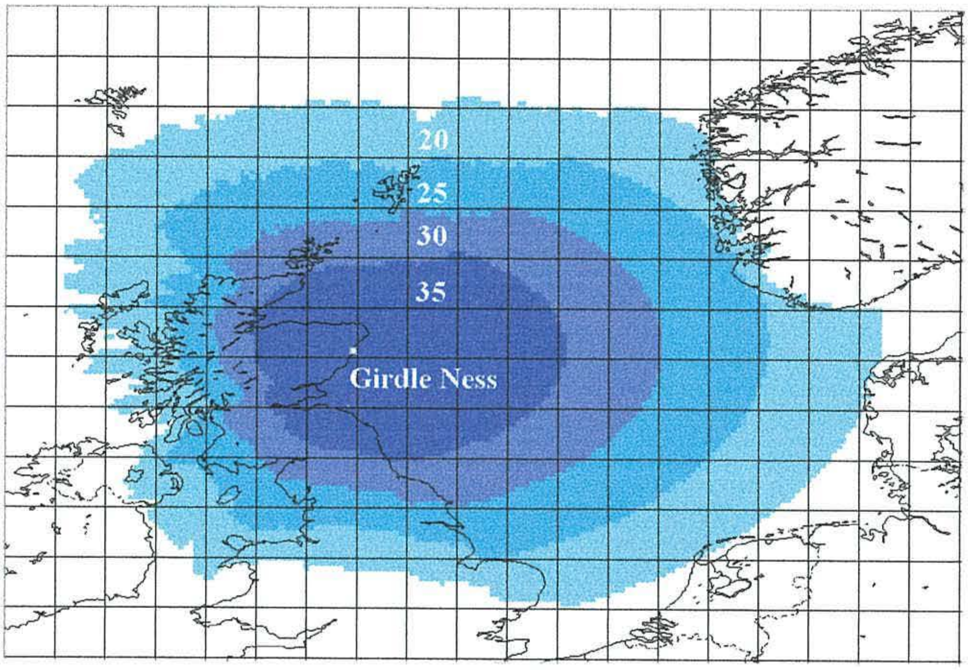

Figure 3. 5: *Groundwave field strength contours in, dBμV/m, of the radiobeacon at Girdle Ness near Aberdeen. The rates of attenuation are clearly much higher over land than over sea [57].*

3.2.3 Skywave Propagation

In addition to groundwave signals, radiobeacon transmissions reach the user via skywave propagation, the signals being refracted back to earth from the ionosphere [48]. An important distinction between radiobeacon DGNSS signals and those of other low-frequency navigation systems is that in this case, messages received via skywave are as valuable as those received via groundwave and may even extend the ranges of the stations. In other systems (such as Loran-C) that work by measuring distances over the ground, skywave components are undesirable. However, skywave components of radiobeacons signals may cause fading. Thus in coverage prediction it is important that we estimate the strengths of skywave signals.

The skywave signal received is mainly the component reflected (or, strictly, refracted) back from the E-layer of the ionosphere. Since the height and ionisation of this layer depend on solar activity, the strength and delay of the skywave signal change with time of day and season of year. During daytime the skywave signal virtually ceases to exist because of attenuation in the D-layer that lies below the E-layer. At night, however, the skywave field strength may rise to a considerable level.

Fig. 3.6 shows the skywave field strength of a 1kW radiobeacon at 300 kHz; these ITU curves are again based on extensive data gathered over a long period and in many regions [48]. The strength is low near to beacon site and reaches its peak about 200km away, beyond which it is slowly attenuated with distance.

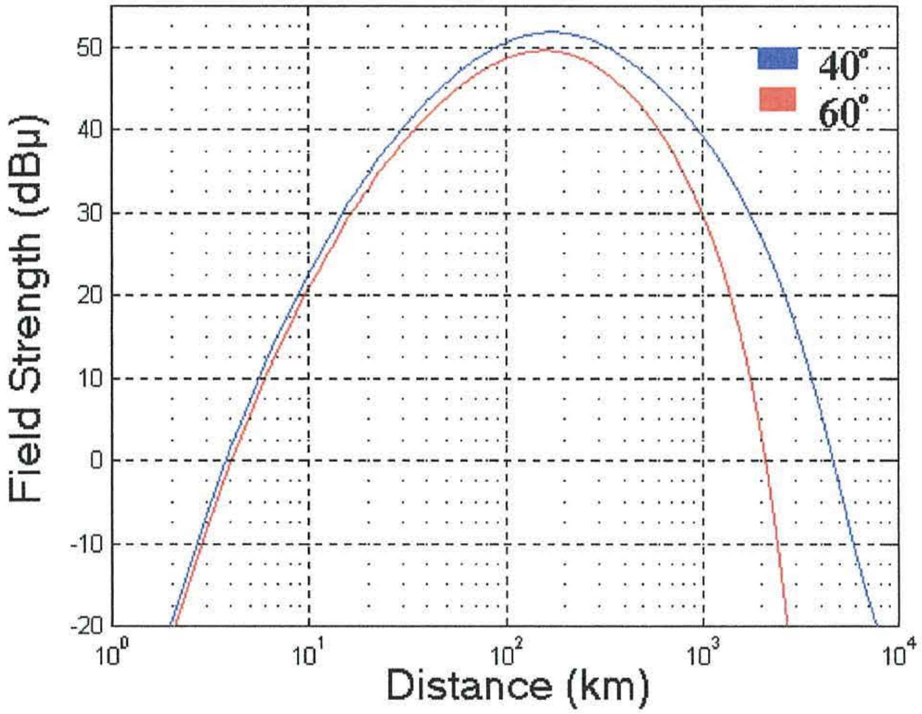

Figure 3. 6: *ITU skywave field strength curves for a 1 kW radiobeacon at 300 kHz. The rate of attenuation changes with geomagnetic latitude. Curves are shown for latitudes 40° and 60° [48].*

Skywave field strengths may also be estimated by an ITU method [58]. The median strength, Sky_{dB} (dbµ), at any range d (km) is given by:

$$Sky_{dB} = A\text{-}20\log(p) - 10^{-3}\,k\,p + G_S + G_V + \Delta_P, \qquad (3.1)$$

where: Δ_P is the beacon's power with respect to 1kW, p the slant propagation distance in km, k the basic loss factor, G_V the antenna gain factor, A is 106.6 -sin (Φ), Φ is the geomagnetic latitude and G_S the sea gain. We will now examine these individual terms.

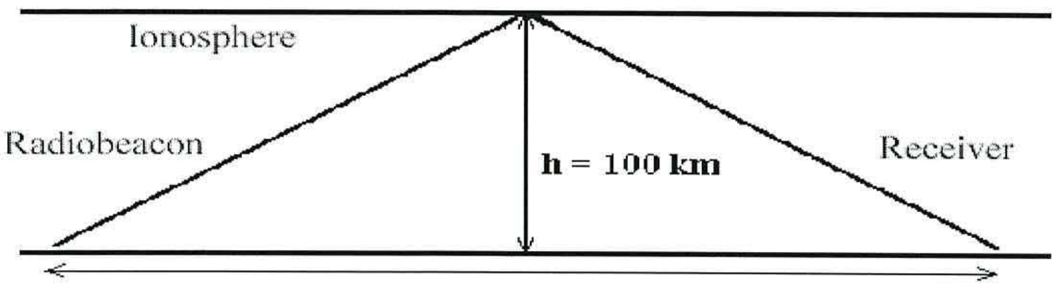

Figure 3. 7: *The path travelled by the skywave signal is longer than that of the groundwave. The total path length followed by the skywave component is known as the slant propagation distance.*

The slant propagation distance is the total path length between the transmitter and the receiver via the ionosphere (Fig. 3.7). For a typical E-layer height of 100km this distance is:

$$P = \sqrt{d^2 + 200^2} \tag{3.2}$$

The basic loss factor attenuation due to the ionosphere is:

$$k = 3.2 + 0.19 f_{KHz}^{\;0.4} \tan^2(\Phi + 3) \tag{3.3}$$

where f_{kHz} is the frequency in kHz.

The skywave field strength also depends on the geomagnetic latitude of the mid-point of the propagation path between the receiver and the radiobeacon. Geomagnetic latitude is the latitude with respect to the poles of earth's magnetic field. The co-ordinates of north geomagnetic pole are currently 78.5°N, 69°W. Geomagnetic latitude is given by:

$$\Phi = \arcsin(\sin\alpha.\sin(78.5°) + \cos\alpha.\cos(78.5°).\cos(\beta - 69°)) \tag{3.4}$$

where Φ is the geomagnetic latitude, α the geographic latitude and β the geographic longitude.

Radiobeacon antennas are almost always vertical monopoles (with or without capacity hats) that are short in comparison to the wavelength. Thus their radiation patterns have a null vertically above the station and a maximum along the horizontal plane. A polynomial fit to the radiation pattern gives the antenna gain with respect to the distance from the transmitter as:

$$G_V = -12.4530 + ld(91.2214 + ld(-26.8642 + 2.6164ld)), \tag{3.5}$$

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

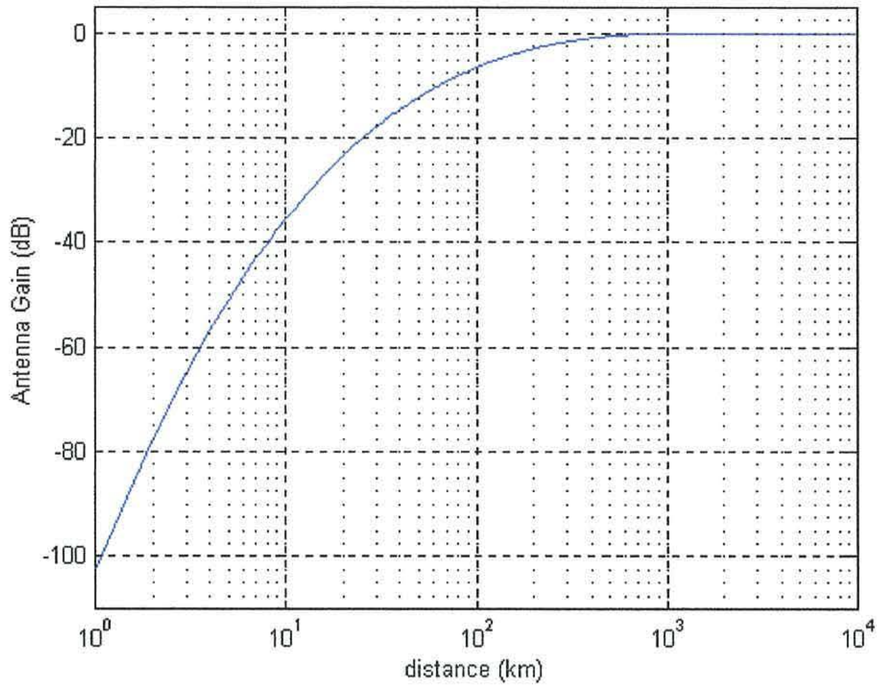

Figure 3. 8: *The antenna gain of a short monopole [48].*

Attenuation due to antenna gain is very high near the radiobeacon site but gets smaller with range. It has negligible effect beyond 300km (Fig. 3.8) [48].

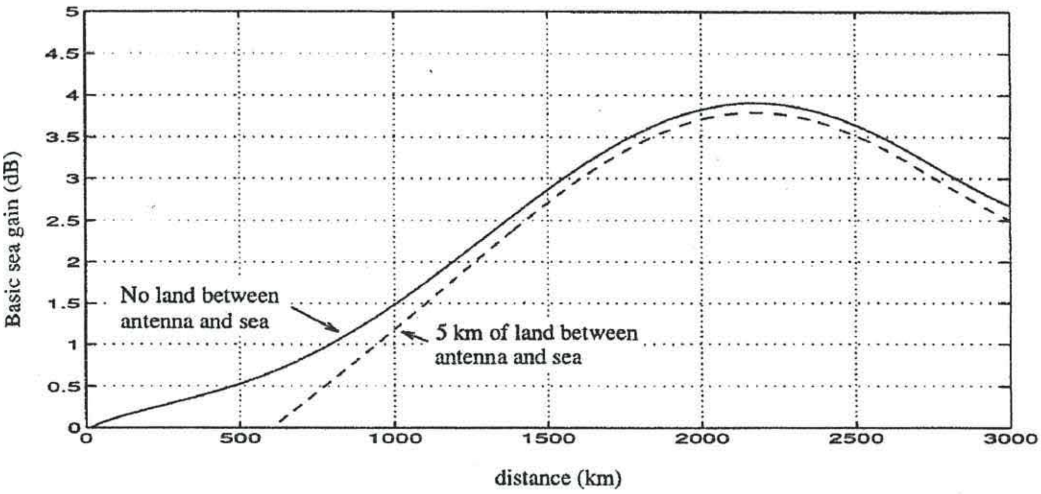

Figure 3. 9: *Change of sea gain with respect to distance between transmitter and receiver. As an antenna is moved away from the sea, the sea gain falls until by 5km there is negligible sea gain [48].*

If either the antenna of the receiver or the transmitter, or both, is near to sea-water, the skywave field strength is a little stronger than otherwise. Fig. 3.9 shows this "sea gain" effect. It illustrates the case where the receiver is 1000km from the transmitter and the sea gain at each end is 1.5dB. Sea gain falls with increasing distance between antenna and sea, becoming negligible by 5km. [48].

All these factors have been built into a computer model by Poppe [27] to simulate the change of field strength. Figure 3.10 shows how the field strength of Girdle Ness in Scotland changes with distance. The effect of antenna gain is clearly seen at the transmitter site and the effect of sea gain is also visible.

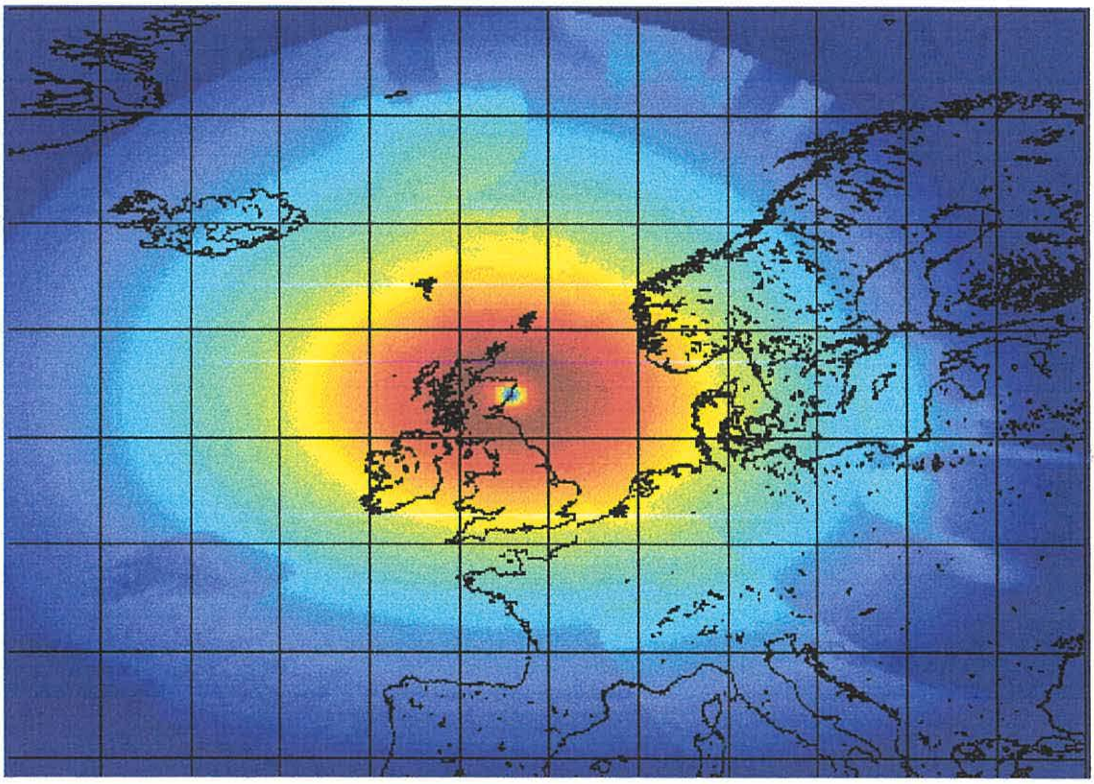

Figure 3. 10: *Skywave field strength contours for Girdle Ness. The minimum at the beacon site is clearly seen. The darkest blue represents field strength of -15dBμV/m and the maximum field strength (brown) is 23dBμV/m.*

3.2.4 Own-skywave interference: Fading

The skywave signal has to travel a longer distance than the groundwave signal to reach the same point. This difference in path introduces a relative delay to the skywave signal; its phase lags the phase of groundwave signal (Fig. 3.11). Fig. 3.12

compares the field strengths of the skywave and groundwave components. The groundwave curves correspond to seawater and poor land paths, respectively. The skywave curves are the median and 95%-ile values.

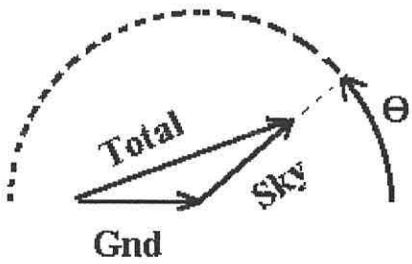

Figure 3. 11: *Representation of groundwave and skywave signal and the phase difference between them [27].*

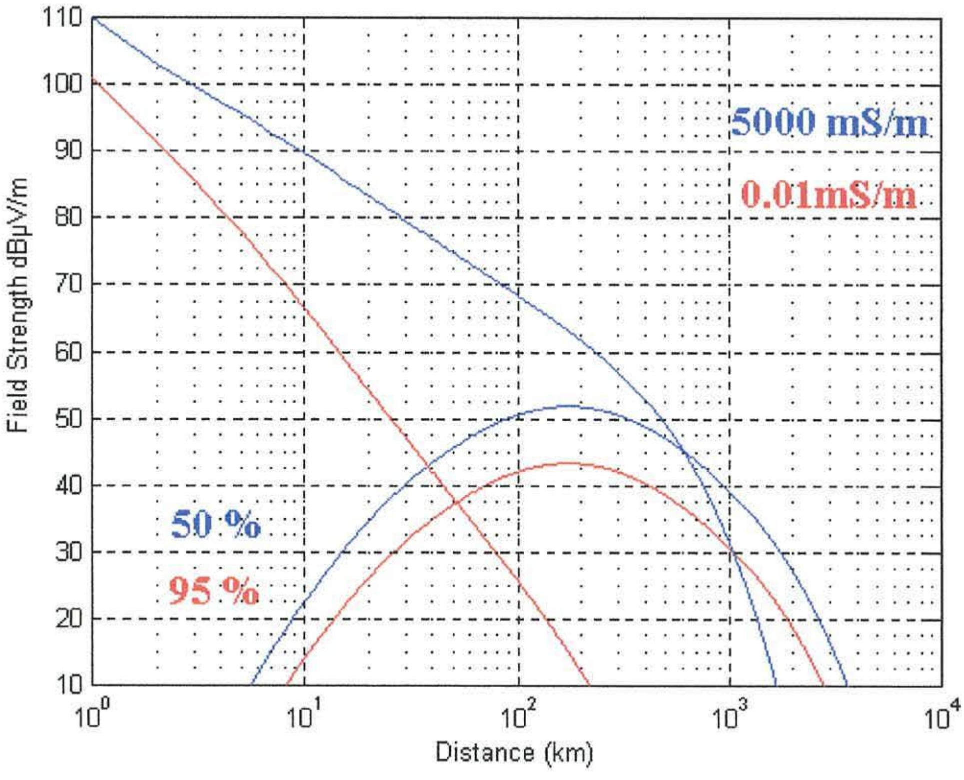

Figure 3. 12: *Groundwave and skywave field strength versus distance from the transmitter. The groundwave curves correspond to seawater and poor land paths, respectively. The two skywave curves are the median and 95%-ile values. Between 45 and 550km the magnitudes of groundwave and skywave components can be comparable, and so fading can occur [27].*

Fig. 3.12 also shows that close to the radiobeacon the groundwave is the dominant component. Far away from the transmitter the skywave component is dominant. In between, from about 45 to about 550km, the magnitudes of the groundwave and skywave components may be comparable with one another. Under these conditions there is a possibility that fading will occur if the phase difference between the two components is such that they can wholly or partly cancel [27,50].The effect of fading is modelled by Poppe [27] and used extensively to evaluate the coverage of radiobeacons throughout this study.

3.2.4.1 Own-skywave fading

The value and, therefore, the effect of skywave delay is related to range:

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

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

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

where Δ_{time} and Δ_{path} are the differences in path length and propagation time between the skywave and groundwave and c is the speed of light. Figure 3.13 shows the delay versus distance graph and the zone where field strengths are comparable. In the fading zone, the extra delay of the skywave over the groundwave is between 0.03 and 0.24ms, the value varying from moment to moment as ionospheric conditions change. These delays are equivalent to many cycles of the 300 kHz carrier with its period of approximately 0.003ms. Thus it is reasonable to consider that the phase difference between the two components varies randomly. There are equal probabilities that the components will add, giving an enhanced signal, or cancel giving fading.

