European Radiobeacon DGNSS: Making the most of the Frequency Band

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The rapid development of differential GNSS transmissions via low-frequency maritime radiobeacons has further increased the occupancy of an already over-crowded frequency band. This has resulted in interference between stations, with consequent reductions of coverage. The paper suggests a re-allocation of channels within this band in Europe to be carried out, taking careful account of the known groundwave and skywave propagation of both wanted and interfering signals and the distribution of atmospheric noise. A novel algorithm is proposed for re-allocating frequencies. The resulting band plan is shown to offer substantially increased coverage for DGNSS radiobeacons while preserving the performance of marine and aeronautical direction-finding beacons, the latter remaining on their original channels.

1. INTRODUCTION. Recent years have seen rapid development in the provision of differential broadcasts of GNSS corrections by low-frequency maritime radiobeacons. These beacon stations, long used for direction-finding, are widely available and already licensed as aids to navigation. It is straightforward to add the extra DGNSS transmissions to them. As a result, this system has become the principal means of distributing differential corrections to users at sea.[1,2] Its parameters have been standardised world-wide and approved by the International Telecommunication Union, ITU.[3,4]

However, in Europe, the frequency band used for radiobeacons (283·5–315 kHz) is already over-crowded with marine and aeronautical direction-finding beacons. The 64 channels are currently occupied by more than 400 stations, an average of more than six per channel. Adding the new service has exacerbated the problem of interference between transmissions.[3,4]

Traditionally, channels have been allocated to beacons using a relatively simple method that was appropriate when only conventional marine and aeronautical stations were in use. It ignores a number of factors that affect DGNSS radiobeacon transmissions: specifically attenuation due to land paths, fading of the wanted signal caused by ionospheric propagation and skywave-borne interference from distant co-channel and adjacent channel beacons.[5] As a result, the coverage achieved by many of the new DGNSS beacons is much less than it might be, since they have been allocated frequencies on which there are high levels of interference, especially at night.[6]

The allocation of frequencies to maritime beacons is co-ordinated by IALA, the International Association of Marine Aids to Navigation and Lighthouse Authorities.

This paper describes a software package developed to assist IALA in their task by helping them optimise frequency assignments throughout the European Maritime Area (EMA) on the basis of minimising mutual interference. The software estimates the levels of interference between all pairs of beacons via both groundwave and skywave propagation. It then identifies the groups of beacons that can safely share the same channel. Finally, it allocates channel numbers to those groups, taking into account interference on adjacent channels up to 6 kHz apart, in accordance with ITU and other standards. The software also includes options to leave the frequencies of the aeronautical beacons unchanged and to continue, where required, the common practice of operating co-sited pairs of conventional and DGNSS beacons on adjacent channels.

The paper shows how this software succeeds in fitting all the radiobeacons of the EMA into the 64 channels of the frequency band. The new allocations result in the DGNSS beacons enjoying much improved coverage. Thus we demonstrate that the DGNSS service may be substantially improved at the cost of a simple revision of channel assignments. Finally, recent steps by IALA to implement such changes are described.

2. COVERAGE AND INTERFERENCE.

The radiobeacon band contains transmissions of three types: 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 ITU, the International Civil Aviation Organisation (ICAO), IALA and, in the US, the national administration.[3–5,7,8]

Several factors determine whether the minimum conditions for coverage are met. The signal from the DGNSS station is normally received via groundwave propagation. Its strength depends on range and on the nature of the propagation path: signals that have travelled over seawater are much less attenuated than those arriving via paths over land, especially desert or mountainous terrain.[9–11]

At night, signals that have travelled as skywaves via the ionosphere also arrive and can interfere with the groundwave signals: where the skywave is comparable in strength to the groundwave, there can be deep fading. As a consequence, the signal level that can be guaranteed for, say, 95% of the time at night may be significantly weaker than the daytime groundwave at the same point. Skywave intensity varies randomly, its mean value over an interval being a function of range, latitude, time of day and season of the year. Thus, establishing the strength of the radiobeacon's signal requires not only the groundwave path to be taken into account but also these factors.[12]

The strength of the beacon's signal and that of the atmospheric noise together determine the signal-to-noise ratio (SNR). Noise intensity also varies in a random fashion, its mean value being a function of geographical location, time and season.

Like the wanted signal, unwanted interference from other stations is received via both groundwave and skywave propagation. Near the edge of coverage, where the wanted signal is weak, skywave interference from strong stations at considerable distances may be severe and so cause loss of service. We customarily estimate the strength that these interfering components exceed for more than, say, 5% of the time.