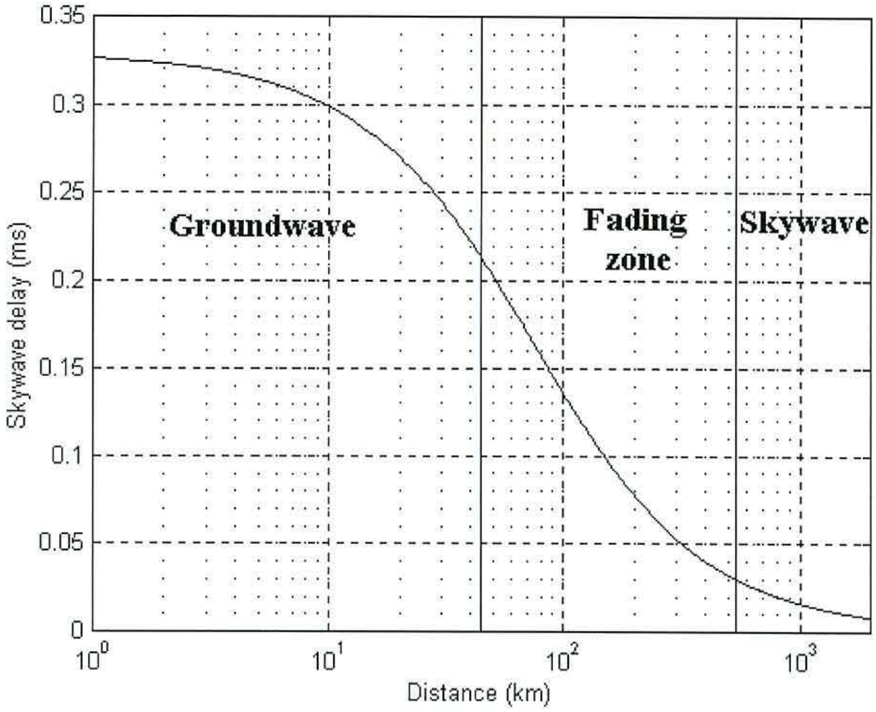

Figure 3. 13: *Skywave delay relative to the groundwave. Fading can occur in the fading zone where the field strengths of the two components are comparable [27].*

In contrast, the delay of the skywave component with respect to the groundwave has little effect on the quality of the data message. The MSK signals used in DGPS, with their bit rates of 100 or 200bps, have bit durations of 10 to 5ms – much greater than the delays experienced in the fading zone. Thus delay causes negligible corruption of the navigational message itself [50].

In order to calculate the nighttime performance of radiobeacons (since skywave is only present at significant levels during night), fading has to be introduced into the calculations. Figure 3.14 shows the effect of fading on total field strength as a function of the ratio of skywave-to-groundwave field strength, SGR [27]. The value of total field strength that can be guaranteed 95% of the time is given by:

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

where:

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

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

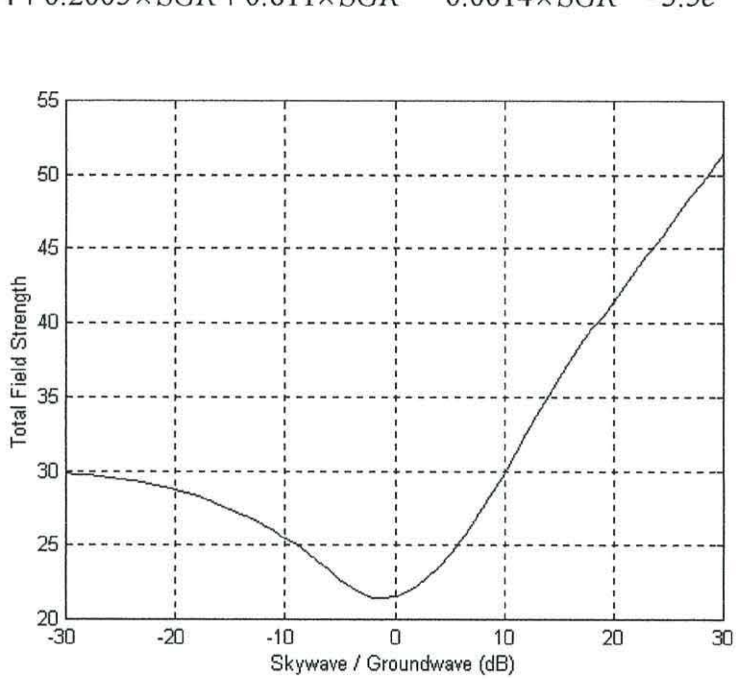

Figure 3. 14: *Total field strength of the fading signal that can be guaranteed 95% of the time as a function of skywave:groundwave ratio. The groundwave signal strength is 30dBμV/m.*

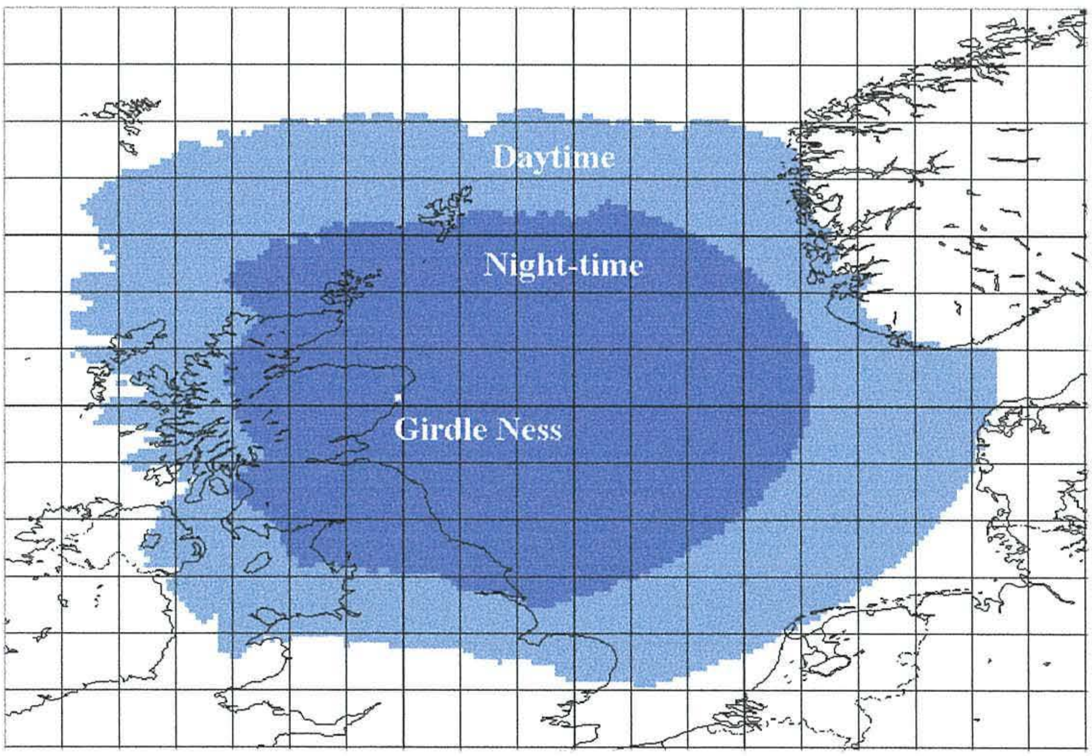

Figure 3. 15: *The effect of fading on Girdle Ness' coverage. The darker area is the region within which the field strength can be guaranteed to exceed a specified minimum 95% of the time at night. The lighter area is the part of the daytime coverage lost due to fading at night [57,59].*

The effect of fading can be seen in Fig. 3.15 where the darker area shows the region within which the field strength of Girdle Ness can be guaranteed to exceed a specified minimum 95% of the time, allowing for fading. The lighter area is the difference between this night-time and the daytime coverages, that is, the coverage lost due to fading [57,59].

3.2.5 Atmospheric Noise

In the LF and MF frequency bands, 30–3000kHz, atmospheric phenomena, particularly thunderstorms and lightning discharges, are the major sources of noise affecting radio systems. This atmospheric noise is a mixture of low-level Gaussian noise and high-level short-duration spikes. The frequent equatorial storms can greatly increase the noise power at low and mid latitudes, the noise generated within them travelling over great distances via groundwave, and especially skywave, propagation [49].

Like the skywave field strength of the beacon's signal, the intensity of atmospheric noise changes with the time of day and season of year and varies randomly over short intervals. Extensive measurements have been carried out and collated by ITU. The results have been issued in the form of maps of atmospheric noise intensity at 1 MHz at various time of day and seasons of the year. The 24 standard maps are divided into four seasons and six 4-hour time blocks. By way of example, Fig. 3.16 shows the daytime noise for summer between 0800-1200 hours, local time. It is expressed in dB above thermal noise, the contours representing a range from 10-90 dB. A separate curve (Fig. 3.17) is then used to convert these 1 MHz values to the corresponding noise levels at any desired frequency.

When converted for use at 300 kHz, the noise levels range from 35 to 115dB [49]. The field strength of the noise can be derived from these values with respect to thermal noise by:

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

where E_n is the rms noise field strength in bandwidth b at frequency f_{MHz}, F_{am} is the median noise level from the world map at the applicable frequency, f_{MHz} is the frequency in MHz and b_{Hz} is the noise bandwidth in Hz.

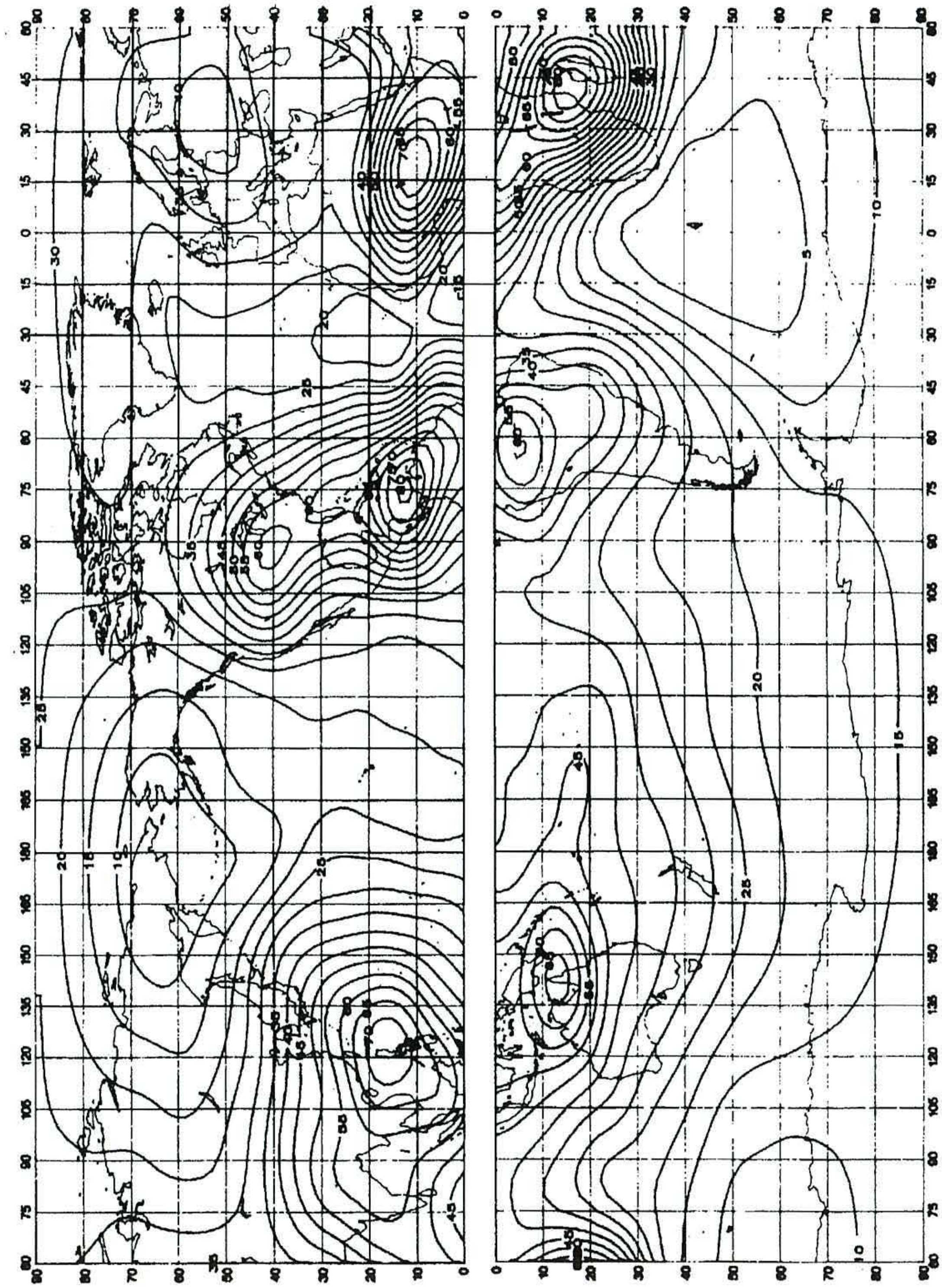

Figure 3.16: *ITU world map of radio noise. The contours represent dB above thermal noise at 1MHz during the summer at times from 0800-1200 local [49].*

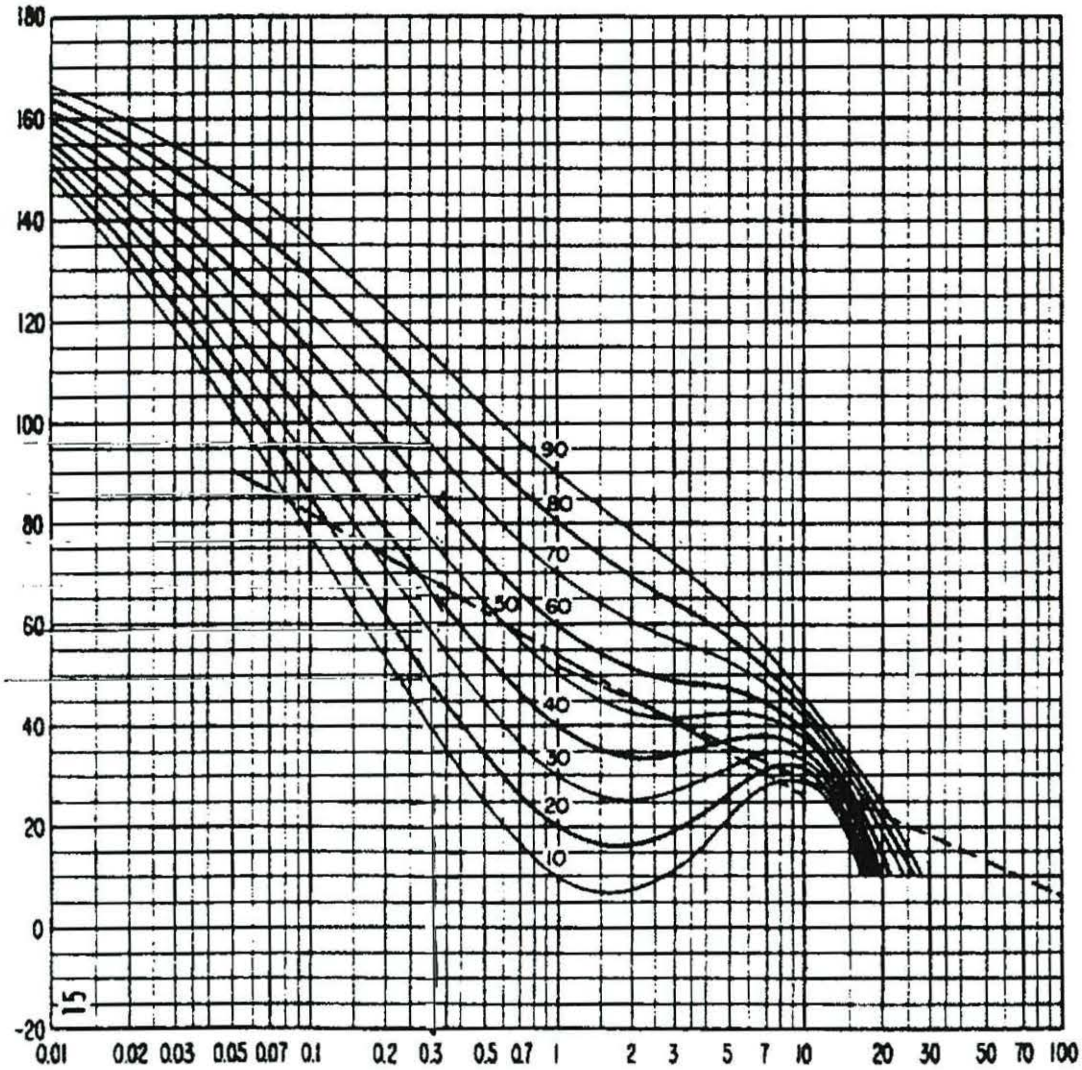

Figure 3. 17: *ITU noise conversion curves for the summer 0800-1200 time-season block [49].*

Latitude	Longitude	-30	-20	-10	0	10	20	30	40	50	60
80		65	65	65	65	65	65	65	65	65	65
70		64	64	64	64	66	67	70	70	70	68
60		60	60	62	64	69	72	74	74	71	68
50		58	61	65	67	71	75	75	74	71	69
40		58	60	63	65	68	68	68	67	66	66
30		55	57	60	63	66	66	66	66	68	70
20		54	55	65	74	79	79	74	69	71	75

Table 3.4: *The median noise values, in dB above thermal noise during summer 0800-1200 period, throughout the EMA.*

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

Table 3.5: *95% annual average noise figures for the EMA in dBμ [57].*

The coverage prediction process requires that the noise field strength be calculated at each point in order that it may be compared with the wanted signal there to establish whether the resulting signal-to-noise ratio exceeds the minimum specified. The way in which the constant variations in noise are handled is as follows. The median noise field strength is calculated (as above) at each of an array of points spaced with a resolution of 10° of latitude by 10° of longitude covering the EMA. A table is prepared for each of the 24 time-season periods: Table 3.4 is the one for the summer 0800-1200 period. The values of atmospheric noise of interest are normally two: the value not exceeded 95% of the time during a specific period of interest; and the average value not exceeded 95% of the time throughout the year, as in Table 3.5. By interpolation between adjacent points in either table (Fig. 3.18), the value at any point in a coverage array may be estimated.

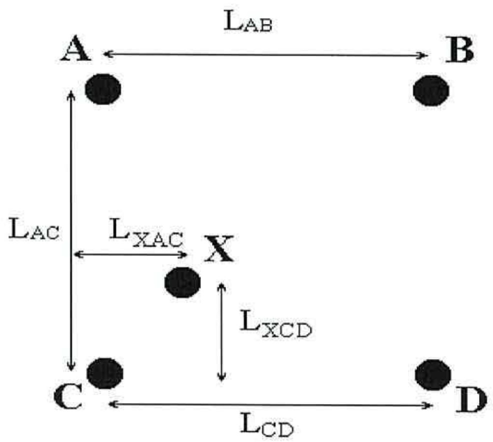

Figure 3. 18 *The noise field strength at location X is found by interpolation between the values at the points A, B, C and D on the 10-degree grid.*

3.3 Interference

The factors affecting the coverage of a radiobeacon can be grouped into two, natural and man-made. The natural causes are groundwave attenuation, skywave attenuation, fading and atmospheric noise which have been described in sections 3.2.2 to3.2.5. These are the factors that determine the performance of a radiobeacon in the absence of interference from other beacons. This performance is essentially independent of the specific frequency within the narrow radiobeacon band on which the beacon operates. The principal man-made factor is interference from other radiobeacons in the band; its effect on the coverage of a specific beacon depends, of course, on the frequency on which that beacon operates [57,59]. The natural factors, together with the power of the transmitter, determine the maximum possible coverage of a radiobeacon: the "interference-free coverage". Once that has been established we can quantify the effects of interference. That is, we should analyse the effects of interference separately and after those of the natural factors.

Like the wanted signal, the unwanted interfering signals from other stations are received by both groundwave and skywave propagation. The problem of minimising the effects of interference in a crowded spectrum are shared between the system provider and the receiver designer. The receiver should be designed to work with the highest possible levels of interference and the band-plan should be organised to minimise interference [13,37,60]. The protection ratios shown in Table 3.2 specify the minimum ability of a receiver to reject unwanted signals on the same frequency as the wanted signal, or on adjacent channels.

3.3.1 Assessing the Interference

In order to assess the effects of interference on coverage one must first estimate at each array point the strengths of the wanted signal and natural factors and establish whether the point is within the interference-free coverage. Then one estimates at the point the strengths of the interfering signals. The ratios of the wanted to interfering signals are calculated and compared to the protection ratios, taking into account the frequency separations between the signals. The results show whether the array point remains in coverage or is lost to interference. A new program is developed based on the background material introduced in the previous sections to do this task and the performance of radiobeacons around Europe has been evaluated.

Figs. 3.19 and 3.20 shows the interference-free and actual coverages of Girdle Ness in Scotland and Mantyluoto in Finland, respectively. Girdle Ness is losing 70%, and Mantyluoto 90%, of their potential coverage due to interference! In both figures the overall shaded area is the potential nighttime coverage (with fading) and the blue area is the coverage area lost due to interference, the grey area represents the area where all the minimum performance specifications are met.

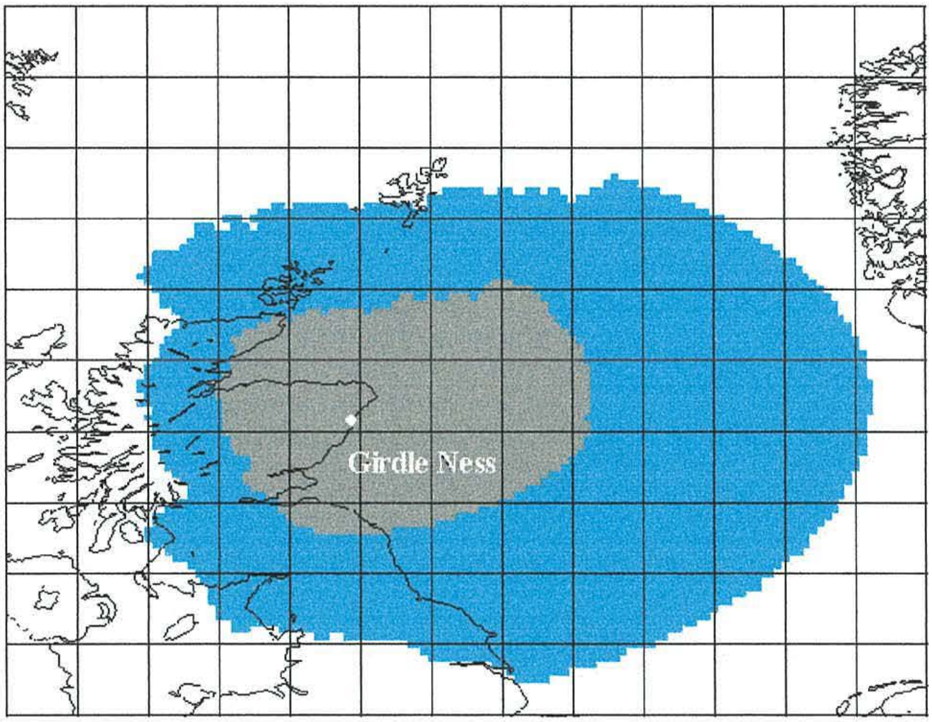

Figure 3. 19: *Coverage of Girdle Ness at its present frequency. The blue area is the coverage lost to interference, the grey area the remaining coverage. Nearly 70% of interference-free coverage is lost to interference.*

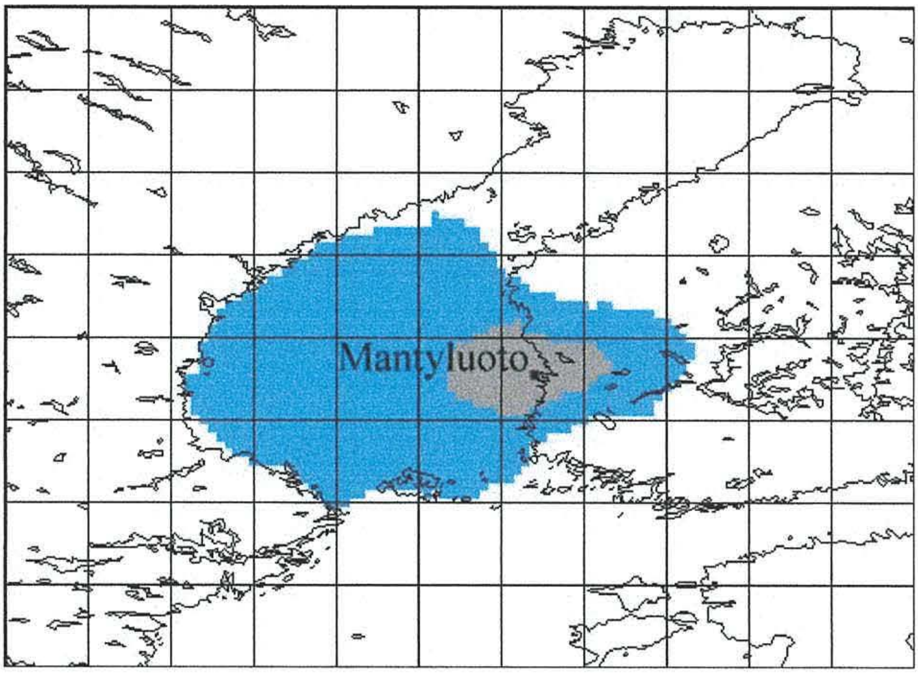

Figure 3. 20: *Coverage of Mantyluoto at its current frequency. Some 90% of coverage is lost due to interference.*

These results demonstrate dramatically that currently radiobeacons are losing potential coverage due to inefficient frequency planning. The next chapters will discuss what needs to be done to rectify this situation and get the most out of the radiobeacon network of EMA.

3.4 Conclusions

A coverage prediction model is introduced in this chapter along with the factors that affect the coverage. These factors are then examined in detail and classified into two groups: natural factors and man-made factors.

The natural factors are the attenuation of the signal in both groundwave and skywave propagation, fading due to skywave-groundwave interaction, and atmospheric noise. They are essentially independent of the frequency within the band on which the beacon operates.

Attenuation of groundwave is a major factor in calculating the interference-free coverage. In order to calculate groundwave attenuation, accurate information about ground conductivity is necessary. This depends on the type of terrain. Paths of mixed type must also be analysed. Data and recommendations of the ITU are used for calculating the groundwave attenuation.

Skywave attenuation is different from groundwave in that it is almost independent of ground conductivity, apart from the sea gain introduced if the beacon or receiver antenna is within a short distance of the coast. Skywave signals are of no concern close to the station but increase with range, peaking at about 200 km from the beacon then falling slowly. The skywave attenuation shows temporal variations and a statistical approach is used with the values of skywave attenuation reached 95% of the time is employed.

Where groundwave and skywave signals are received with comparable strengths, their sum may be greater than either, or there may be fading below the value of either. Since the skywave travels a longer path it is delayed with respect to groundwave and this delay can cause the fading of a beacon's signal at that point. This fading model is used for estimating the night-time interference-free coverage of radiobeacons which is used for frequency selection in the next chapter.

Atmospheric noise due to storms and lightning has a significant effect on DGPS coverage. A noise database has been created that covers the EMA with a resolution of 10° by 10°. It contains the average noise field strength not exceeded 95% of the time throughout the year. Linear interpolation is used for calculating the noise at coverage array points.

The only man-made factor is the interference and the effect of interference can be drastic if the operating frequencies are not chosen appropriately. The serious coverage losses of beacons in the current band are demonstrated.

Chapter 4

Frequency Selection

4.1 Introduction

In Chapter 3 we introduced the factors affecting the coverage of radiobeacons. Using a coverage prediction model [52,61] we showed that potential coverage is lost due to interference. It was clear that, in remote geographical areas where only a small number of radiobeacons share the frequency band, it is natural factors that determine the radiobeacons' coverages. In contrast, in areas like the EMA where the number of beacons per channel is high, the main limiting factor is the man-made factor, interference. The quality of the received signal can be seriously degraded by the transmissions of other radiobeacons [27,57].

In this chapter we will investigate the reasons for losing as much as 90% of potential coverage. Existing methods of evaluating interference between radiobeacons will be examined and their adequacy assessed. Later, a new method for calculating the interference between radiobeacons, in which the fraction of the maximum potential coverage area that is free of interference is used as a quantitative measure of the reduction of radiobeacon performance caused by interference, will be introduced.

It will be clear from the previous chapter that the techniques that will be employed in this research for evaluating both the potential coverage and the field strengths of unwanted transmissions are based on the work by Poppe [27]. This study takes her coverage evaluation tool and uses its components to create a new design tool for finding the optimum frequencies for radiobeacons, that is, the frequencies on which they will receive and cause the least interference. The first major objective in this work is a technique to allow the best frequency for an individual radiobeacon to be identified. This will be described and its use illustrated by means of real-life examples. The second, and much greater, objective will be a solution to the problem of optimising the frequency allocations of all the occupants of the radiobeacon frequency band; this will be described in Chapter 5.

4.2 Conventional methods of evaluating interference

The various known methods for evaluating interference between radiobeacons, or between transmitters in general, needs to be examined to assess their appropriateness for the task of allocating frequencies to radiobeacons. If the methods currently employed for radiobeacon frequency assignment turn out to be inadequate, a new method needs to be devised.

4.2.1 IALA method

The principal method used in recent years for frequency planning in the radiobeacon band is known as the "IALA Method"; though it was not developed by IALA themselves, it is the method they have generally employed [62]. It was, in fact, developed by the ITU and is set out in the ITU Report on the Regional Administrative Radio Conference for the Planning of Frequencies for Maritime Radiobeacons in the European Maritime Area held in 1985 [46].

The IALA frequency allocation procedure is based on establishing that two beacons, which are to share a frequency, are sufficiently separated in distance. It makes sure that the distance between them is at least the sum of the nominal range of the one and the 'interfering distance' of the other.

This 'interfering distance' is the distance at which the transmission of a beacon has fallen to a level weak enough not to cause interference to the signals of any other beacon on the same frequency. To explain this concept, let us define two signals: the "wanted signal" and the "interfering signal". The wanted signal is the signal broadcast by the transmitter whose coverage area is to be evaluated. The interfering signal is the signal coming from any other transmitter that can corrupt the wanted signal. For a signal to be usable for direction-finding (which is all that concerned the ITU), the ITU specification requires that its field strength should be at least 34 dBμV/m and that it should be at least 15 dB stronger than an interfering signal on the same frequency [46]. Thus, the interfering distance for any transmitter is the range at which its field strength has fallen to 34-15 dBμV/m, i.e. 19 dBμV/m.

It is clear from the degree of interference experienced by beacons in the present system that the IALA method of frequency planning is inadequate when it comes to inserting DGNSS beacons into the band. Let us examine why this is. The IALA method was devised when only conventional marine and aeronautical beacons were in use. These beacons are designed to provide significantly higher field strengths than DGNSS transmissions: for DF the minimum is 34 dBμV/m, whereas for DGNSS it is the much lower 20 dBμV/m [13,37]. The field strength falls to these lower field values much further from the beacons, of course. Moreover, these weaker wanted signals are susceptible to interference from much lower levels of signal than the stronger DF signals, and thus to interference from beacons much further away. The interfering distances need to be adjusted to take these changes into account, but that has not been done. In addition, the nominal ranges of DGNSS radiobeacons are still defined in terms of marine beacons' ranges, as was explained in Section 3.2.1.

A further weakness of the IALA method is that it ignores the attenuation caused by land paths. Section 3.2 showed that signals attenuate more rapidly over land than over sea-water. Interfering distances, however, are calculated assuming seawater paths only and the resulting values are thus inaccurate if there are land paths. Most seriously, the IALA method ignores the fading of the wanted signal due to ionospheric propagation; we saw in the last chapter that, at long ranges, the skywave signal and the groundwave signal interact with each other, causing fading at night. The IALA method also underestimates the effects of skywave-borne interference from distant beacons by taking the median skywave field strength as the basis of its calculations. These are serious shortcomings at the relatively long ranges at which DGNSS transmissions are used [50,57], much more serious than at the shorter ranges of traditional DF radiobeacons. Indeed, we have seen that at night skywave interference becomes the dominant factor in determining the range and coverage of the wanted beacon. The shortcomings of the IALA method in this respect alone require its replacement.

4.2.2 'Edge of coverage' approach

Another commonly-used method of evaluating interference in radio systems is to check the field strength of each interfering signal at the edge of the coverage area of each wanted transmitter closest to the interferer. This approach has been used by Yasuda et al. for planning systems of radiobeacons; they assumed circular coverages for the individual beacons [51]. A similar method has been adopted for planning cellular phone systems, the coverage areas there being assumed to be polygonal [63].

In this method, the field strength of an interfering transmitter is evaluated at a single point only. It is assumed that this is the highest level of interference anywhere in the coverage area of the wanted station. If the interference there is unacceptable, the two beacons are not allocated the same frequency. Similarly when using polygonal coverage plots, the interference is evaluated at the corners of the coverage area. Looking at single points in this way is a shortcoming of these methods because, due to propagation factors (land or sea paths in the case of radiobeacons, topography in the case of telephone cells) there may be greater interference elsewhere in the coverage area than at the single point at which it is evaluated.

Also, in our problem the number of frequencies available are so limited that it may not be possible to allocate frequencies in such a way that there is no interference at all to any beacon. An all-or-nothing approach of this kind simply will not work under those circumstances. Instead, we need to find a way to quantify the levels of interference between radiobeacons so that we can make decisions with the aim of minimising interference, even if the interference cannot be reduced to zero everywhere.

It was therefore decided to seek a better way of evaluating interference than those offered by the existing methods examined above.

4.3 A new method for quantifying interference

The Bangor Coverage Prediction Model embodies techniques and software on the basis of which it should be possible to develop the method for quantifying the mutual interference between beacons we require for optimising frequency assignments. This is because the model provides means of calculating the field strength of the signal of any beacon at any point, via groundwave or skywave propagation and including fading effects, and also of estimating atmospheric noise.

The new way we propose to work was foreshadowed at the end of the last chapter and will now be set out in detail. It is as follows. First, the coverage area of a radiobeacon is determined, taking into account all factors except interference. That is, point-by-point throughout the array we compute the field strength of the wanted signal by groundwave and skywave, take account of its fading, and also calculate the strength of the atmospheric noise. Then we check the field strength and SNR available to the receiver at each point against the minimum criteria. The resulting coverage we call the "Interference-Free Coverage Area (IFCA)" of the beacon.

Now we estimate the effect (if any) of each of the other beacons in the band on the coverage of our beacon and, as will be seen, the effect of our beacon on them. We work through the other beacons one-by-one, evaluating its interference at each point in the wanted beacon's array. We take into account both the groundwave and the night skywave propagation of the interference. Then, for each potential interferer, we evaluate the percentage of the points within the original IFCA that have survived its interference. The result we call the "figure of merit (FoM)"; if there is no reduction of coverage the FoM is unity; if all the coverage were lost it would be zero. This is the way we are going to measure interference for use in the algorithms we will develop for optimising frequency allocations [57,59].

This new way of evaluating interference between radiobeacons will first be tested in the context of the development of the software for allocating the best frequency for a single new beacon.

4.3.1 Determining the Interference Free Coverage Area (IFCA)

The interference-free coverage of a beacon is the area in which the signal would be acceptable if there was no interference to it. That is, the field strength value is higher than the minimum value and the signal-to-atmospheric noise ratio is higher than the minimum SNR. Calculation of field strength, taking into account groundwave propagation, skywave propagation, fading and atmospheric noise, has been described in Chapter 3.

Now let us consider this process in more detail. In the new software, as in Poppe's, an array of grid points is created with the beacon at its centre. At each grid point the field strengths of the signal components and of the noise are calculated and the results compared to the minimum service requirements; if the requirements are fulfilled, the point is in the interference-free coverage area of the radiobeacon. Once all grid points have been considered in this way the IFCA is known.

In the new software, the field strength will be pre-computed and stored at each point in a very large array centred on the beacon and spaced by 0.1° of latitude and 0.1° of longitude (approximately 12 km by 8 km at latitude 50°N). In doing this we have re-employed Poppe's algorithms but the array sizes are enlarged from her original 550km limit to 1200 km for the groundwave strength and 2000 km for the skywave. These distances are the ranges at which Poppe showed that the field strengths of even the strongest transmitter (370km nominal range) can be guaranteed to have fallen below the minimum value that can cause interference [27].

For daytime operation the field strength is simply the groundwave field strength. But at night, the groundwave and skywave values are used to calculate the total field strength that can be guaranteed more than 95% of the time, fading being modelled by the method developed by Last and Poppe [27,50]. Field strength and 95%-ile atmospheric noise establish the SNR value, which is compared with the minimum specified for the service. If both field strength and SNR criteria for DGNSS stations are met, the point is deemed to lie within the interference-free coverage of the station. For example, in Fig. 4.1, the coverage (in blue) is the set of array points at which the field strength exceeds 10 μV/m (20 dBμV/m) 95% of the time at night and the atmospheric SNR exceeds 7 dB. The fine dots represent the array points at which the field strength is evaluated.

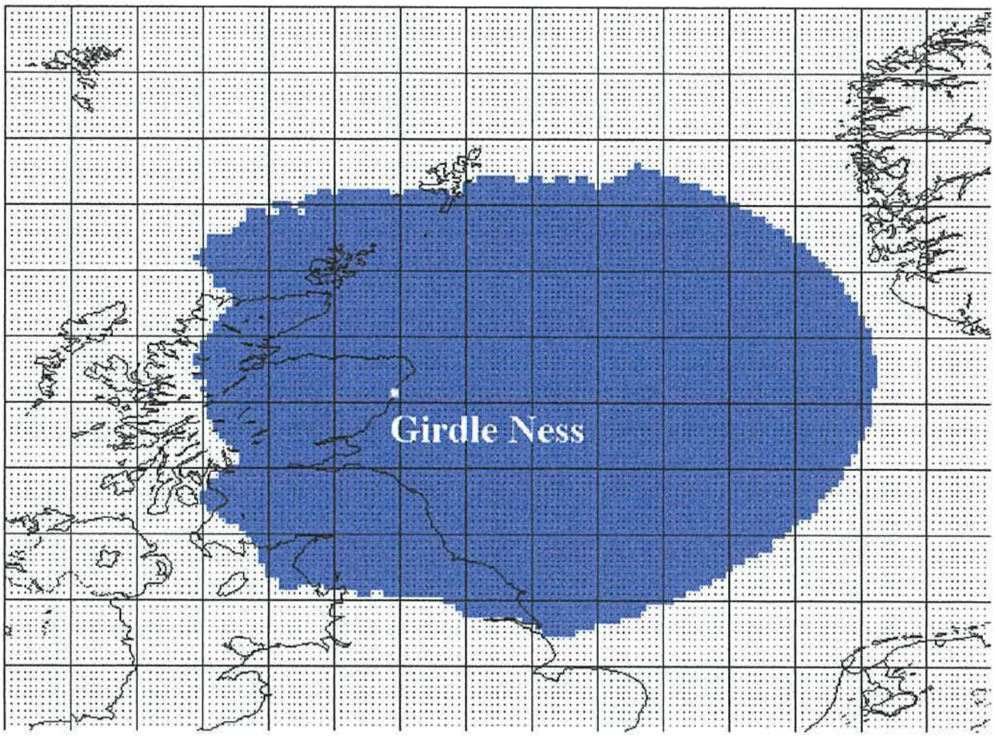

Figure 4. 1: *Array points and Interference-Free Coverage Area (IFCA) around Girdle Ness. At each point, the field strength and signal-to-noise ratio are evaluated. The points at which the criteria are fulfilled are in the IFCA.*

Fig. 3.15 illustrated the substantial differences between daytime and nighttime interference-free coverages [57,59]. In most of Europe, lying as it does in a temperate rather than a tropical zone, atmospheric noise levels are relatively low, especially at the higher latitudes. Thus atmospheric noise plays a minor part in setting the coverage boundary. Only in the south of the EMA is atmospheric noise the limiting factor reaching 14dBμV/m and violating the SNR criteria of 7dB, set at Table 3.1, for DGNSS transmissions with the minimum field strength value of 20dBμV/m; elsewhere, the coverage boundary is determined by the minimum field strength criterion [49].

4.3.2 Quantifying the interference: FoM approach

The potential of the new beacon and each existing beacon to cause interference within one another's service areas are quantified by means of a set of figures of merit (FoMs). Each FoM is calculated as follows. Taking each existing beacon in turn, the strength of its signal is computed at each array point within the interference-free coverage of the new beacon and the resulting signal-to-interference ratio there compared with the protection ratio from Table 3.2, having regard to the type of beacon and type of interferer. Then the fraction of the points within the interference-free coverage of the new beacon that survive interference from the existing beacon is computed and from it the figure of merit (FoM). The FoM is 1 if there is no unacceptable interference anywhere in the IFCA and 0 if all the previously interference-free coverage is lost.

The relationship between each pair of interferers is characterised by a set of such FoMs. The 'co-channel daytime FoM' is the fraction of the daytime interference-free coverage of the new beacon that survives interference received via groundwave propagation only from the co-channel interferer. Other daytime FoMs are then computed by assuming that the frequencies of the two beacons are separated by first one channel, then each number of channels up to 6, at the standard 500Hz spacing, the appropriate protection ratios in Table 3.2 being employed. The result is a set of 7 daytime FoMs that describe the potential for the reduction of the new beacon's daytime IFCA by interference from the other station [57].