3. THE FREQUENCY PLANNING PROBLEM.

To evaluate the performance of a DGNSS service, a Coverage Prediction Program is used.[9] This determines the strengths of the groundwave and skywave components of the radiobeacon's signal and of the atmospheric noise. All geographical locations at which the field strength and SNR exceed the specified minima for the DGNSS service in Table 1 are deemed to lie within the 'interference-free coverage (IFC)'.

Table 1. Minimum field strength and SNR for MB, NDB and DGNSS services in the European Maritime Area of ITU Region I[5,8,13].

	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 SNR	dB		15	15	7

But when interference from other stations is taken into account, the coverage may be reduced below this interference-free value, often dramatically. The degree of coverage reduction depends on the frequency on which the beacon is operating since it is determined by the other stations that occupy that, and the neighbouring, channels. Figure 1 shows the interference-free coverage of a DGNSS radiobeacon at

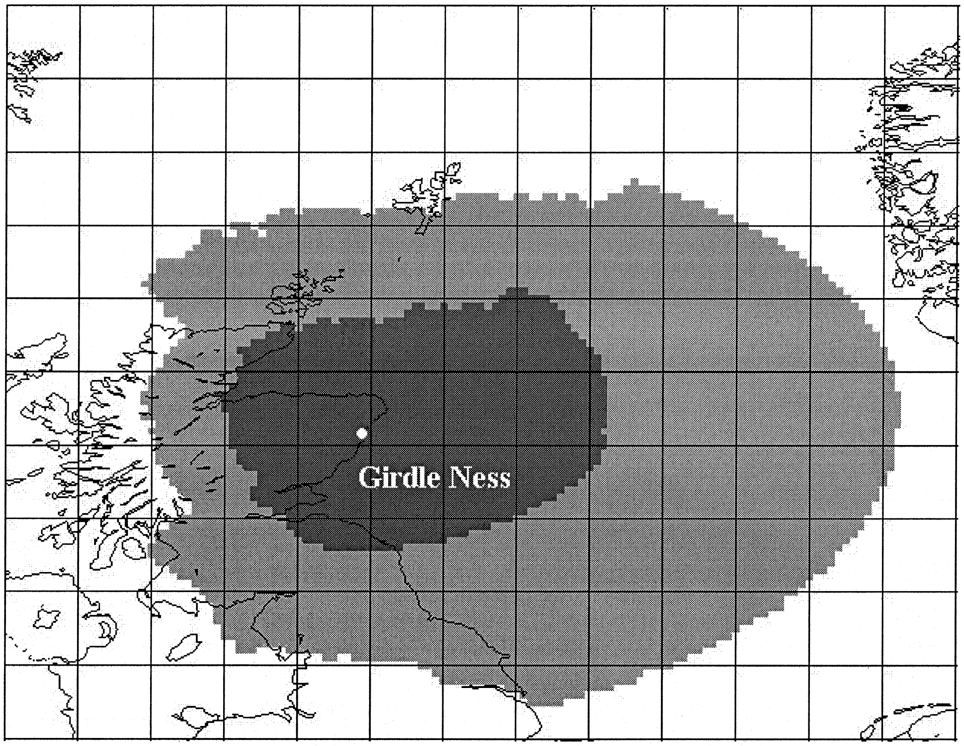

Figure 1. Night-time coverage of DGNSS radiobeacon station at Girdle Ness in Scotland. Lighter area: interference-free coverage. Darker area: reduced coverage due to interference.[6]

Girdle Ness in Scotland; the darker area is its reduced coverage due to interference. The interference is principally from stations at Oostende in Belgium and Tory Island in Ireland.

4. OPTIMIZING THE BAND–PRINCIPLES.

Similar reductions of coverage to that shown in Figure 1 are experienced by almost all European DGNSS radiobeacons. In this paper we seek to minimise such interference, and so maximise coverage, by judicious re-allocation of channels to stations across the frequency band. We assume that each DGNSS beacon should be usable out to the range at which its field strength has fallen to the minimum level acceptable to receivers.[4,8,13] Table 1 shows that the minimum field strengths and SNRs for marine and aeronautical radiobeacons are much greater than those for DGNSS since these direction-finding stations are required to serve much smaller areas. Consequently, their coverages are less reduced by skywave fading at night or by interference. Nevertheless, in proposing amended frequency allocations within the band, we will also ensure that these beacons continue to enjoy interference-free operation within their coverage areas.