Now we consider interference at night. Another corresponding set of 7 FoMs is calculated, using the night-time interference-free coverage of the new beacon. The interfering signal is taken to be the stronger of the groundwave or night skywave components. Then, each of the 7 daytime FoMs is compared with its nighttime counterpart and the lower is chosen; the resulting 7 FoMs describe the interference that the existing station can cause to the new station.

The process is now repeated and a further set of 7 such FoMs computed that describe the interference in the opposite direction, that is, the interference the new station can cause to the existing one. Then, taking co-channel operation and each of the seven adjacent-channel cases in turn, we select the lower of the FoMs for the two directions. The resulting set of FoMs describes the potential for mutual interference between the proposed new beacon and the existing beacon. For example, Table 4.1 shows the FoMs for a proposed beacon at Girdle Ness and the existing beacon at Torshavn, Faroe Islands. If the new beacon were allocated the frequency on which Torshavn operates, the FoM would be 0.04; that is, only 4% of the interference-free coverage of one of the beacons would survive the interference from the other. Fig. 4.2 shows the coverage area of Girdle Ness if it were to be operated co-channel with Torshavn in this way; the lighter area is the coverage lost to interference.

Table 4.1 further shows that if the new beacon were to be operated one channel higher, or lower, than Torshavn, a much larger 98% of the IFCA would survive. Any greater frequency separation, and there would be no loss of coverage due to interference within the IFCA. Clearly, one would try to avoid operating these particular two beacons on the same channel!

Frequency separation (kHz)	Figure of merit
0	0.04
0.5	0.98
1.0	1.00
1.5	1.00
2.0	1.00

Table 4.1: *Figures of merit describing the potential for interference between a proposed new beacon at Girdle Ness and an existing beacon at Torshavn, Faroe Islands.*

Using this novel way it is possible to quantify the degree of interference between radiobeacons. With this approach a program is developed to select the best ferquency for the radiobeacons.

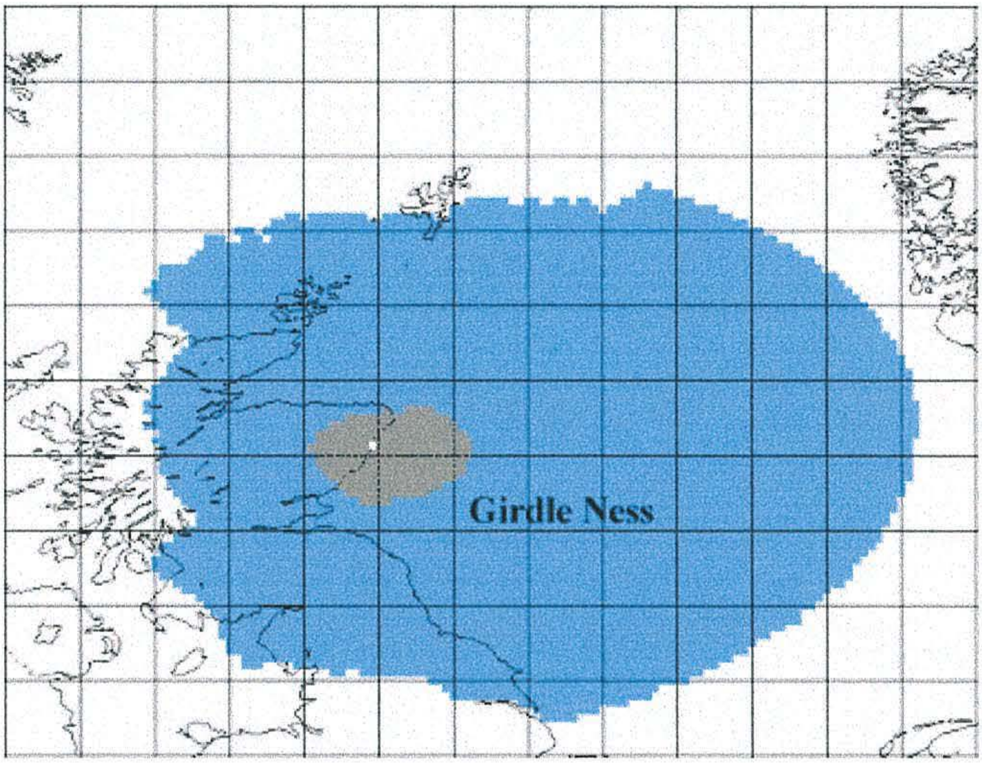

Figure 4.2: *Coverage of Girdle Ness if it were to operate on the same frequency as Torshavn.*

4.4 Choosing Frequencies

Ideally, frequencies should be allocated in the radiobeacon band in such a way that no signals exceed the interference protection ratios anywhere within the IFCAs of any of the beacons in the band.

When a new DGNSS service is to be established, the system designer first evaluates the (interference-free) coverages from individual candidate sites. The Bangor Coverage Prediction Software may well be employed to estimate the coverages of the individual candidate beacons or of a whole system of beacons. Usually the objective is to achieve the highest quality or most extensive coverage from the smallest number of sites. However, when interference is then taken into account, the coverage of an individual beacon may be seen to be reduced below its interference-free value, perhaps dramatically. The degree of coverage reduction, of course, depends greatly on the frequency on which the new beacon is to operate since each potential channel is affected by a different set of co-channel and adjacent-channel interferers. The question frequently arises: on which channel will the beacon enjoy maximum coverage? That is, which would be the best frequency for the new beacon?

In principle, one could identify the best frequency by predicting the new beacon's coverage when operating on each of the 64 channels of the band in turn and comparing the resulting plots. Not only would this be exceedingly time-consuming, it would also ignore any interference the new beacon might cause to existing beacons. Minimising interference in this direction is an even more demanding task: we must examine the coverage of every beacon on the same channel, or within 6 channels either side of the new beacon - and this must be done 64 times, once per possible channel! A new program needs to be developed to identify the channel on which the proposed new beacon will both receive, and cause, the least interference. This is the objective of the New Beacon software.

4.4.1 Bangor *New Beacon* Software

The first problem was the evaluation of the IFCAs for the existing radiobeacons. At first it was decided to calculate the IFCA for every beacon when a new frequency is to be chosen. However this is a very long task and it made more sense to calculate the IFCAs for all the radiobeacons and store them in a database. A question that then arises is how flexible this approach is if one later changes the power of the transmitter. It was decided to calculate and store the values of the attenuation of the signal between the transmitter and the grid points. Field strength values could then be calculated using these attenuation values and the known transmitter power.

Files of such attenuation values were generated for groundwave and skywave propagation for all existing beacons throughout the EMA. Likewise, all stations on frequencies just outside the EMA, or within the frequency band but outside the boundaries of the EMA, that could cause interference to services within the band and the EMA were included.

This set of computations took some 8 days on a 166 MHz Pentium PC. Now, when the software is used to identify the best frequency for a new beacon, it is only necessary to compute the groundwave and skywave attenuation arrays for the new beacon – which takes some 40 minutes.

Once the attenuation files have been produced the next task was to evaluate the figures of merit, as in section 4.3 above, for the new beacon. Then, knowing which existing beacon operates on which channel, the program sets out to identify the channel on which the least mutual interference would be caused if the new beacon were to operate on it. Finally, assuming that this recommended channel is adopted, it assesses the coverage the new beacon should achieve and any impact it might have on the service areas of existing beacons. Identifying the best frequency once all the arrays are computed takes a further 50 minutes.

For example, let Girdle Ness be our new transmitter. We have calculated the FoM between Girdle Ness and Torshavn back in section 4.3.2. Since Torshavn is on Channel 7, the co-channel FoM of 0.04 describes the degree of interference that would be experienced should Girdle Ness be allocated that channel; 0.98 would apply if Channel 6 or Channel 8 were chosen, and so on.

Table 4.2 shows a small portion of the very large table that combines the FoMs of all 408 existing beacons in this way. We see there that if our new beacon at Girdle Ness were allocated Channel 8, for example, although Torshavn would now have little effect, there would be strong interference to or from the beacon at the Hoek van Holland that operates on this channel. Only 0.22 of the coverage of one of them would be spared. Thus by taking the lowest FoM in this row, we obtain a worst-case FoM for Channel 8 of 0.22.

Channel	**Cala Figuera (Ch. 6)**	**Torshavn (Ch. 7)**	**Hoek van Holland (Ch. 8)**	**Farstugrunden (Ch. 9)**	**Worst-case FoM for channel**
0	1.00				1.00
1	1.00	1.00			1.00
2	1.00	1.00	1.00	1.00	1.00
3	1.00	1.00	1.00	1.00	1.00
4	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00	1.00
6	1.00	0.98	1.00	1.00	0.98
7	1.00	0.04	1.00	1.00	0.04
8	1.00	0.98	0.22	1.00	0.22
9	1.00	1.00	1.00	0.92	0.92
10	1.00	1.00	1.00	1.00	1.00
11	1.00	1.00	1.00	1.00	1.00
12	1.00	1.00	1.00	1.00	1.00
13		1.00	1.00	1.00	1.00
14			1.00	1.00	1.00
15				1.00	1.00

Table 4.2: *Individual figures of merit for a small sample of channels due to interference to, and from, 4 of the 408 existing beacons. The last column characterises the interference to be expected should the new beacon at Girdle Ness be allocated the channel number shown in the first column.*

4.4.2 Identifying the optimum channel

There remains the simple task of identifying the channel out of the 64 with the highest FoM. Table 4.3 shows the result: either Channel 4 or Channel 48 would be best for Girdle Ness; each offers interference-free coverage. In practice, because of compromises involving other beacons in the new British Isles system of which Girdle Ness is just one component (see section 4.4.4 below), the third choice, Channel 0, has been used. The result is an FoM of only 0.65.

Choice	**Channel**	**Interference-free %**
First (equal)	4	100
First (equal)	48	100
Third	0	65

Table 4.3: *Equal-best frequencies for Girdle Ness are Channels 4 and 48, each of which offers full interference-free coverage. Third choice Channel 0 offers only 65%.*

Let us now run the coverage prediction program to illustrate the coverage of the Girdle Ness beacon when operated on Channel 0. Fig. 4.3 compares its night-time coverage with its interference-free coverage. The loss of coverage is seen to be mainly in the south-east corner. Further examination shows it to be principally due to skywave-borne interference from an aeronautical beacon close to Brussels National airport in Belgium.

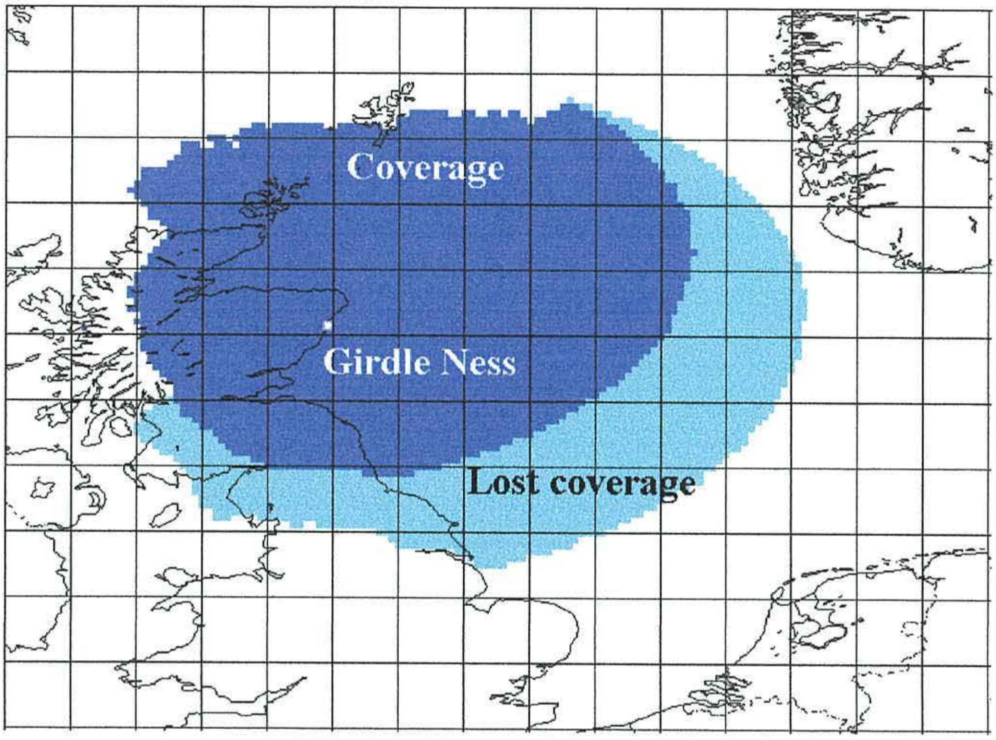

Figure 4. 3: *The outer area is the interference-free night-time coverage of Girdle Ness. The inner is the part that survives interference when Girdle Ness operates on Channel 0. The principal interferer is an aeronautical NDB in Belgium.*

4.4.4 Planning a new DGNSS system using the *New Beacon* software

A new free-to-air network of DGNSS stations has recently been established by the General Lighthouse Authorities (GLAs) of the British Isles. In the initial planning of the system, the Bangor DGPS Coverage Prediction Software was used extensively to explore the interference-free coverages of various candidate sites and so minimise the number of stations required. This resulted in the choice of the 12 sites listed in the first column of Table 4.4 [57,59].

Station	Conventional method		New method	
	Channel chosen	Interference -free %	Channel chosen	Interference -free %
Flamborough	38	96	38	96
Lizard	1	93	1	93
Loop Head	57	27	51	92
Butt of Lewis	21	57	23	86
Girdle Ness	56	7	0	65
Sumburgh Head	41	64	24	86
Point Lynas	43	39	54	71
Tory Island	60	39	53	86
Mizen Head	34	55	13	68
St Catherines	19	32	48	90
Nash Point	31	22	4	100
North Foreland	54	47	60	48

Table 4.4: *Channels chosen for 12 new DGNSS stations using the conventional IALA method and the new method. With the conventional method, the proportion of interference-free coverage can be as low as 7%. With the new method it is never lower than 65%.*

Frequencies were originally chosen using the conventional IALA method described in section 4.2.1, the channels allocated being those shown in the second column of Table 4.4. Using the *Coverage Prediction* software shows that the fraction of the IFCAs that survive interference with this set of allocations are at most 96%, and in the worst case only 7% (see column 3 of Table 4.4)!

Then, the New Beacon software was used to identify the best channel for each station. If any beacon has an FoM higher than 0.9, it is left at the frequency chosen using IALA method. For the rest of the beacons the best frequencies are first identified and then frequencies are assigned on a trial and error basis. The results appear in the last two columns of the Table. Comparing the existing and new results, we see that using the conventional method, only two of the 12 beacons have been allocated the best possible channel. Interference to all other beacons is worse than it needs be whereas the New Beacon software has allocated channels in such a way as to maximise coverage. The proportion of the Girdle Ness coverage free of interference is increased from 7% to 65% and all the other beacons have greater coverage than before. This result both shows the benefits of the new software, and confirms the severe interference environment in the radiobeacon band in Europe!

4.5 Conclusions

The man-made factor affecting the performance of radiobeacons, interference, is explained and its effect on coverage demonstrated. Existing methods for evaluating interference are investigated and their shortcomings explained. In regions such as the EMA where the radio spectrum is over-crowded, interference is often the dominant factor determining coverage. The only way to solve the problems caused by unwanted interference is to select each beacon's frequency carefully.

A new method has been developed, and software written, for selecting the optimum channel for a radiobeacon so as to maximise the area within which it can offer the required quality of service and minimise any interference it may cause to existing services. The program is based upon widely-accepted data collated and published by the ITU. It takes into account atmospheric noise and also the groundwave and skywave propagation of both wanted and potentially-interfering signals.

The factors described in Chapter 3 are used for calculating the maximum coverage area of a radiobeacon in order to assess the real impact of interference. This interference-free coverage area is then used to calculate the interference between the wanted radiobeacon and every other radiobeacon in the network. The principle employed is to assess point-by-point throughout the area of potential coverage the field strength, signal-to-noise ratio and signal-to-interference ratio of the resulting service. Interference caused to the new beacon by any of the 408 existing beacons with which it must share the frequency band is taken into account as is the interference it may cause within their coverage areas.

The operation of the new software has been demonstrated by using it to identify the optimum frequency for a proposed new DGNSS beacon at Girdle Ness in Scotland. This station is one of a set of 12 radiobeacons designed to provide a DGNSS service around the British Isles. When the program is applied to all these beacons it becomes clear that the traditional frequency allocation method designed for conventional radiobeacons is inadequate. The new software, in contrast, offers much lower levels of interference and more extensive service areas.

Chapter 5

Optimising the Band

Chapter 4 examined the effect of interference on radiobeacon coverage and analysed the existing frequency allocations and the tools used for creating the present assignment. It showed that traditional methods of allocating frequencies are not appropriate and that the quality of DGNSS radiobeacon service is currently being seriously undermined due to beacons interfering within each others' coverage areas. All over Europe radiobeacons are losing possible coverage as a result. A new method for evaluating the interference was developed which was then incorporated into a program for selecting the best frequencies for beacons. This chapter will take this frequency planning method a great deal further as we try to minimise the loss of coverage due to interference for all stations in the band.

Radiobeacons and their transmissions have three dimensions: space, time and frequency. If all three dimensions could be allocated optimally for each radiobeacon the problem would be minimised. Thus for example, the same space and time may be used for two different tasks if the frequency separation is sufficient. Similarly, the same frequency and space may be used if the timing of broadcasts is different; or time and frequency may be shared if the two transmitters are spaced sufficiently far apart.

Since radiobeacons in the EMA operate continuously, the dimension of time is fixed. Thus we may let beacons use the same frequency only if they are far enough apart not to cause mutual interference, otherwise we must separate them in frequency. The frequency assignments throughout the band must be re-planned and we need a program for assigning the frequencies in an optimal manner.

Although (as will be demonstrated later) various algorithms are available to solve the problem of frequency allocation, it was decided to seek a novel approach to the problem of optimising the allocation of all frequencies. This decision was taken for the following reason. It was foreseen at the start of the research programme that a unique window of opportunity might arise, probably in 1998, to re-organise the frequency plan for the whole band, and the goal was set that the results of this research should be employed for that purpose. Subsequently it became clear that, if that was to happen, a method had to be available prior to a frequency planning meeting scheduled to be held at IALA Headquarters in Paris in September 1998. A judgement was, therefore, made in August 1997 to make a quick dash for a viable solution. In addition to carrying out a frequency optimisation process, this solution had to be in a form that would allow additional constraints specific to radiobeacons to be incorporated; none of the conventional frequency-assignment algorithms known at the time would allow that to be done. An example of these additional constraints was the "pairing constraint" (see section 5.4.4) according to which co-sited DGNSS and maritime radiobeacons must be allocated adjacent frequencies so that they can share a transmitter and antenna. For these reasons, the decision was taken to try to devise a purpose-designed algorithm aimed at solving this problem in the time available. Then later, if time permitted, the method could be refined and other candidate algorithms examined in an attempt to get a better solution. The algorithm developed, and the results it produced, are presented in this chapter. Chapter 6 will then give an extensive review of existing algorithms, alternatives to our novel algorithm, and will compare the performance of our novel algorithm to those of these alternatives.

5.1 Optimisation of frequencies

The strategy adopted for minimising interference will be briefly summarised here before its implementation is described in detail. First, we evaluate the potential for interference between each pair of beacons. The stations to be considered are those within the EMA that operate in the band 283.5-315 kHz and are shown previously in Fig. 2.7. However, it will also be necessary to include all known stations that lie sufficiently close to the boundaries of the EMA, or are on frequencies sufficiently close to the band edges, that they might cause interference. We know that skywave interference can be effective up to 2000 km. this means that the area we need to consider is the EMA plus 2000 km in every direction from EMA. This means an area from about 10°N to North Pole and from Greenland to the west to 80°E.

When the potential for co-channel interference has been quantified, groups of beacons are identified that can share a channel without mutual interference. We then assign a frequency to each such group, if necessary using all 64 channels within the band. In Chapter 3 it was shown that interference can occur up to the 6th adjacent channel, so while assigning the frequencies we ensure that "adjacent-channel" interference between beacons separated in frequency by up to 6 channels (3 kHz) is avoided.

In re-allocating frequencies, it is important to recognise that though we must take into account interference from and to stations lying outside the EMA and outside the band; such stations will not, of course, have their frequencies re-allocated. Thus the method employed must be able to accommodate stations that remain on their existing channels as well as stations whose frequencies are changed.

5.1.1 Adjusting the FoM

It is recognised that the 64 channels of the band may not be sufficient to accommodate all the stations in the band with completely interference-free coverage. Two possible methods of dealing with this situation have been devised. The first would be to try to pack as many beacons as possible into the frequency band with no interference and then accommodate the rest on the remaining frequencies, where there might be severe interference. The second method was to allow a degree of interference for every radiobeacon. The second approach, that of "equal pain", was chosen, since it was judged to be more acceptable both technically and politically. Distributing the loss of coverage to all beacons as equally as possible ensures a consistent level of service throughout the network. With the alternative approach, there would be areas where the system's coverage would be complete and others where the coverage would be inadequate. There would certainly be problems if some countries' beacons suffered from high interference and other did not!

We effect this solution by defining a maximum level of allowable interference in terms of a "figure-of-merit limit". FoM was defined in Chapter 4 as the percentage of the IFCA surviving interference. Frequency allocations may then be attempted iteratively, since the higher the allowed level of interference the fewer the number of channels required. If it is found to be impossible to fit all the beacons into the available 64 channels, the FoM will be reduced progressively until all beacons can be fitted into 64 channels.

The principles of the method set out here are followed in all cases. We will now consider the optional additional constraints, designed to make the resulting frequency re-allocation more acceptable to users of the band.

5.1.2 Additional Constraints

The radiobeacon frequency band is shared by DGNSS, maritime and aeronautical radiobeacons. DGNSS and maritime radiobeacons are co-ordinated by IALA whereas aeronautical radiobeacons are co-ordinated by ICAO. Since this re-allocation of channels is for the benefit of the maritime community alone, IALA indicated that they would not be seeking to change the current allocations of aeronautical radiobeacons. Thus, our frequency re-allocation method must be designed to allow these allocations to be retained.

The second constraint is the pairing of direction finding and DGNSS radiobeacons installed at the same site. If such transmitters are assigned neighbouring frequencies, it becomes possible for the two transmitters to share a single antenna. This sharing arrangement was very common when a DGNSS service was first added to the transmissions of existing DF beacons. Now DF stations are being decommissioned in most parts of the world. However, it was foreseen that a few European administrations would still wish to operate marine radiobeacons paired with DGNSS beacons on adjacent channels. So this "pairing" option was built into the method.

This chapter will describe a new algorithm devised to optimise the frequency allocations in the radiobeacon band and show the results it produces.

5.2 Evaluating the Interference

The method of calculating Figures-of-Merit was described in Chapter 4. There, FoM was evaluated between the proposed new beacon and every other beacon. For the optimisation process, a set of such FoM values has to be calculated for every pair of beacons. For a list of 408 radiobeacons this is more than 83,000 pairs.

Beacon	No:	1	2	3	4	5	6	7	8	9	10	11	12
St Catherine's Point	1	0	0.1	0.08	0.57	1	0.16	0.85	1	1	0.33	0.17	1
Girdle Ness	2	0.1	0	0.08	0.15	0.32	0.66	0.2	1	0.37	1	0.31	0.6
Mizen Head	3	0.08	0.08	0	0.95	1	0.25	1	1	0.99	0.42	0.34	1
Hoburg	4	0.57	0.15	0.95	0	1	1	0.07	0.96	1	1	0.99	0.5
Andenes	5	1	0.32	1	1	0	1	0.84	0.07	0.24	1	1	0.99
Cala Figuera	6	0.16	0.66	0.25	1	1	0	1	1	1	0.16	0.04	1
Almagrundet	7	0.85	0.2	1	0.07	0.84	1	0	0.8	0.97	1	1	0.27
Helnes	8	1	1	1	0.96	0.07	1	0.8	0	0.55	1	1	0.75
Jan Mayen	9	1	0.37	0.99	1	0.24	1	0.97	0.55	0	1	1	1
Cap de Gata	10	0.33	1	0.42	1	1	0.16	1	1	1	0	0.2	1
C Bear	11	0.17	0.31	0.34	0.99	1	0.04	1	1	1	0.2	0	1
Stirsudden	12	1	0.6	1	0.5	0.99	1	0.27	0.75	1	1	1	0

Table 5.1: - *A small portion of the large array of FoMs that describe the co-channel interference. Similar tables describe adjacent-channel interference for each possible separation of up to 6 channels.*

Table 5.1 shows, by way of example, the results of these calcualtions using just a small group of just 12 stations, chosen to offer a wide geographical spread. The table contains the co-channel FoMs of the pairs of stations identified. To explain further, if St. Catherine's Point and Cala Figuera were to be assigned the same channel, the table shows their mutual FoM to be 0.16; that is, only 16% of the IFCA of the more seriously-affected of them would survive. Note that the matrix is symmetric since each FoM represents the worst case interference in the two directions. A similar table is created to describe adjacent-channel interference for each integer separation of up to 6 channels [64-67]. The use of these tables will be described in the following section.

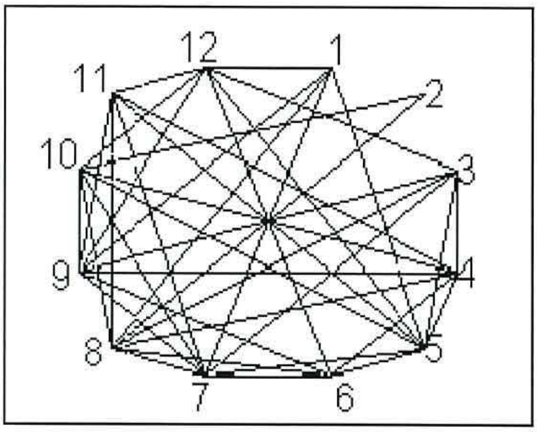

Figure 5. 1: *Constraint graph for the 12 beacons of Table 5.1, with an FoM limit of 0.8. The numbers representing the beacons are the "nodes", or "vertices", of the group and the lines joining them are the "edges".*

5.3 Grouping beacons

The next task (which is really the core of the method) is to identify from the co-channel interference array those groups of beacons that can share a channel without their mutual interference exceeding a specified FoM. Here we introduce a graphical method of illustrating this process. In Fig. 5.1, the numbers around the outside represent the 12 beacons of Table 5.1. The minimum FoM has been set, by way of example, to 0.8. If, in this figure, a line connects two beacons, they may share a frequency since their FoM is greater than 0.8. Thus Beacon 2, for example, may share with Beacons 8 and 10, but not with Beacon 1. This figure is a "constraint graph" that represents interference; conventional usage in this topic refers to each station as a "node", or "vertex" and a line that joins two nodes as an "edge".

We have now devised an algorithm to "partition" this graph; that is, to divide it into groups of beacons where a line is present between each pair of members of the group. These members can share a frequency. The rules of the algorithm are as follows:

1. Check whether there are any beacons left ungrouped; if there are none, end the process.
2. Identify the beacon with the smallest number of connections (that is, the "most-unpopular" beacon). Make it the first member of a new group.

3. Identify beacons that have connections to all the members of the new group. Add the most unpopular of them to the new group.
4. Return to Step 3 and continue the process until no more beacons can be added to the new group.
5. Remove the beacons that are members of this new group from the array.
6. Return to Step 1.

If, in Steps 2 or 3, there is more than one equally unpopular beacon, the choice between them is arbitrary. It was decided to name this algorithm the "Most Unpopular Algorithm" (MUA) since it works by identifying the most unpopular beacon at each step!

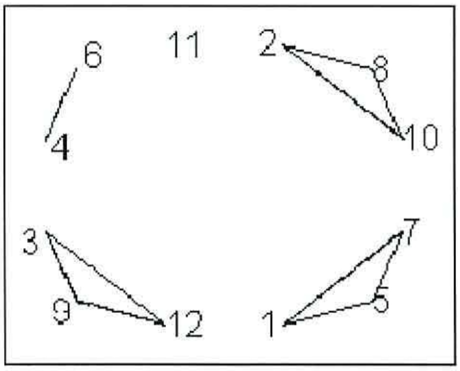

Figure 5. 2: *Groups identified from the set of beacons in Fig. 5.1 using the "most unpopular" algorithm.*

Fig. 5.2 illustrates the result of applying MUA to the set of beacons in Fig. 5.1. Five groups have been identified; three of them contain three beacons each, one two beacons and one a single beacon.

Let us now examine the effect of increasing the minimum FoM, seeing its effect on the number of groups. Table 5.2 shows the result. When the minimum FoM is increased from 0.8 to 0.95 the members of the individual groups change, but the number of groups required remains at 5. When the minimum FoM is further increased to unity (that is, no coverage lost to interference), the number of channels required becomes 6. As had been expected, the number of groups required increases with increasing minimum FoM and falling interference.

FoM Limit	Groupings	Number of Groups
0.80	2,8,10	5
	1,5,7	
	3,9,12	
	4,6	
	11	
0.95	2,8,10	5
	1,5,12	
	3,4,9	
	6,7	
	11	
1.00	2,8,10	6
	1,5	
	3,12	
	6,7	
	9,11	
	4	

Table 5.2: *The table shows how the number of groups increase, and the members of the groups change, with increasing values of the minimum FoM, that is, with progressively less interference allowed.*

5.4 Allocating frequencies

Once the MUA had been developed it was tested by running it on the 408 beacons cited in the then current IALA list of radiobeacons. There were 62 DGNSS beacons (of which 46 were members of co-sited pairs), 120 aeronautical and 226 marine. Calculating the FoM between a single beacon and every other beacon took about 50 minutes on a Pentium 166 MHz PC. The estimated time for calculating the FoM of every pair of beacons was about 400 hours! Therefore it was decided to copy the attenuation files necessary for evaluating the interference to CDs and run the program on 12 machines (in a teaching laboratory) in parallel. The task took 35 hours on 12 Pentium 166 MHz PCs, spread over a weekend. The results were the 7 matrices of FoMs, one for co-channel interference and 6 for the various adjacent channel steps. These formed the raw material required to allow the algorithm to be run to place the radiobeacons into groups.

After that had been done, it was planned that a channel would be assigned to each group. If there were no further constraints, channels could be assigned arbitrarily.

But if the number of groups was found to exceed 64, the FoM limit would be reduced progressively until the number of groups was reduced to 64. The result of this process would be a new frequency allocation plan for the band.

When software embodying the new algorithm had been written and debugged it ran successfully. First, it was tested with a figure-of-merit limit of unity; that is, the ideal case with no loss of coverage to interference. It succeeded in fitting the 408 beacons into just 62 groups, two fewer than the number of channels available! This was a very important result because it showed that it was possible for every radiobeacon to have a full coverage. It demonstrated the necessity of replanning the frequency band, since (as we have shown) under the current plan beacons were losing up to 90% of their IFCA, apparently unnecessarily [64-67].

5.4.1 Checking the initial results

The MUA was the first algorithm developed. It was felt wise, however, to examine alternative ways of tackling the problem. A particular concern was that the MUA might have identified just a local minimum; there might be an even better result than 62. So two broadly-similar algorithms were developed and tested. In the first, the MUA was modified so that, instead of choosing the most unpopular beacon, the most popular beacon was chosen, that is, the beacon that causes the least interference. The flow of this Most Popular Algorithm is as follows:

1. Check if there are any beacons left ungrouped; if there are none, end the process.
2. Find the beacon with the highest number of connections (the "most-popular" beacon). Make it the first member of a new group.
3. Identify beacons that have connections to all the members of the new group. Add the most popular of them to the new group.
4. Return to Step 3 and continue the process until no more beacons can be added to the new group.
5. Remove the beacons that are members of the new group from the array.
6. Return to Step 1.

If, in Steps 2 or 3, there is more than one equally popular beacon, the choice between them is arbitrary.

The result of the Most Popular Algorithm (MPA) was far from being competitive with the MUA. It required 72 channels for a FoM limit of unity instead of the 62 found by the MUA.

The second algorithm developed was a mix of the MUA and the MPA. The selection of beacons in steps 2 and 3 was done randomly, choosing either the most popular or the most unpopular beacon. For an FoM limit of unity, the results of this third algorithm varied on different runs between 64 and 69. These results showed that of the algorithms developed, the MUA clearly gave the best results but not necessarily the global optimum.

5.4.2 Adjacent channel interference

The effects of adjacent-channel interference were now taken into account. This was important since transmissions on neighbouring channels can certainly cause degradation of the wanted signal if they are powerful enough. This means that one should ensure that no two beacons that can cause adjacent-channel interference to one another are assigned to neighbouring frequencies, taking the channel separation and transmission types in to account. One possible way of dealing with this problem is to first partition the graph into groups of beacons, as before, but then assign them frequencies in such a way that no adjacent channel interference is observed. However this method is not appropriate since some beacons are to keep their present frequencies and this may prevent us assigning frequencies to their groups. A second method would be to start assigning frequencies to groups of radiobeacons as soon as they have been formed. Then, any member of the group that is found to have unacceptable interference with a previously-assigned beacons, is temporarily deleted from the list of radiobeacons. This second approach was chosen, since it offers flexibility and ensures that beacons whose frequencies are to be retained are free from adjacent channel interference as well as those whose frequencies are to be re-allocated. The algorithm works as follows:

Channels are allocated in turn to groups of beacons as they are formed, starting with the lowest channel in the band. However, prior to creating each new group, we temporarily eliminate from the array any beacons that suffer adjacent-channel interference with any beacon in the 6 previously created groups, that is, beacons on the 6 lower-side adjacent channels. By this means we ensure that the beacons assigned to each new channel cannot cause, or suffer, adjacent channel interference with the beacons to which channels have already been assigned. Once a group of beacons is chosen beacons temporarily removed from the list are returned to the list.

The MUA algorithm, modified in this way to incorporating adjacent channel interference-handling capability, was now tested using the 408 beacon list with an FoM limit of unity. The result was that many beacons were allocated to different channels from before, but the beacons were still fitted into only 62 channels. This result meant that, if we were given a clean slate and interference was the only constraint, a frequency allocation could be made in which every beacon would enjoy full coverage - and 2 channels would be left free!

5.4.3 Aeronautical constraint

Now let us consider the further constraint of leaving all aeronautical beacons on their original frequencies. The algorithm must ensure that not only do the aeronautical beacons stay in place but also that co-channel and adjacent channel interference between them and the marine and DGNSS beacons is avoided. We do this by first assigning the aeronautical beacons to their original frequencies and then letting the algorithm work around them. In order to achieve this we need to reverse the order of the grouping and frequency-allocation processes. So, first we create 64 empty groups, one per channel. We place the aeronautical beacons into the groups that occupy their existing channels, remove them from the array, and then proceed as previously. However, in checking for adjacent-channel interference, this time we check not only the lower 6 lower adjacent frequencies but also the 6 upper ones. If any beacons are found that had already been assigned to a frequency that cause interference, step 2 is by-passed and the algorithm continues from step 3.

When this aeronautical constraint was introduced, with the FoM set to unity, the number of channels required increased to 67. So, for the first time, the number of available frequencies were exceeded and the decision to develop an algorithm that could allow us to decrease the channel use while limiting the degree of interference, was justified. We will now incorporate the final constraint, that of pairing, and look to reduce the FoM limit progressively until we can fit the beacons into 64 channels.

5.4.4 Pairing constraint

Finally, we introduce the option to place pairs of co-sited beacons on adjacent channels. Although most European countries are decommissioning their direction finding transmitters, some, such as Spain, Norway and Portugal, continue to provide a direction-finding service. Therefore it is necessary for the algorithm to include this option if the frequency plan is to be acceptable to those administrations.

In this case, the solution chosen was to apply the most-unpopular algorithm first to all beacons that are members of pairs, and assign a pair of adjacent channels to each pair of beacons. As this is done, the pair of beacons is added to the list of beacons that must remain on their frequencies. The paired beacons are then removed from the array, just as if they were aeronautical beacons. Finally, the remaining beacons are grouped and assigned frequencies, working around the pairs.

When this constraint was added to the others, the number of channels required increased to 69. Examining the effects of the various constraints we see that the pairing channel constraint has little impact on the number of channels and that the aeronautical constraint has the greatest impact. This is because the interference assessment and planning of those beacons were also done using the inadequate tools mentioned in Chapter 4 and keeping them at their current frequencies causes interference. The results will now be examined in detail.

5.5 Results

Table 5.3 summarises the results of the various test runs. With co-channel interference alone considered, 62 channels are required. With the co-channel interference constraint also in operation, we still need only 62 channels. Then progressively introducing the additional constraints increased the number of channels required to 69.

FoM = 1.00 No interference	
Constraint	**No. of channels required**
Co-channel interference	62
+ Adjacent-channel interference	62
+ Aeronautical beacons staying on channels	67
+ Paired beacons on adjacent channels	69

Table 5.3: *Number of channels required to accommodate all beacons, with various constraints applied cumulatively.*

5.5.1 Reducing the FoM

When the program is run with all the constraints implemented and a FoM of unity it requires 69 frequencies for the 408 beacons. We now need to reduce the FoM limit until we can fit the beacons into 64 channels. Table 5.4 shows the results: the highest FoM at which all beacons could be fitted into the 64 channels was 0.94. That is, all beacons could be accommodated in the band, with all constraints applied, providing a coverage loss of not more than 6% could be tolerated. This is a massive improvement when compared to the current situation with radiobeacons losing up to 90% of their potential coverage. Without the "equal pain" method, spreading the losses to a higher number of beacons, most beacons would have perfect coverage but some will be suffering coverage losses of more than 6%!

Table 5.5 shows a sample of three channels of the resulting band plan with all constraints in place and an FoM limit of 0.94.

FoM Limit	No. of channels required
1.00	69
0.95	66
0.94	64
0.90	63
0.85	61

Table 5.4: – *Number of channels required falls as FoM limit is reduced and more interference is allowed.*

Channel	Name	Type	Latitude	Longitude	Range (km)
39	C_FERRET	DGNSS	44N39	01W15	74
	BALTIYSK	MB	54N38	19E54	148
	BORKUM	MB	53N35	06E40	37
	KAUPANGER	NDB	61N11	07E13	55
40	MIZEN_HEAD	DGNSS	51N27	09W49	185
	BALTIYSK	DGNSS	54N38	19E54	90
41	SVINOEY	DGNSS	62N19	05E16	70
	C_PENAS	MB	43N39	05W51	88
	ANNECY_MARCELLAZ	NDB	45N51	06E01	46
	CHALONS_MARNE	NDB	48N47	04E11	90
	METRO	NDB	50N17	08E51	46
	NICKY	NDB	58N46	16E56	90

Table 5.5: *A small sample of the re-arranged 64-channel band plan with all constraints in operation.*

5.6 IALA's operation to reorganise the band

Currently, the pattern of radiobeacons in the EMA is changing rapidly: many administrations are closing their maritime DF services and introducing new DGNSS beacons. It is these changes that give the window mentioned at the start of this chapter to change the frequencies of all the beacons in the band at once and so the possibility of optimising the use of the band in terms of spectrum efficiency and system performance. IALA is co-ordinating this process, with the approval of the ITU (who are the ultimate authority for frequency allocations). The software being developed that embodies this research is designed to provide them with the tool they require to carry out this re-organisation.

IALA's way of working was first to request each administration to submit details of its future requirements. They then co-ordinated the individual submissions. The result, a list produced in October 1998, showed that administrations planned to reduce the number of beacons from 408 to 350. The principal reason for the reduction was the removal of a large number of maritime direction-finding beacons and a smaller number of aeronautical beacons. However, at the same time the number of DGNSS stations was to be increased.

5.6.1 Paris Run

IALA held a meeting at their headquarters in Paris where the software described in previous sections was run to produce a band-plan using the "October 1998" list, the then current list of proposed beacons. It was found that, despite the reduction in the number of stations, the FoM limit was 0.62. Thus, some beacons would lose as much as 38% of their potential coverage. That is a much poorer result than we had achieved with the current, much greater, number of 408 beacons!

When the list of beacons was examined in an attempt to identify the reason for this disappointing result, it became obvious that most of the DF beacons removed had been of much lower power than the new DGNSS ones introduced! The total radio energy transmitted in the band had increased substantially; hence the increase in interference.

IALA responded to this situation by asking administrations to reduce the power levels of their proposed DGNSS stations wherever possible and to co-operate area-by-area to eliminate excessive overlapping of DGNSS coverage. For example, parts of the Baltic Sea appeared to be covered by 4 different DGNSS radiobeacons. Also, Spain had asked for 44 transmitters, of which 38 were paired, all with ranges of 180 km. This had caused serious interference problems in Spain and France. The ideal would be a band plan that totally eliminated mutual interference [65,66].

Administrations then reconsidered their future requirements. The Norwegian Administration decided to remove some of their paired DF beacons. This was a valuable contribution since exceptionally large numbers of DGNSS beacons had been proposed for Scandinavia in an attempt to provide coverage of inland lakes and even land areas, as well as maritime. As a result of these efforts, a new list of beacons was produced in April 1999.

5.6.2 Checking the Sofware

However before the software was run to generate a second band-plan for this April 1999 list, it was carefully checked for bugs and mistakes. Each part of the FoM and MUA software was examined and the results checked by hand. During this process a programming error was discovered in the program that calculates FoM values. The bug specifically affected the FoMs of aeronautical beacons by increasing the signal-to-interference ratio requirements by 15dB, making the co-channel protection ratio 30dB and decreasing the FoM between NDBs and any other transmitter, almost 30% to its original value. The rather over-pessimistic estimates of interference in the Paris Run seen to have lead to a lower FoM limit for the band-plan presented in Paris than should have been the case. This bug would not have affected the original development runs using the 408 beacons.