The strategy adopted for minimising interference is as follows. First, we evaluate the potential for interference between each pair of beacons. The stations considered are those within the EMA that operate in the band 283·5–315 kHz. Also included are 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. At this stage, only co-channel interference is taken into account, the criteria being the protection ratios shown in the top (zero frequency separation) row of data in Table 2.

Table 2. Protection ratios (dB) minimising interference between beacons[7,13].

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	—	—

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 group, if necessary using all 64 channels within the band. In doing so we ensure that 'adjacent-channel' interference between beacons separated in frequency by up to six channels (3 kHz) is avoided, by taking account of the protection ratios in other rows of Table 2. The frequencies of stations outside the EMA or outside the frequency band are not changed.

It is recognised that the 64 channels of the band may be insufficient to accommodate all stations with completely interference-free coverage. We tackle this problem by defining a maximum level of allowable interference in terms of a 'figure-of-merit' (see below). Frequency allocations are attempted iteratively; the allowed level of interference being progressively reduced until either all 64 channels have been used or interference-free coverage has been achieved.

The principles described above are followed in all cases. A number of additional optional constraints, designed to make the resulting frequency re-allocation more acceptable to users of the band, are then introduced progressively:

(i) *Aeronautical Constraint:* Since this re-allocation of channels is for the benefit of the maritime community alone, current allocations to aeronautical radiobeacons are retained.

(ii) *Pairing Constraint:* For practical reasons, some national administrations operate co-sited marine and DGNSS beacons on adjacent channels. This 'pairing' option is retained.

The implementation of these principles will now be described.

5. ESTIMATING THE INTERFERENCE-FREE COVERAGE. The interference-free coverage of a beacon depends on the field strengths of its groundwave and skywave components and on the atmospheric noise level. These factors are computed and stored at each point in a large array centred on the beacon and spaced at 0·1° latitude by 0·1° longitude. To allow power changes during the design process, the program actually computes and stores attenuation values. It first determines the Great Circle path across the Earth's surface from the transmitter to each array point and the conductivity profile along this path.[14] The attenuation is calculated using ITU curves, with Millington's method for mixed-conductivity paths.[15,16] The values are stored in the station's Groundwave Attenuation Array.

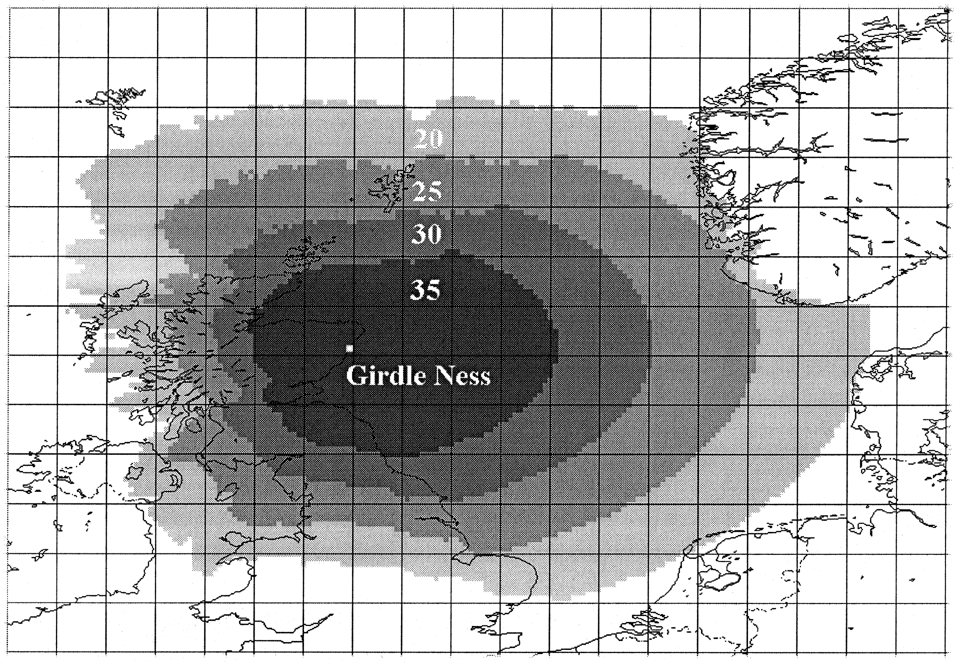

Figure 2. Groundwave field strength contours of Girdle Ness DGNSS radiobeacon (dBμV/m). Note much greater range out to sea than over low-conductivity land of Scotland.