Once the bug had been fixed, it was decided not to re-run the Paris list (a very time-consuming process) but to move ahead to the April 1999 list.

5.6.3 April Run

The new list of radiobeacons had 354 radiobeacons; however this time beacons from North Africa and Middle East that IALA had omitted from the previous list, because they were thought not to be interfering with the beacons in the EMA, were incorporated as well. However the beacons belonging to countries that do not take part in this exercise are kept at their current frequencies.

When the software, with the bug removed, was used to produce a band-plan for the April 1999 list, it achieved an FoM limit of 0.91. This was a great improvement over the Paris result. In absolute terms also it was very promising: throughout the EMA none of the proposed new population of beacons need lose more than 9% of its potential coverage.

5.6.4 The Final Run

In the months following the April run it was discovered that IALA had omitted a number of beacons in Italy, Georgia, Turkey, Russia, Ukraine and other Balkan

States. Also, when IALA circulated the proposed band-plan to administrations, a number of administrations found minor errors or took the opportunity to make last-minute amendments to their plans. Altogether 73 transmitters needed to be added to the list of radiobeacons. This resulted in a list of 427 radiobeacons.

A new run of the software, the "Final run" was conducted. The FoM limit was 0.8. As would be expected, adding more beacons had increased the interference and pushed down the limit. The main reason was the increase in the number and ranges of Italian radiobeacons and the introduction of Russian and Ukrainian beacons which can cause interference in already-crowded parts of the EMA, especially Spain, Italy and Scandinavia [68,69]. However, the new band-plan is still a very big improvement compared to the current situation while accommodating a dramatic increase in the numbers of DGNSS stations and, consequently, in the quality of this service across the EMA.

The band plan produced in this run has subsequently been accepted by the Radionavigation Committee of IALA as the new band-plan for the EMA. Individual administrations will now apply to ITU for the new frequencies and it is hoped that this process will be successfully completed in time for the plan to be implemented late in the year 2000.

5.7 Conclusions

The program described in this chapter has been developed for optimising the coverage of European DGNSS beacons by re-planning their frequency band to minimise interference. It makes use of the interference calculation method described in Chapter 4.

The MUA algorithm has been proposed, developed, tested and validated, and then employed for the real task of reorganising the radiobeacons of the EMA. The operation of the new algorithm was first demonstrated by using it to identify an optimum frequency plan for the present 408 radiobeacons. Aeronautical beacons have been left on their present frequencies and co-sited pairs of beacons allocated adjacent frequencies. With this new band plan applied to the present list of radiobeacons, no beacon would lose more than 6% of its coverage due to interference. This is in marked contrast to the previous plan, created using the traditional frequency allocation method, which resulted in up to 90% coverage losses. For some beacons the new software thus offers much lower levels of interference and more extensive service areas.

Real-life application of the software to three different lists of beacons is also described. The results have been used to encourage negotiations between national administrations. The final result of the algorithm is to be implemented as the new frequency plan for the radiobeacons in the EMA.

Chapter 6

Performance Analysis

6.1 Introduction

The frequency assignment algorithm described in Chapter 5 was devised as a first solution to the problem of ensuring that a new band-plan could be produced even if it was not the best possible. That done, let us now consider more broadly the question of optimising the band plan and let us try to establish how close to optimal the MUA algorithm may be. As a result we may devise an even better approach.

The task is to analyse the problem itself and see whether an efficient algorithm for its solution exists. The efficiency of an algorithm may be quantified in terms of its "execution time function", $O(n)$; this is a function that expresses the execution time, O, in terms of the size n of its input. By definition [70] an algorithm is efficient if its running-time is $O(P(n))$, where $P(n)$ is a polynomial in n, as opposed to certain other functions, notably exponentials. For example, assume a problem with a running-time function that is a 3rd order polynomial. If the algorithm can find the result in 1 ms, when the input size is increased 100-fold it will take 17 minutes to reach a result. If, in contrast, another algorithm has a running time function of 3^n and the result takes 1 ms to find, increasing the input size 100-fold results in the algorithm needing $1.6E^{35}$ centuries to find the result! That is why a problem that meets this *polynomial* criterion is said to be tractable; we mean that an exact, or optimum, solution can be found within a reasonable time. Such problems are deemed to be in "class *P*", *P* here meaning "polynomial time".

If our problem of frequency assignment were a member of class *P*, we would know that an efficient algorithm must exist. We could then seek to implement that algorithm and compare the result it gave with the result we obtained previously using the MUA and, in that way, establish the performance of the MUA. Unfortunately, we will see that problems of frequency assignment in general, and our clique partitioning problem in particular, are not members of class *P*. Our problem instead belongs to a class of problems known as "*NP-complete*" where *NP* stands for "non-deterministic polynomial" [71,72].

The difficulty with NP-complete problems is that the execution time increases so rapidly with the number of inputs that for all but the smallest numbers of inputs it is impracticable to obtain an exact solution; these problems are deemed, but not proven to be, intractable [73]. In other words no class-P exact algorithm has yet been found for this class of problems. In consequence, there are only two ways to assess the quality of our MUA algorithm. The first is to compare its results with those of alternative algorithms, taking into account the execution time, and see which gives the smallest number of channels for a given number of beacons and FoM limit. The second is to compare its results with a lower bound established by examining the problem and showing, for example, that even an ideal algorithm could not reduce the number of channels below some minimum figure.

This chapter will first explain what NP-Completeness means and show why our (and other) clique-partitioning problems fall into that class. Next it will introduce the use of lower bounds as a means of evaluating the quality of a solution. It will then identify various possible alternative algorithms and compare the results obtained by our MUA to those provided by the others. Finally, a lower bound will be established and the results of our MUA compared with it.

6.2 NP-Completeness

To define what NP-Complete is, the concept of a non-deterministic algorithm needs first to be introduced. A non-deterministic algorithm can be thought of a process which, when confronted with a choice between possible alternative solutions, can reproduce a copy of itself for each alternative and follow up the consequences of each course of action [74]. This repeated splitting may well increase the number of copies in an exponential, or factorial, manner. But if any one of them gives a valid result, that one is accepted.

A simple example of a non-deterministic algorithm is one that could be used to solve a minimum clique problem in graph theory. A graph is a diagram consisting of vertices and edges as shown previously in Chapter 5. In our case, the radiobeacons are represented by vertices and acceptable interference between any pair of radiobeacons is represented by an edge. For such, a graph trying to find the largest set of radiobeacons that do not interfere with one another is a minimum clique problem. In general for a given graph, $G(V,E)$ where V is the set of vertices (sometimes called "nodes") and E is the set of edges connecting $v \in V$. The minimum clique problem is to find whether it is possible to identify a clique of size k, a subset $V' \subseteq V$, such that every pair of vertices in V' are joined by an edge in E. In other words, a number of nodes some of which are connected to one another, and some are not. We are then trying to find a group of nodes consisting of k vertices, such that every node has a connection with every other member of the group. That is, we are looking for a group of radiobeacons that can share a frequency without unacceptable mutual interference.

First, a set M of vertices is formed which is empty initially. Vertices V are then examined one-by-one and a choice made as to whether or not to place them into set M. When all the vertices have been examined it is possible to verify whether or not M contains a clique of size k. Fortunately, this can be done using an algorithm with a polynomial execution time function, since now we only need check whether every vertex in M is connected to every other vertex in M. The output of this non-deterministic minimum-clique algorithm is "yes" if a clique of size k exists and "no", otherwise.

Now, the issue of transforming one function into another function in polynomial time (polynomial reducibility) needs to be addressed. Let U be all possible inputs to a decision problem to which the answer is either "yes" or "no" and let $L \subseteq U$ be all inputs for which the answer is "yes". Let $L1$ and $L2$ be two problems from the input spaces $U1$ and $U2$, where an input space means the collection of all possible inputs to the problem. For example, in our case the radiobeacon network is an input, and the collection of all possible networks is the input space for the frequency allocation problem. *L1* is defined as being polynomially reducible to *L2* if a polynomial time algorithm exists for converting $u1 \in U1$ to $u2 \in U2$ such that $u1 \in L1$ if, and only if, $u2 \in L2$ [70,73,74].

The class of problems, which consist of non-deterministic algorithms, the running-times of which are related to the size of the input by a polynomial, is called NP. Two subclasses of NP must now be defined. In the first, a problem *X* is called an *NP-hard* problem if every problem in NP is polynomially reducible to *X*. In the second, a problem *X* is called an *NP-complete* problem if *X* belongs to NP and *X* is NP-hard [70,73,74].

These definitions would themselves be hard to use if one were obliged to employ them directly in order to prove NP-completeness. A simpler approach, given in Manber [70], is to combine the two definitions into a further definition: a problem *X* is an NP-complete problem if *X* belongs to NP and *Y* is NP-complete and *Y* is polynomially reducible to *X*. This definition comes from the fact that if *Y* is NP-complete it is also NP-hard and every problem in NP is polynomially reducible to *Y*. Since we know that *Y* is polynomially reducible to *X*, by transition every problem in NP is reducible to *X,* suggesting that *X* is NP-hard [70]. Since *X* is both NP and NP-hard then, by definition, it is NP-complete.

6.2.1 The NP-Completeness of clique partitioning

In order to show whether a problem is, or is not, NP-complete the combined definition given above is very useful. The process actually employed is as follows:

1. Show that problem, *X*, is NP,
2. Select a known NP-complete program, *Y*,
3. Construct a transformation *f* from *Y* to *X*, and
4. Prove that *f* is a polynomial transformation.

Let us now examine our problem of clique-partitioning, or frequency assignment, to show that it is NP-complete. Our original problem was to partition a graph into *k*, or fewer, disjoint cliques; that is, to allocate the beacons to k, or fewer, groups and hence channels. The question is to prove the polynomial reducibility of an NP-complete problem. The NP-Complete problem chosen for this proof is to find whether, for a given graph, is it possible to assign at most k colours to vertices such that no two vertices joined by an edge have the same colour. This problem is known as the "Graph K-Colourability problem".

In Step 1, one can assign the vertices into k cliques using a non-deterministic algorithm by just guessing, and then checking, whether the assignment is true. This process can be carried out in polynomial time. This shows that the clique-partitioning problem is NP. In Step 2, the problem to select is the Graph K-Colourability problem, which is known to be NP-complete [70].

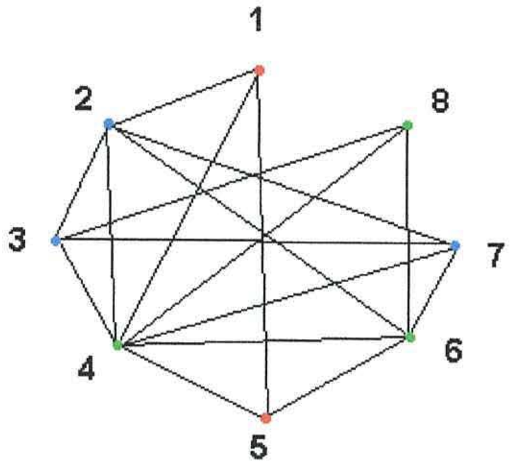

Figure 6. 1: *The graph can be partitioned into three cliques with three colours, as shown. Every vertex has a connection to the others that have the same colour.*

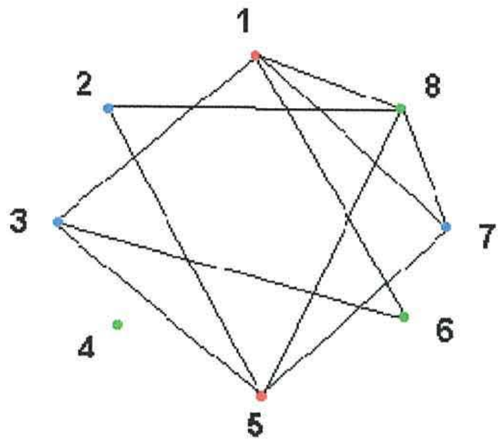

Figure 6. 2: *The inverse problem of clique partitioning is Graph K-Colourability where vertices that do not have a common edge with each other are assigned the same colour. It can be seen that the answer to the problem is same as clique-partitioning and the transformation process is that of taking the complement of every edge in the graph.*

Now consider the complementary problem. In step 3 we take the complement of a graph used in K-Colourability (Fig. 6.1). For the same set of vertices, if an edge is present we remove the edge. A new edge is established between all pairs of vertices where there was no edge previously (Fig. 6.2). As can be seen from Figs. 6.1 and 6.2,, those vertices that have the same colour are now connected to one another, forming a clique. In this step, taking the complement of every edge transformed an NP-complete problem to our problem of clique-partitioning. In Step 4 we must prove that this transformation has a polynomial execution time function. The running-time function we have employed simply complements each edge in turn. Supposing there are n vertices, (n is our input size) and that evaluating each edge takes m seconds, the running-time function will be in the form:

$$O(n)=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}m, \tag{6.1}$$

or,

$$O(n)=m\times\frac{n^2-n}{2}, \tag{6.2}$$

which, happily, is a (second-order) polynomial in n.

To summarise, in step 1 we have shown that clique-partitioning is NP. In steps 2 and 3 we have chosen a suitable problem known to be NP-complete and found a transformation. In the final step it has been shown that the transformation algorithm employed is polynomial. Thus we have completed the four steps required and proved that our clique-partitioning problem is NP-complete.

6.3 Setting a lower bound

Since the problem of clique-partitioning has been shown in the previous section to be NP-complete, we now know that, unfortunately, no exact solution to it is possible except for trivial numbers of radiobeacons. Instead of seeking an exact solution, our task must be to develop an algorithm that is computationally efficient in fitting the beacons into the smallest number of channels with the highest possible FoM limit.

A pragmatic mark of success would be to fit them all into the 64 available channels with no reduction of coverage below their interference-free boundaries. However, even if we could achieve that, we would still not know how close to the optimum our solution was. One way to assess the answer to this problem would be to try to find a lower bound. This would be the minimum number of channels into which the radio-beacons could ever be fitted. We can say for a start that the number of channels cannot be less than the number of mutually-incompatible radiobeacons; that is, the number of members of a group in which every member interferes with every other member!

To find our mutually-incompatible beacons, we have devised a program that embodies a new method of working we call the *sieving method*. Here, we start with a guess as to the number of mutually-incompatible beacons. Then, any beacon that is found to have a smaller number of interferers than the number guessed is removed from the whole set of beacons. This is done iteratively, the number guessed being increased each time until the number of beacons left is equal to the assumed number. The final result is a set of mutually-incompatible beacons. When this program was run the resulting group contained 58 mutually-incompatible beacons. Thus 58 is a clear lower bound; that is not, however, to say that it is an attainable bound, just that no lower figure is attainable.

Another lower bound algorithm has been developed by Smith and Hurley [75]. They normally employ it in the context of cell-phone frequency assignment problems. This algorithm also tries to find the largest clique of mutually-incompatible beacons, but in addition to the co-channel information that our sieving method uses, adjacent channel interference is also taken into account. Their algorithm returns a lower bound for our problem of 61. That is, it shows that no algorithm, however, efficient, could fit the beacons into fewer than 61 channels.

Our MUA algorithm succeeded in fitting the beacons into 62 channels with no mutual interference. Thus, it achieved a result only 1 channel greater than the minimum that could ever be achieved. We conclude that its performance is very good and further, that, in seeking an even better solution, we are not going to gain a great deal of improvement for additional effort.

6.4 Analysis of frequency assignment

Since we have now established that our problem of frequency assignment is NP-Complete, we can say that it is not possible, with the current state of knowledge, to find an exact solution to it. We can, though, compare the results of our MUA with those achieved by other algorithms. The literature contains many possible alternative types of algorithm. This section will identify and analyse those classes of algorithm that appear suitable for use in radiobeacon frequency assignment problems; the results of comparative tests using the various methods will be presented in the next section, Section 6.5.

To re-capitulate, in the literature, frequency planning problems are identified as examples of so-called "graph colouring problems", which are characterised as follows. We have a given graph with a set of nodes, or vertices, and a set of connections between the nodes such that some pairs of nodes are connected to each other with a line and some pairs are not; the problem is then to paint the nodes using the smallest possible number of colours. The colours must be assigned in such a way that no two connected nodes have the same colour [76-80].

In the case of our frequency-assignment problem, the vertices represent the transmitters and a connection between two vertices means that two transmitters cause interference in one another's coverage areas. Colours are frequencies; that is, we seek to assign colours to nodes (that is, frequencies to transmitters) in such a way that no two neighbouring vertices have the same colour (that is, no two mutually-interfering transmitters have the same frequency). We will now examine the several sub-classes of graph-colouring algorithm, including sequential, exhaustive, simulated annealing, tabu search and genetic algorithms, that might be used as alternatives to our MUA for assigning frequencies to radiobeacons.

6.4.1 Sequential algorithms

Sequential algorithms work through the list of transmitters, assigning frequencies transmitter-by-transmitter [81]. In the list, the transmitters are in some particular order; so the first transmitter is assigned to Frequency 1. Then the next transmitter to be assigned is selected and assigned a frequency. There are several options in this sequential algorithm procedure that will now be identified.

6.4.1.1 Initial Ordering

In order to assign frequencies, the transmitters are first placed in an order that depends on their number of interferers. Either:

- *Largest degree first-1 (LF1),* Transmitters are listed in descending order of their number of interferers - that is, of their *degree* (i.e. number of edges in the graph).
- *Largest degree first-2 (LF2):* the transmitters are again listed in descending order of degree, but this time the calculation of degree excludes transmitters that have already been ordered, or removed from the constraint graph, since they will have been assigned frequencies previously, together with all other transmitters that are connected to their vertices.
- *Smallest degree last (SL):* the transmitters of smallest degree are removed from the constraint graph. When all transmitters have been removed, the list is reversed to give the final ordering.

Alternative orderings can be made by counting the adjacent channel interferers as well as the co-channel ones.

6.4.1.2. Selecting the next transmitter

Methods used for selecting the next transmitter are as follows:

- *Sequential (S):* here the next unassigned transmitter in the list generated by the initial ordering is selected.
- *Generalised saturation degree (GSD):* the selection is done by calculating the number of frequencies not suitable for each unassigned transmitter. The calculation includes channels unsuitable due to adjacent channel interference as well as to co-channel. Later the transmitter with the highest GSD is chosen and a frequency allocated to it.

6.4.1.3. Selecting a frequency

Four methods are used in the final step of sequential algorithms. These methods are as follows:

- *Smallest acceptable frequency (SAF):* the lowest frequency on which there will be no interference is selected.
- *Acceptable occupied frequency (AOF):* the selected transmitter is assigned to any acceptable occupied frequency. The occupied frequencies are not ordered and the first acceptable one found is used. If there is no acceptable occupied frequency, the transmitter is assigned to the lowest available frequency,
- *Smallest acceptable occupied frequency (SAOF):* the method is to try to minimise the number of frequencies used in the assignment. The selected transmitter is assigned to the lowest acceptable occupied frequency. If there is no acceptable occupied frequency, the transmitter is assigned to the lowest acceptable frequency.
- *Smallest acceptable most heavily occupied frequency (SAHOF):* the selected transmitter is assigned to the lowest acceptable and most heavily occupied frequency. If there is no acceptable occupied frequency, it is assigned to the lowest acceptable frequency.

6.4.2 Exhaustive search

Exhaustive search techniques try all possible assignments of frequencies to transmitters and seek the best one. However, for large numbers of stations, these techniques are impractical since a non-intelligent exhaustive search algorithm would be obliged to check a number of assignments that was equal to the number of frequencies raised to the power of the number of transmitters! More intelligent search techniques might be able reduce this number. Exhaustive search techniques are very time-consuming and are generally only used where the number of transmitters is less than 30. However, for completeness, the two common forms of this approach will be presented briefly [82].

6.4.2.1. Backtracking

Backtracking is the simplest exhaustive-search technique. Transmitters are assigned frequencies successively. Let the first frequency, d, be assigned to transmitter i, i.e. $f_i = d_k$, k = 1. The backtracking algorithm then checks for constraint violations (that is, for unacceptable interference) with all transmitters that have already assigned frequencies f_j, $\forall j < i$. If there are no violations, the algorithm moves on to the next transmitter. If there is a violation, the algorithm checks whether the next frequency is a possibility, i.e. $f_i = d_{k+1}$. If no frequency can be assigned to f_j, the forward move fails and the algorithm then backtracks from the previous transmitter i-1 by changing its frequency f_{i-1}.

If the algorithm unsuccessfully tries all frequencies for the first transmitter, it stops and it becomes clear that there is no solution to the problem [83].

6.4.2.2. Forward checking (FC)

In forward checking, a new transmitter is selected if the new move will not cause any interference to previously assigned transmitters. FC works by keeping a new list of frequencies L^c, different from the actual frequency list L. At the start this second list is the same as the actual list, but when a transmitter i is assigned to a f_i, any transmitter j that may have interference with i is identified. Then, the frequencies of such interfering transmitters j are deleted from the new domain, $L_j^c, j > i$. This approach guarantees that when a frequency is assigned to a transmitter it does not interfere with transmitters to which frequencies have already assigned.

A backward move is necessary when a transmitter assignment leaves no possible frequency in the new list, $L_j^c = 0, j > i$. The algorithm backtracks in the same way as in the backtracking technique above. While doing so, the frequency lists are updated.

6.4.3 Simulated Annealing

Simulated annealing (SAn) is a method for finding near-global-minimum solutions to large optimisation problems. In many problems, in which it is not possible to find the global optimum because they are NP-complete, the solutions have many local minima. These optimisation problems require a procedure for searching through the solution space in an attempt to identify an at least nearly-optimal solution in a reasonable time, and this is what simulated annealing does. The method is named by reference to an analogy with the area of thermodynamics in which materials are changing their states from liquid to solid. If a material in a liquid state is cooled slowly, molecules align themselves into regular crystals: that is, a minimum energy, or optimum, state is achieved. If, however, the molten material is cooled too quickly, the resulting solid has a higher energy state, corresponding in the mathematical sense to a sub-optimal solution.

SAn was first introduced as a method for numerical minimisation by Metropolis et al [84]. They assumed that a simulated thermodynamic system changes its energy from E_{old} to E_{new} by a series of moves or similar configurations. The probability of a change P is given as

$$P = e^{(-(E_{new} - E_{old})/Bt)}, \tag{6.3}$$

where B is the Boltzmann constant and t the temperature. E_{old} and E_{new} are the old and new energy levels.

A generalised SAn algorithm is applied to frequency planning by first assuming a start temperature. Then a random assignment of frequencies to transmitters, X_{old} is generated. Using a cooling scheme, for example reducing the temperature by 10 percent at every loop, new frequency assignments, X_{new}, are generated from the old assignment. The energy levels for the old and new assignments are calculated, i.e. the number interfering pairs of transmitters, and if the new assignment has a lower energy level than the older one the new assignment is chosen. This is done until a certain number of iterations have been reached. Sometimes, in order to escape from a local minimum, a new assignment is accepted even if it has a greater energy provided the probability of change, P, is greater than a random number [85].

A more detailed explanation of the way in which the energy of assignments is calculated is given in Appendix B.

6.4.4 Tabu search

The "tabu (or taboo) search (TS)" was first suggested by Glover [86] and has since been widely used to find optimal, or acceptable suboptimal, solutions to such problems as scheduling, time-tabling, travelling salesman, and layout optimisation.

A tabu search browses through the solution space of all feasible solutions in a sequence of moves seeking the optimum solution. To escape from local minima, but not the global minimum, and to prevent cycling, some moves, for example repeating moves, are classified as forbidden or tabu. All moves are recorded in both a short-term and long-term history list and the algorithm then decides which moves are tabu; for example, a move might be classified as tabu if the reverse move has been made recently, or frequently. Sometimes, for example when it is deemed favourable to escape a minimum, a tabu move can be overridden [87,88].

In an optimisation problem, a tabu search might be applied as follows. Suppose h is the cost function or the energy function on a search space, S, where h is the number of constraint violations and the search space is the combination of all possible solutions, and it is required to find $s \in S$ such that $h(s)$ has its minimum value. For frequency planning, s is the frequency assignment of transmitters and $h(s)$ is the number of interfering pairs. For intractable problems, this condition is relaxed in order to find an $s \in S$ such that $h(s)$ is sub-optimal or, in other words, a solution close to a lower bound or the optimum. If an acceptable solution is achieved after a certain number of iterations, that solution is deemed to be sub-optimal.

The tabu search method starts with a (possibly random) solution, $s_0 \in S$, and finds a sequence of frequency assignments, $s_0, s_1, ..., s_n \in S$. At each iteration, s_{j+1} (1<j<n) is selected from the neighbourhood set $N_{set}(s_j)$, which is the set of feasible solutions. The selection operation first determines the tabu set $T_{set}(s_j) \subseteq N_{set}(s_j)$, (the forbidden moves set) of neighbours of s_j. Then the aspirant set $A_{set}(s_j) \subseteq T_{set}$, tabu moves allowed to escape local minimum of tabu neighbours. A local minimum is a frequency assignment that is not optimal but better than its neighbouring assignments Then s_{j+1} is the neighbour of s_j which is either an aspirant or not tabu and for which $h(s_{j+1})$ is minimal; that is $h(s_{j+1}) \leq h(s') \; \forall \; s' \in (N_{set}(s_j) - T_{set}(s_j)) \cup A_{set}(s_j)$.

A typical tabu search algorithm starts by generating initial assignments. For a pre-set number of iterations the set of viable solutions is identified along with the moves that are forbidden, i.e. the tabu set. Then the moves that have previously been identified as forbidden moves are identified. Depending on the cost function a new move is chosen [89].

A more detailed explanation of the way in which the cost function for assignments is calculated is given in Appendix B.

6.4.5 Genetic Algorithms

Genetic algorithms function by mimicking processes such as evolution and natural selection. To survive in nature, living things need to adapt to their surroundings. The necessary information for survival is encoded in the chromosomes of creatures, and undergoes transformations when reproduction occurs. These transformations can give rise to species that are more likely to survive and so have a greater chance of passing on their improved characteristics to their offspring. If the changes are not beneficial, the species are more likely to die out [90,91].

In order to mimic nature in an optimisation problem, the first step is to represent a solution to the problem by the equivalent of the string of genes, known also in this context as a "chromosome". An initial population of valid chromosomes can be constructed at random. Thereafter, at each iteration step, after allowing for some change, the fitness of each chromosome in the population is measured. We define a "fitness value" as a cost function of the problem; a high fitness value chromosome would represent a better solution than a low fitness value one. The fitter chromosomes are then selected to produce offspring for the next generation. Assuming that the best traits of parental chromosomes are propagated, then after many generations of selection, the resulting population should be substantially fitter than the original one.

All genetic algorithms first represent solutions as chromosomes. After a number of random solutions have been generated these solutions are evaluated for their fitness and the fittest solutions are reproduced using the "crossover" and "mutation" operations explained below until the best solution has been found or a set number of iterations has been reached.

The problem of frequency assignment needs to be represented in a way that allows a genetic algorithm to solve it. In this case, each chromosome consists of N genes where N is the number of transmitters. Each gene carries the frequency to which the corresponding transmitter has been assigned,

$$f_1 f_2 f_3 \ldots f_i \ldots f_N \tag{6.4}$$

where i is the gene and f_i the frequency. The initial population is first set up arbitrarily. The fitness of the individual could then be assessed using a formula similar to the one given in Appendix B. Once the parent chromosomes have been identified according to their fitness, the crossover and mutation operations can be performed on the offspring [89].

In the crossover operation the characteristics of two parents are combined. Some portions of genes are exchanged between two solutions to create a better solution. A detailed explanation of crossover operation is given in Appendix C.

A mutation operation is used randomly, or when the parent and offspring genes are the same, to change the value of a gene in the offspring chromosome [89]. In this way if a local minimum has been reached or algorithm has gone into a closed cycle an escape from the local minimum is provided.

6.4.6 Hill Climb Algorithms

In hill climb algorithms, a random frequency assignment is assumed and the number of constraint violations that it embodies is calculated. One-by-one each transmitter is then assigned to a different frequency and the resulting violations are assessed. If the new assignment causes fewer violations then the previous one, it is retained. The next transmitter is then handled in turn until no further improvement results [89].

6.4.7 Hybrid Algorithms

The above methods can be used not only on their own but also in combinations, or hybrids. In particular, it is common for the output from one method to be used as the starting point for a different one. For example, a sequential algorithm could be used to give a starting assignment to a genetic algorithm or the best assignment from a genetic algorithm could be refined using a local search algorithm such as simulated annealing or tabu search. Hybrid algorithms can help the iterative searching algorithms to find their solutions faster.

6.5 Comparison of Frequency Assignment Algorithms

Instead of comparing the results given by our MUA directly with those provided by each of the types of algorithm described in Section 6.4, we will first compare the results of these algorithms with one another (in the context of frequency selection problems) and then compare our MUA to the best of them. In this section, such comparisons are presented. They are based on the 5 most extensively-used types of frequency-selecting algorithm identified from the literature.

The algorithms in examples 1 to 4 are compared using an application known as the "Philadelphia Problem". It was devised by Anderson [92] as an example of the problems of mobile phone cell planning and has since been used by Gamst [71], Funabiki and Takefuji [93], Lochti and Mehler [94], Kim et al [95], Janssen and Kilakos [96], Leese [97], Sivarajan et al [98]. Example 5 is a military radio link-assignment problem. In all these examples, the task was to find the frequency assignment that uses the minimum number of frequencies, with no interference.

6.5.1. Mobile phone examples

Examples 1 to 4 are based on a mobile phone cell planning application in an area around Philadelphia, Pennsylvania, in which 21 base stations were required, but with different number of transmitters in each example. In Example 1, 493 transmitters had to be assigned frequencies. Algorithms by Sivarajan et al [98], Wang and Rushforth [99] and Leese [97] identified assignments with 460, 432 and 427 frequencies, respectively. TS and SA algorithms by Hurley et al [89] produced an assignment of 428 frequencies. However the lower bound value of 426 calculated by Janssen and Kilakos [96] was achieved by Smith et al [100] using a sequential and TS hybrid algorithm, as shown in Table 6.1.

In Example 2, with the same application, frequencies were assigned to 488 transmitters. The lower bound value was shown to be 426 and Smith et al [100] succeeded in achieving this value using a sequential TS hybrid algorithm (Table 6.1). In Example 3 the number of transmitters was 482. A hybrid sequential and tabu search algorithm by Smith et al [100] found a frequency assignment using 257 frequencies, which again corresponded to the lower bound. For Example 4, where there were 477 transmitters, the same algorithm by Smith et al found an assignment with 252 frequencies.

6.5.2 Example 5

Example 5 is based on a radio link problem that arose in a military application. In this frequency assignment problem there were 100 sites and 190 transmitters. A channel spacing of four or more was imposed on co-located transmitters. In addition, there were co-channel constraints, and interference could occur on up to the 3rd adjacent channel. The lower bound was found by Smith and Hurley [75] to be 67. An algorithm written by Hurley et al, called FASoft, gave an assignment of 75 using SA, and 70 using TS [89].

Example	No. of Txs.	Lower Bound	Best Span	Algorithm
Example 1	493	426	426	TS [100]
Example 2	488	426	426	TS [100]
Example 3	482	257	257	TS [100]
Example 4	477	252	252	TS [100]
Example 5	190	67	70	TS [89]

Table 6. 1: *Comparison of results given by various algorithms. Algorithms that employ, tabu searches were found to be the best in every case.*

6.5.3 Results of comparison

The problems examined in Examples 1 to 5 were tackled by various researchers using a variety of algorithms. The nature of the problems was very similar to our radiobeacon frequency-planning problem, with the interference information capable of being represented as a graph. Examining the results of Examples 1 to 5, in columns 3 to 5 of Table 6.1, it is seen that tabu search algorithms gave the best solutions. In fact, in the first four examples, tabu search actually achieved frequency assignments equal to the lower bound values. Hurley and Smith's FASoft algorithm [89,100], which incorporates a tabu search plus the other methods mentioned previously in this chapter, was able to find the optimal solution in 4 of the 5 cases and so was judged the best of all the algorithms considered.

6.6 Comparison of MUA with FASoft

We have shown that the performance of our MUA algorithm can best be assessed by comparing the result it gives with those of another algorithm of known high performance, since the NP-completeness of our problem precludes absolute assessments. We have already employed the only other way of assessing it, in section 6.3, where we estimated a lower bound from the constraint data, and saw that our algorithm required only one channel more than the minimum possible number of 61.

So now let us compare our algorithm with the FASoft algorithm. Hurley & Smith at Cardiff, the authors of FASoft kindly offered to run their algorithm using our data. We sent them our FoM matrices for co-channel and adjacent channel interference, and a list of the beacons whose frequencies were to be retained. They input this data into FASoft. A frequency assignment was successfully produced, first without any channels being retained for NDBs; FASoft required 62 channels! That is, the two algorithms gave the same result for the same data and constraints. Both fitted the beacons into only one channel more than the minimum set by the lower bound. But notably, our MUA was 4-5 times faster than FASoft. It took 5-8 min to run where FASoft took 20-30 min on similar computers.

When the constraint of retaining aeronautical NDB frequencies was introduced, the number of channels required by our algorithm had increased to 67. In this case, FASoft succeeded in fitting the beacons into two fewer channels, 65. In a sense, however, neither solution was acceptable, since both exceeded the maximum number of channels available, 64. We showed earlier that when the FoM limit was reduced, our MUA succeeded in fitting all the beacons into the available frequency band of 64 channels with an FoM of 0.98. In fact, with an FoM limit of 0.98 both algorithms were able to fit into available 64 channels, MUA and FASoft requiring 63 and 62 channels respectively.

This result appears to be in conflict with the previous statement that the MUA required 64 channels for an FoM limit of 0.98. To explain, see Table 6.2 which shows how the results of frequency assignment change in response to changing the FoM limit, after Turhan et al [101]. With an FoM limit of 0.99, FASoft was able to fit all beacons into 64 channels, the highest channel used being channel 64. With the MUA, although the frequency assignment required 64 frequencies the highest channel used was channel 65 which is not allocated for maritime radiobeacons. Thus, with the NDB constraint in place, there is no significant difference between the performance of the two algorithms. Note that the number of frequencies used can be higher than the highest channel no because of the channels assigned to NDBs.

FoM Limit	**Highest channel no.**	**No. of channels**	**Highest channel no.**	**No. of channels**
	MUA		**FASoft**	
1.00	67	67	65	65
0.99	65	64	64	64
0.98	64	63	64	62
0.97	64	61	64	59
0.96	64	60	64	59
0.95	64	60	64	58
Execution Time	5-6 min		20-30 min	

Table 6. 2: *Comparison of radiobeacon channel assignments produced by the MUA and FASoft algorithms.*

It was not possible to compare the performances of the two algorithms with the final constraint, that of pairing co-sited MB and DGPS radiobeacons, included. This was because, unlike the MUA, the competing algorithm had never been designed to accommodate this extra condition; it is not something that arises in the context of mobile phone base stations or radio links for which FASoft was designed.

6.7 Conclusions

This chapter has shown that our band-planning problem belongs to a class of problems known as NP-Complete, for which the search for optimal solutions is intractable due to the large search space. We can, however, assess the performance of our algorithm by calculating a lower bound for the result. Doing this showed that the MUA managed to fit the 408 radiobeacons into 62 channels, where the absolute minimum set by the bound was 61; this was deemed an excellent performance.

The results given by the MUA were then compared with those produced by the frequency assignment software, FASoft, identified as the best of 10 algorithms from a field that included a wide variety of methods of optimisation, including tabu search, simulated annealing and genetic algorithms. The results showed that both algorithms were capable of producing band plans using numbers of channels that were very close to the lower bound. However, our MUA was found to be much faster than FASoft, while FASoft was able to give band plans with just one or two frequencies fewer when beacons that retain their frequencies were taken into account.

It was also noted that our radiobeacon problem was unique in allowing the pairing of co-sited transmitters; other algorithms, such as FASoft, could not accommodate this requirement.

Chapter 7

Conclusions

The primary objective of this research was to evaluate the interference between radiobeacons and, on that basis, to develop techniques for re-assigning their frequencies in order to maximise their coverage throughout the European Maritime Area.

Existing methods of evaluating the interference were examined and found to be inadequate. The principal reasons were that they assumed the transmitters to have circular coverage areas or that they evaluated interference at the edges of coverage only. In doing so they also ignored attenuation due to different types of terrain and the effects of skywave propagation. The research presented here, in contrast, has proposed and investigated a quite different method for evaluating interference. Specifically, the interference is computed point-by-point throughout the whole of the interference-free coverage area. The results are then incorporated into a program designed for selecting the best frequency to be allocated either to proposed new radiobeacons that are to be introduced into an existing beacon network or to all existing beacons.

The general approach adopted by others in assigning channels in a limited spectrum with a fixed number of channels has been to fit as many transmitters as possible into the frequency band with no interference and then assign the rest to frequencies where they might suffer heavily from interference. Instead, this research proposes a different way of dealing with interference. In the new method a percentage of coverage loss is allowed (hopefully a small one) and the loss of coverage is distributed among the beacons in a much more equitable fashion.

The performance of radiobeacons obtained using the band plan generated by the method developed in this research is compared with their performance under the current band plan. Substantial coverage improvements are seen to result from the change: specifically, under the current plan coverage losses up to 90% are observed, while under the new plan at worst beacons will lose 20% of their coverage. In order to assess the performance of the technique proposed, the result of the new algorithm on which it is based are compared to algorithms from the literature. The measurements show that the new method is as good as the best of the others. Further, when its results are compared to the lower bound, it is shown to be capable of producing near-optimal band plans.

7.1 Review of the thesis

Chapter 2 gave an introduction to GPS and how it operates, identifying the error sources. Similar systems, such as GLONASS and Galileo, were also introduced. A description of Differential GPS was then followed by an introduction to radiobeacons and a description of how they were used prior to the introduction of their new role of sending GPS correction signals.

Chapter 3 discussed coverage prediction for radiobeacons and described the factors affecting the signal such as attenuation and the effects of atmospheric noise and interference. The two modes of propagation, groundwave and skywave, were analysed together with the fading of the combined groundwave and skywave signal. The way in which atmospheric noise was calculated was analysed. Coverages of radiobeacons, predicted by a model that takes these factors into account, and the loss of coverage due to interference were demonstrated. This allowed the need for changing the frequencies of the radiobeacons to be explained.

Chapter 4 analysed the methods of evaluating interference between radiobeacons and proposed a novel method for quantifying the effects of interference in terms of the reduction of the coverage with respect to the Interference-Free Coverage Area. This evaluation of interference was then used as a basis on which to develop a program for selecting the best frequencies for individual new radiobeacons. The program was then demonstrated as it was used to assess the performance of a set of radiobeacons in the British Isles, operating under the current frequency assignment. It was then used to choose the best possible frequencies for these beacons and the resulting substantial increases in coverage evaluated.

Chapter 5 developed methods for re-assigning the frequencies of all the radiobeacons in the EMA. To do this, a novel algorithm, the MUA algorithm, was developed. Also, methods were proposed for incorporating constraints such as retaining the frequencies of certain radiobeacons and assigning co-sited transmitters to adjacent frequencies. The development of the algorithm was demonstrated in detail with these various constraints applied cumulatively. The program was used with various different lists of radiobeacons supplied by IALA and the results of different runs presented as the new band-plan was fine-tuned in response to the requirements of the national administrations. A final list of radiobeacons was used to produce a band plan, which will be implemented as the radiobeacon network in the EMA.

In Chapter 6 the performance of the novel frequency planning algorithm proposed was evaluated. The classification of the problem of optimising the band-plan was first analysed. This showed that the problem belonged to a particularly difficult class. Various algorithms for tackling such problems were identified in the literature and their performances compared using a benchmark problem. The best performer was then chosen to be compared for comparison with the algorithm developed in this research. Results were given for a number of cases. It was shown that the MUA developed in this research gave results as good as the best of the algorithms from the literature.

7.2 The *New Beacon* and *Optimisation* programs

As part of this research two computer programs have been developed. The first is used to select the best frequency on which to operate a new radiobeacon to be introduced to a network of radiobeacons, or an existing beacon whose frequency is to be changed. The frequency is selected on the basis of minimising both interference received from existing beacons within the coverage are of the new beacon and interference to the coverages of existing beacons caused by the new one. The second program is the one for re-assigning the frequencies of the whole population of radiobeacons in the EMA. This is the program that has been used to design the new band-plan encompassing the proposals of IALA member-nations.

User guides for these two programs, the *New Beacon* program and the *Optimisation* programs, are given in appendices D and E, respectively.

7.3 Suggestions for further work

The Optimisation program could further be developed by incorporating an iterative algorithm such as a tabu search following the use of the MUA. This might allow the already-good results achieved by the MUA to be refined further. It would allow the process to escape from a local minimum if one were encountered and the global optimum found. Judging by the lower bound calculated during the development, 61 channels, and the minimum allocation found by MUA, 62 channels, there could still be room for a further small improvement. More valuably, it might also be possible to achieve a higher FoM limit by the use of such a hybrid algorithm.

The data files used to store the attenuation values are as large as 1.2 Mbytes and require storage place, in fact the whole database that contains the files for some 800 transmitters take about 1.2 Gb. The data could be compressed using surface-fitting techniques which would represent the attenuation values by a function. Doing this might reduce the memory requirements of the program.

The reorganising of the band plan done, as for the EMA, could be carried out for other parts of the world. In fact, at the time of writing, IALA are looking at doing this for South America and the Far East.