Figure 2 shows the field strength contours of the Girdle Ness DGNSS station computed in this way.

The strength of the night skywave component is computed at each array point by employing the ITU skywave curves for 300 kHz.[17] The method takes into account the radiated power of the signal, its variation in the vertical plane, range, average magnetic latitude and the proximity of seawater to either end of the path. Transmitter and receiver antennas are assumed to be short monopoles. The resulting annual average skywave intensity values not exceeded 95% of the time at night are stored in the station's Skywave Attenuation Array.[12]

The atmospheric noise level is found using ITU records, based on extensive measurements and published for 24 combinations of time and season.[18] The annual average levels of noise not exceeded 95% of the time in a receiver bandwidth of 100 Hz are calculated and stored in an array of points spaced by 10° latitude and 10° longitude. The value at any point may be interpolated with a precision of 1 dB.

The IFC of a station is represented by the set of array points at which the minimum field strength and SNR criteria are met. For daytime operation, the field strength is simply the groundwave strength. But at night, groundwave and skywave values are used to calculate the total field strength that can be guaranteed 95% of the time, given fading.[12] Figure 3 shows Girdle Ness daytime and night-time IFCs.

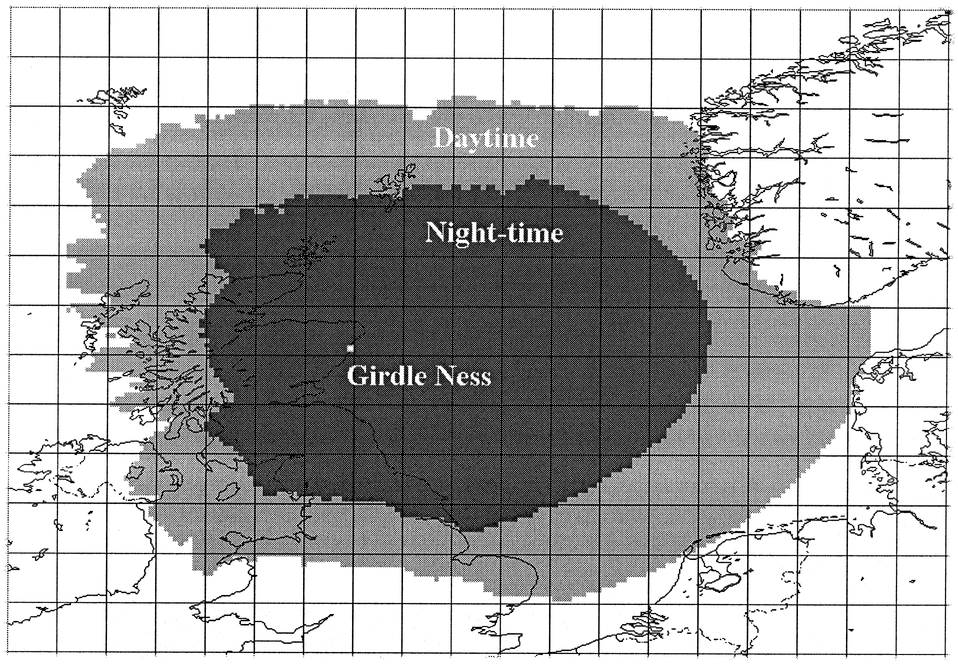

Figure 3. Daytime (outer) and night-time (inner) IFCs of Girdle Ness DGNSS beacon. Night-time coverage is less than daytime because of signal fading.

6. EVALUATING THE INTERFERENCE.

Now the potential for interference between each pair of beacons is assessed. Taking each beacon of the pair in turn, the strength of its signal is computed at each array point within the IFC of the other. The resulting signal-to-interference ratio is then compared with the protection ratio for that type of interferer, assuming the two beacons to be co-channel and daytime propagation to apply. The fraction of the IFC that survives interference is computed as a figure-of-merit (FoM): 1 if there is no unacceptable interference, 0 if all coverage is lost. The process is then repeated under night-time conditions; the IFCs are now the night-time IFCs and the interfering signal in each case the stronger of the groundwave and night skywave components. This gives us four FoMs, one each for day and night in the two directions. The lowest of the four is selected and called the 'co-channel FoM'. Then, assuming that the frequencies of the two beacons are separated by first one channel then by each integer number of channels up to six (at the standard 500 Hz spacing), the appropriate protection ratios in Table 2 being employed, six additional FoMs are calculated. The resulting set of seven FoMs describe the potential for mutual interference between the two beacons.

Table 3. FoMs representing interference between Girdle Ness and Torshavn[6].

Frequency separation (kHz)	0	0·5	1·0	1·5	2·0	2·5	3·0
Figure of merit	0·04	0·98	1	1	1	1	1

For example, Table 3 shows the FoMs for the DGNSS beacons at Girdle Ness and Torshavn, Faroe Islands. If the two beacons were on the same channel, only 0·04 (i.e. 4%) of the IFC of one of them would survive; if one channel apart, 98% would survive; any greater separation and there would be no interference. Clearly, one would try to avoid operating these two particular beacons on the same channel!

Table 4. A small portion of the large array of FoMs describing co-channel interference. There is a similar table for adjacent-channel interference for each separation of up to 6 channels.

Beacon	Number	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

We calculate a set of such FoMs for every pair of beacons. The co-channel FoMs are then arranged in a large array. Table 4 shows a small part of this array in which a selection of just 12 stations, chosen to offer a wide geographical spread, are included. To explain this Table, if St Catherine's Point and Cala Figuera were to be assigned the same channel, only 16% of the IFC of the more seriously-affected of them would survive, since their mutual FoM is 0·16. Note that the matrix is symmetric because a single FoM represents interference in the two directions. A similar array is created to describe adjacent-channel interference for each separation of up to six channels.

7. GROUPING BEACONS. The next task is to identify, from the co-channel interference array, 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 Figure 4, the numbers represent the 12 beacons of Table 4.

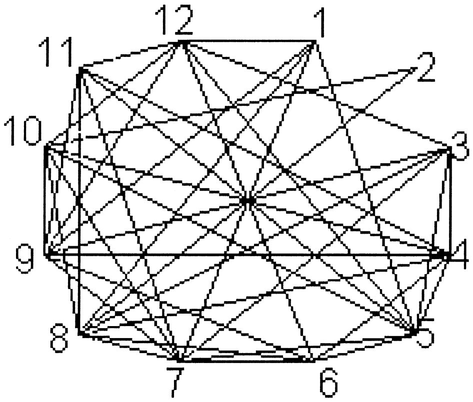

Figure 4. Connectivity diagram for the 12 beacons of Table 4, with an FoM limit of 0·8.

The minimum FoM is set to 0·8. If a line connects two beacons, they may share a frequency. Thus Beacon 2, for example, can share with Beacons 8 and 10, but not with Beacon 1.

The problem of gathering co-channel beacons into mutually-compatible groups and allocating a channel to each group must now be addressed. This is an example of a recognised class of problem in graph theory: the 'clique partitioning' of a graph. Such problems are members of a category called 'NP (non-deterministic polynomial)-Complete' for which, unfortunately, it is normally not feasible to establish optimum solutions when the graphs contain large numbers of items. The limitation is the extreme sensitivity of computation time to number of items.[19–21] With one algorithm tested by Garey and Johnson,[20] changing from 10 to 50 items increased computation time from 0·001 seconds to 35 years! Various algorithms have been developed to find feasible solutions within a reasonable time.[22,23] Instead of a global optimum we have chosen to seek an algorithm that is computationally efficient in fitting the beacons into the smallest number of channels with the highest possible FoM limit. A measure of success would be to fit them all into the 64 channels with no reduction of coverage below their interference-free boundaries. To this end, we have developed an algorithm, the 'most-unpopular algorithm', which operates in an acceptable time even though we have an input size in excess of 400. This is how it works:

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

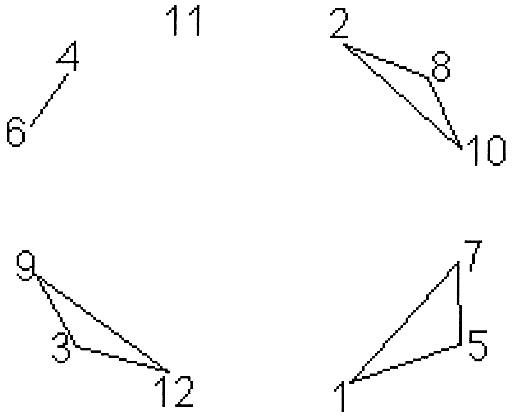

Figure 5. Groups identified from the set of beacons in Figure 4 using the 'most unpopular' algorithm.

Figure 5 illustrates the result of applying this algorithm to the set of beacons in Figure 4. Five groups have been created; three of them contain three beacons each, one two beacons and one a single beacon.