7.4 Conclusions

This work has introduced, implemented, and analysed tools for frequency management that have been shown to be capable of increasing substantially the performance of DGPS radiobeacons in the European Maritime Area. These programs may be used individually or may be used together, by first employing the optimisation program then using the new beacon program to manage subsequent changes. The programs allocate frequencies to radiobeacons in such a way that they will be sufficiently separated in distance and frequency. In doing so, factors affecting propagation, including groundwave attenuation, skywave attenuation, fading and atmospheric noise are all taken into account in a formal manner. Throughout this work, both programs were used to evaluate the performance of and design radiobeacon networks as they were developed. The new frequency plan produced by the optimisation program offers much better performance than the existing plan, delivering at least 80% of possible coverage area where the current situation is as low as 10%, and that with a greater number of high-powered DGNSS stations. The new plan is expected to be implemented at the end of the year 2000.

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Appendices

Appendix A

Millington's Method

The method recommended by ITU for calculating the attenuation of groundwave signals that propagate over paths of mixed terrain conductivity is known as Millington's Method. Fig. A.1 illustrates the use of Millington's method to calculate the total attenuation between a transmitter and receiver. The attenuation, A1 (green), of the first, over-sea, section of length d1 is taken from the ITU curve for seawater. For the second, land, section of length d2, the additional attenuation is A2 (red) and the attenuation of the final, sea, section is A3 (orange).

The total attenuation from transmitter to receiver is then A1+A2+A3. The process is then repeated in the direction from the receiver to the transmitter. Millington's method assumes that the since the attenuation is the same regardless of direction of travel, any discrepancy between the forward and backward attenuations is due to errors in the calculation. Such errors are assumed to be equal in magnitude but opposite in sign for the forward and backward attenuation. The best estimate of the attenuation of the path is then assumed to be that found by averaging the forward and the backward attenuations [9].

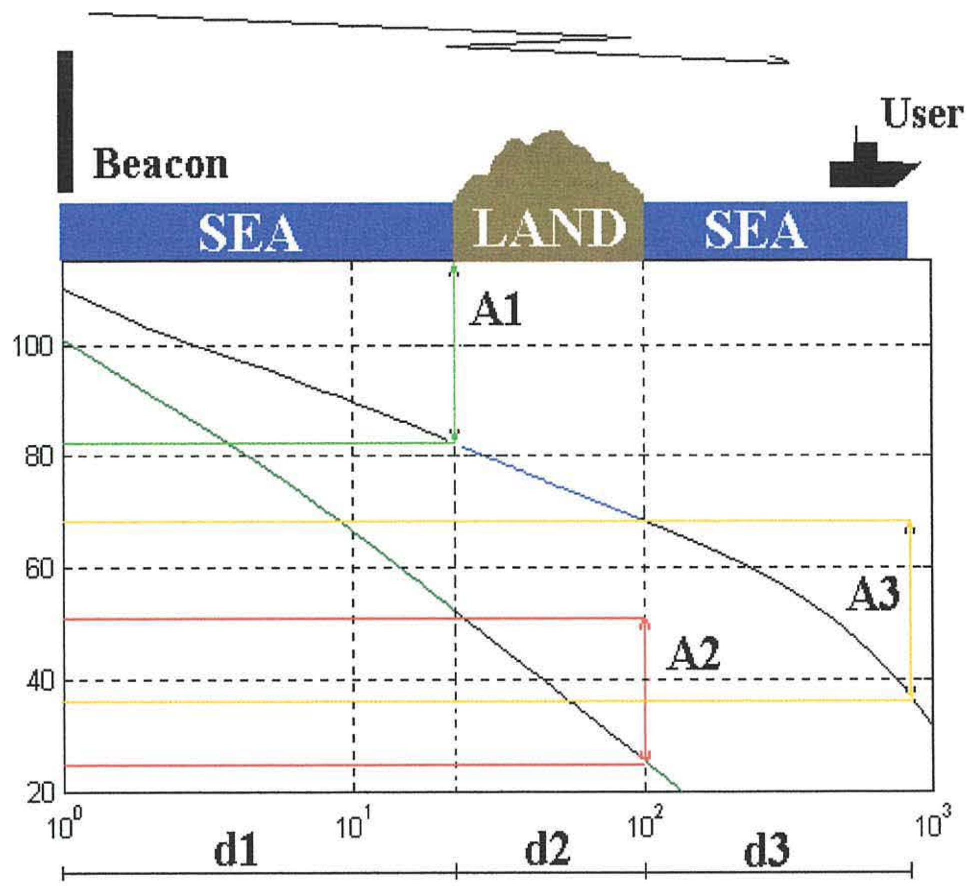

Figure A.1: *Millington's method for calculating the total attenuation of paths that consist of sections with different rates of attenuation. The upper curve is that for sea-water at 300 kHz and the lower is that for the land section of the path. The total attenuation of the forward path is the sum of A1, A2 and A3 [9].*

Appendix B

Energy Functions for Frequency Assignments

In order to implement simulated annealing or other iterative search algorithms that depend on minimising a cost function or an energy function, an energy function E needs to be formulated. One such function, given by Hurley et al [89], is:

$$E = \mu_1 e_{vio} + \mu_2 e_{sum} + \mu_3 \left(f_{large} - f_{small} \right) + \mu_4 e_{order} + \mu_5 f_{large} + \mu_6 l_{vio}, \quad \text{(B.1)}$$

where μ_i are weights,

e_{vio} is the number of violated constraints,

e_{sum} is the sum of the amounts by which each constraint is violated,

f_{large} is the largest frequency used,

f_{small} is the smallest frequency used,

e_{order} is the number of distinct frequencies used, and

l_{vio} is the largest of the constraint violations.

For example, a solution that has four violations (i.e., $e_{vio} = 4$) with the sum of the constraint violations equal to 4 i.e., $e_{sum} = 4$ (one for each of the violated constraints)) could be considered more useful than a solution that has one violation (i.e., e_{vio} 1) but a constraint violation sum of 4 (i.e., e_{sum} 4) by setting the weights accordingly. These situations correspond to a small amount of interference for a small number of transmitters in the first case, and to perhaps two transmitters that interfere severely with each other in the second.

Once the energy function has been determined, the algorithms given in Chapter 6 can be implemented.

Appendix C

Crossover Operators for Genetic Algorithms

Crossover operators are classified as one-point, two-point and or uniform and are defined as follows:

In a one-point crossover, we take two frequency assignments and randomly choose a transmitter. This transmitter is called a "point" and the part of the assignment from the chosen transmitter to the last transmitter is called a tail. Then these two "chromosomes" exchange their tails. Here the point is transmitter 6 and the tails are the frequencies of transmitters 6 and 7. The resultant assignments are the "children" of the first two assignments.

Parent$_1$ $f_1\ f_2\ f_3\ f_4\ f_5 \vee f_6\ f_7$

Parent$_2$ $g_1\ g_2\ g_3\ g_4\ g_5 \vee g_6\ g_7$

Child$_1$ $f_1\ f_2\ f_3\ f_4\ f_5\ g_6\ g_7$

Child$_2$ $g_1\ g_2\ g_3\ g_4\ g_5\ f_6\ f_7$

A two-point crossover is similar to a one-point version, except that two random points are chosen and the genes in the middle are exchanged,

Parent$_1$ $f_1 \vee f_2\ f_3\ f_4\ f_5 \vee f_6\ f_7$

Parent$_2$ $g_1 \vee g_2\ g_3\ g_4\ g_5 \vee g_6\ g_7$

Child$_1$ $f_1\ g_2\ g_3\ g_4\ g_5\ f_6\ f_7$

Child$_2$ $g_1\ f_2\ f_3\ f_4\ f_5\ g_6\ g_7$

A uniform crossover generates a mask for each gene and that mask determines which gene is going to which offspring,

Parent$_1$ f_1 f_2 f_3 f_4 f_5 f_6 f_7

Parent$_2$ g_1 g_2 g_3 g_4 g_5 g_6 g_7

Mask 1 1 0 0 1 0 1

Child1 f_1 f_2 g_3 g_4 f_5 g_6 f_7

Child2 g1 g2 f_3 f_4 g_5 f_6 g_7

All three crossover operators are used either randomly or in order to have a better frequency assignment.

Appendix D

User Guide For New Beacon Program

The new beacon program consists of three programs. The first two calculate the attenuation files and the third program evaluates the interference and finds the best frequency. All programs are located in the directory "C:\NEWBEC\".

D.1 Gndwatt.Exe

This program calculates the Groundwave Attenuation files. Since it is based on the Coverage Prediction Software, the same directory structure is used. The program needs an input file named "INPUT.LST" in the "C:\DGPSCOV\" directory. The file starts with the number of transmitters for which the program is to be run, the name(s) of these transmitter(s) and their type of transmission. For example if we are going to run the program for two DGNSS radiobeacons, Girdle Ness and Point Lynas, INPUT.LST will contain:

2
GIRDLE_NESS DGP
PNT_LYNAS_LSTN DGP

Note the underscore character, which replaces spaces in the original name.

The second file the program require is a list of the other radiobeacons in the band. It contains the name, type, latitude, longitude, range in km and range in NM. The name of the file and the directory are "C:\DGPSCOV\FILES\BECNINF.DAT". The file will contain lines containing information regarding the beacons so for the beacons mentioned above the file will look like:

33 300.0 GIRDLE_NESS DGP 57N08 02W03 277 150

33 300.0 PNT_LYNAS_LSTN DGP 53N24 04W17 277 150

43 307 THIRA NDB 36N24 25E29 148 80

59 313 SPLITMB 43N30 16E28 37 20

45 306 MOLUNAT MB 42N27 18E26 185 100

31 299 KAMENJAK MB 44N47 13E55 185 100

GNDWATT uses this file to get the information about the location of the beacons in the "INPUT.LST" so that it can calculate the attenuation files for the beacons.

Attenuation files created by the program are output to the directory: "C:\NEWBEC\GNDWAVE\". The names of these files will have the form: GIRDLE_N.DGP and POINT_LY.DGP; note that the original DOS-style 8+3 file name type is used here for saving and accessing the files. These arrays are then used for the coverage and interference computations as will be explained in section D.3.

This program is very similar to Bangor Coverage Prediction Model (BCPM) however the array sizes are much larger containing information for a greater area and the program can run for any beacon in the northern hemisphere where as BCPM performs its analysis on a smaller window.

D.2 Skywatt.Exe

This program calculates the skywave attenuation arrays. It needs the same files as the GNDWATT.EXE program. It gets the names of the new beacons from "INPUT.LST" file and uses the "C:\DGPSCOV\FILES\BECNINF.DAT" file for the information about the location of the new beacons. The only difference is that the output files are saved in the directory "C:\NEWBEC\SKYWAVE\". The same file names are used as with the groundwave program.

Again the program is similar to BCPM and the same differences, larger array sizes and generalised run, mentioned in GNDWATT exist.

D.3 FINDFREQ.EXE

This program evaluates the interference and finds the best frequency. To do so it need two files in addition to the attenuation files whose creation has just been described. These are the files "C:\NEWBEC\BECROW.TXT" and "C:\NEWBEC\BECNINF.TXT". The first, BECROW, contains information about the new beacon. The second, BECNINF, contains the information about the existing beacons. Here, by way of example, is the layout of each line in BECROW:

0 283.5 GIRDLE_NESS DGP 57N08 02W03 277 150
0 283.5 PNT_LYNAS_LSTN DGP 53N24 04W17 277 150

This describes the DGNSS radiobeacons named in "INPUT.LST" at the co-ordinates 57N08 latitude and 02W03 longitude, with a range of 277 km or 150 nautical miles for Girdle Ness. In BECROW the channel number and frequency are 0 and 283.5 since the frequencies for the new beacons are not known and assumed to be on channel 0. In BECNINF the information regarding existing beacons is stored as shown below again the same order of channel, frequency, name, type, latitude, longitude, nominal range in km and range in NM is used:

59 313.0 SPLITMB 43N30 16E28 37 20
60 313.5 C_SAN_SEBASTIAN DGP 41N53 03E12 180 97
60 313.5 VISBY MB 57N38 18E17 56 30
61 314.0 BRUX_ELLES NDB 50N49 004E28 45 24
61 314.0 C_SAN_SEBASTIAN MB 41N53 03E12 180 97
61 314.0 FISKA NDB 41N06 22E59 75 41

The output file is called "RESULT.TXT". It is saved in the same directory as the program. The file consists of two columns. Column 1 contains the channel number and in column 2 the FoM when this channel is used. Table D.1 is an example.

Channel	FoM
0	**0.78**
1	**0.94**
2	**1.00**
3	**0.23**

Table D.1: *Table showing the output produced by Findfreq.exe and stored in Result.txt. The first column is the channel and the second s the corresponding FoM.*

The best frequency, or any other frequency required by the system planner, can then be chosen as the operating frequency for the beacon.

Appendix E

Optimisation Program

The optimisation program consists of two parts. The first evaluates the interference between beacons and the second does the frequency allocation. Both programs are situated in the "C:\OPTIM\" directory, which is the home directory for this program.

E.1 Optimd.Exe

This program evaluates the FoM between pairs of radiobeacons. As described in Chapter 6, the task may be distributed between a number of computers equipped with CD ROM drives, and to allow this sets of attenuation files are first copied onto CD-ROMs with the groundwave files to "D:\GNDWAVE\" and skywave files to "D:\SKYWAVE\" directories repectively. Running the program requires two files in the home directory. The first is BECROW.TXT which contains a list of those beacons on which the individual computer is to work. The second is BECNINF.TXT which contains the whole list of beacons. Their structures are as specified in Appendix C above.

When the program is run it produces the set of FoM for every pair of beacon where the first member of the pair is from BECROW.TXT and the second member is from BECNINF.TXT. The output is in the form:

1 2

0.70 0.98 1.00 1.00 1.00 1.00 1.00

1 3

0.05 0.85 0.98 1.00 1.00 1.00 1.00

Here the two numbers 1 and 2 represent the first beacon in BECROW and second beacon in BECNINF respectively. The following 7 numbers are the FoM for that pair of beacons starting with the co-channel FoM and first and other adjacent channel FoMs following .

When more than one computers are be used these resulting files are merged creating a file that contains all the information about. Suppose that three computers are used with the first, second and third parts of the beacon list is assigned to computers A B and C. When the run finishes, RESULT.TXT from computer B is pasted to the end of RESULT.TXT from computer A. To the end of this file RESULT.TXT from computer C is then added. The FoM values are then distributed

Once the FoM calculation is finished the FoM values are copied to files, using EXCEL or similar spreadsheet program, such that all the co-channel figures are stored in a file "CO.TXT" in home directory. The corresponding files for adjacent channel interference figures are "FIRST.TXT", "SECOND.TXT", "THIRD.TXT", "FOURTH.TXT", "FIFTH.TXT" and "SIXTH.TXT", all in the home directory. Example of files are given below using the previous FoM results:

CO.TXT

0.00	**0.70**	**0.05**
0.70	**0.00**	**0.18**
0.05	**0.18**	**0.00**

FIRST.TXT

1.00	**0.98**	**0.85**
0.98	**1.00**	**1.00**
0.85	**1.00**	**1.00**

Note that the FoM for beacons 1 and 2, shown in RESULT.TXT becomes the 1st row 2nd column element in these files, similarly the 2nd row 1st column element is the same as the FoM for a pair of beacon is symmetric. These files are then called by the optimisation program.

E.2 Optimisation

The optimisation algorithm MUA has been written in MATLAB since this is more efficient in handling the matrices and vectors involved. The main file is "GANP.M", in the home directory. GANP stands for **G**et **A** **N**ew **P**lan. To set the FoM limit the file needs to be edited and, in the fifth line, the number after the variable "**inter_main**" must be set to the value one minus the FoM limit. For example, if the FoM limit is 0.8 the value needs to be set to **0.2** as given below.

inter_main=floor(inter_main+**0.2**);

The result is output to the file "FREQMAIN.TXT". The output is in the form:

29	**143**	**383**	**244**	**50**	**374**	**351**	**401**
30	**241**	**172**	**368**	**382**	**231**	**249**	**303**
31	**248**	**208**	**37**	**179**	**182**	**263**	**238**
32	**297**	**36**	**137**	**260**	**12**	**214**	**240**

where the first number in every line shows the channel number and the following numbers are the beacons assigned to that frequency. For example beacon number 143 is assigned to channel 29. 143 is the 143rd beacon in the BECNINF.TXT list. A frequency allocation list can then be obtained using a spreadsheet program such as EXCEL.

If there are beacons that need to be kept on their current frequencies, a file named "NDB.TXT" is required. The file contains the channel and the order of the beacon in the list. For example if the beacons, TRY1 and TRY2 are the 105th and 120th beacons in the list from the top, and they need to remain on channels 32 and 37, respectively, the file would look like this:

32 105

37 120

If there are paired beacons, the information describing the pairs is kept in the file "PAIRS.TXT". For example, if the beacons numbered 23 and 24, 35 and 36 and 48 and 49 in the list are to be paired, PAIRS.TXT will look like this:

23	**35**	**48**
24	**36**	**49**

E.3 List of Files

The files mentioned in the appendices D and E are with the Radionavigation Group in Bangor and copied CD. The contents of the CD is as follows:

D:\SKYWAVE*.NDB

D:\SKYWAVE*.MB

D:\SKYWAVE*.DGP

D:\GNDWAVE*.NDB

D:\GNDWAVE*.MB

D:\GNDWAVE*.DGP

D:\DGPSCOV\BECNINF.DAT

D:\DGPSCOV\INPUT.LST

C:\NEWBEC\BECROW.TXT

C:\NEWBEC\BECNINF.TXT

C:\NEWBEC\ RESULT.TXT

C:\NEWBEC\FREQFIND.EXE

D:\OPTIM\RESULT.TXT

D:\OPTIM\OPTIMD1.EXE

D:\OPTIM\GANP.M

D:\OPTIM\CO.TXT

D:\OPTIM\BECROW.TXT

D:\OPTIM\BECNINF.TXT

D:\OPTIM\ THIRD.TXT

D:\OPTIM\ SIXTH.TXT

D:\OPTIM\ SECOND.TXT

D:\OPTIM\ PAIRS.TXT

D:\OPTIM\ NDB.TXT

D:\OPTIM\FREQMAIN.TXT

D:\OPTIM\ FOURTH.TXT

D:\OPTIM\ FIRST.TXT

D:\OPTIM\ FIFTH.TXT

Appendix F

Awards and Publications

The paper named '*DGNSS Radiobeacons – the European Frequency Problem*' written with J.D. Last presented and in the ION GPS98 conference in Nashville, Tennessee, USA, received the 'Best Paper in Session' award.

The list of publications written during the course of this research is given below. The full texts of selected publications are presented in section F.4.

F.1 Papers Published in Refereed Journals

- 'European Radiobeacon DGNSS - Making the most of the frequency band', (with J.D.Last), Journal of the Royal Institute of Navigation, May 1999 (Full text is given in section F.4).

F.2 Papers Published in Journals

- 'Re-planning Europe's radiobeacon DGNSS band', (with Last, J.D. and Ward N.), Nordic Navigation Forum Journal, December 1999

F.3 Papers Presented in Conferences

- 'DGNSS Radiobeacons – the European Frequency Problem', (with J.D. Last), ION GPS98, Nashville, USA 15-18 September 1998 (Full text is given in section F.4).
- 'DGNSS Radiobeacons - the European Frequency Problem', (with J.D. Last), Differential GNSS Workshop, International Association of Lighthouse Authorities, Paris, 28-30 September1998 (Invited keynote paper).

- 'Maximising Radiobeacon Coverage in the EMA by Optimising the Band Plan', (with J.D. Last), Frequency Planning Conference for the European Maritime Area of ITU Region 1, International Association of Lighthouse Authorities, Paris, 1-2 October 1998 (Invited keynote paper).
- 'Allocating Frequencies for European DGNSS Radiobeacons- a Quart into a Pint Pot', (with J.D. Last), 2nd European Symposium on Global Navigation Satellite Systems (GNSS98), Toulouse, France, 20-23 October 1998
- 'European Radiobeacon DGNSS - Making the most of the frequency band', (with J.D. Last), RIN98, London, UK, 9-11 December 1998.
- 'Minimising Mutual Interference in Radiobeacons', (with J.D. Last), URSI National Meeting, York, 29-30 March 1999.
- 'Redesigning the European radiobeacon DGNSS band', (with N. Ward and J.D. Last), GNSS '99, Genoa, Italy.
- 'Redesigning the European radiobeacon DGNSS band', (with N. Ward and J.D. Last), ILA 28/NAV 99, London.
- 'Land coverage of radiobeacon DGNSS', (with J.D. Last and M. Grafton), ILA 28/NAV 99, London.
- 'Algorithms for Interference Limited Radiobeacon Frequency Assignment', (with S. Hurley, J.D. Last and D.H. Smith), ICICS'99, Singapore (Full text is given in section F.4).