8. ALLOCATING FREQUENCIES.

Once all beacons have been placed into groups, a channel may be assigned to each group. If there were no further constraints, channels could be assigned arbitrarily. Then if the number of groups exceeded 64, the FoM limit would be reduced progressively until the number of groups fell below 64. The result of this process would be a new frequency allocation plan for the band.

However, other constraints cannot be ignored. Adjacent-channel interference must certainly be taken into account and so, optionally, must the *aeronautical* and *pairing* constraints described earlier. To deal with adjacent-channel interference, the algorithm is modified as follows. Channels are allocated in turn to groups as they are formed, starting with the lowest channel in the band. Prior to creating each new group, we temporarily eliminate from the array any beacons that suffer adjacent-channel interference with any beacon in the four previously created groups (six in the case of interference to aeronautical beacons). 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.

Now let us introduce the further constraint of leaving all aeronautical beacons on their original frequencies. We achieve this by reversing the order of the grouping and frequency allocation processes. First, we create 64 empty groups, one per channel. We place the aeronautical beacons into their appropriate groups, remove them from the array, and then proceed as previously. This ensures that the aeronautical beacons stay in place and also that co-channel and adjacent channel interference between them and the marine and DGNSS beacons are avoided.

Finally, we introduce the option to place pairs of co-sited beacons on adjacent channels. The most-unpopular algorithm is first applied to all beacons that are members of pairs, and channels assigned to the pairs. As this is done, the pair are added to the list of beacons that must stay on their frequencies and removed from the array, just as if they were aeronautical beacons. Finally, the remaining beacons are groups and assigned frequencies.

Introducing the adjacent-channel, aeronautical and pairing constraints increases the number of channels required to accommodate the population of beacons for a given minimum FoM and so reduces the minimum FoM at which all beacons can be squeezed into the available 64 channels.

9. OPERATION AND RESULTS.

The algorithm was first run with the FoM limit set to unity to see whether it was possible to fit all 408 beacons into the 64 available channels with no loss of coverage. There are 62 DGNSS beacons (of which 46 are members of co-sited pairs), 120 aeronautical and 226 marine. Table 5 shows the result. With only the co-channel interference constraint in operation, all the beacons could be packed into just 62 channels. Then progressively introducing the additional constraints increased the number of channels required to 69.

Table 5. Number of channels required to accommodate all beacons, with various constraints applied.

Constraint	Number of channels required
Co-channel interference	62
Adjacent channel interference	62
Aeronautical	67
Pairing	69

The program was then re-run with all criteria in operation, the FoM limit being varied. Table 6 shows that the highest FoM at which all beacons could be fitted into the 64 channels was 0·94; that is, all beacons could be accommodated, with all constraints applied, providing a coverage loss of not more than 6% could be tolerated. Table 7 shows a sample of three channels of the resulting band plan.

Table 6. Number of channels required increases as FoM limit is raised.

FoM Limit	Number of channels required
0·85	61
0·90	63
0·94	64
0·95	66
1·00	69

10. PLAN TO REORGANIZE 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. This change gives a window of opportunity to optimise the use of the band in terms of spectrum efficiency and system performance. IALA is co-ordinating this process, with the approval

Table 7. Small sample of the re-arranged 64-channel band plan with all constraints in operation.

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
	ANECY_MARCELLAZ	NDB	45N51	06E01	46
	CHALONS_MARNE	NDB	48N47	04E11	90
	METRO	NDB	50N17	08E51	46
	NICKY	NDB	58N46	16E56	90

of the ITU. IALA first requested each administration to submit details of its future requirements. The result was a planned reduction in the number of beacons from 408 to 350, as direction-finding beacons were removed and a smaller number of DGNSS stations introduced.

The software described in this paper was then run, in October 1998, to optimise the band plan for this new population of beacons. It was found that, despite the reduction in the number of stations, the FoM limit fell to 0·62. The reason for this disappointing result was that most of the DF beacons removed had been of much lower power than the new DGNSS ones introduced! IALA asked administrations to reduce power levels and co-operate area-by-area to eliminate excessive overlapping of DGNSS coverage; the aim is to maximise the FoM and, ideally, to achieve a band plan that totally eliminates mutual interference.

11. SOFTWARE ISSUES. Groundwave and skywave attenuation arrays for all beacons in the EMA, and those stations outside that must be taken into account, have been pre-computed once and for all. This process took some 200 hours on a 166 MHz Pentium PC using a program written in C-code. A further C-code program was then used to evaluate the interference between pairs of beacons; the task was shared between twelve 166 MHz Pentium PCs, taking typically 35 hours on each. All this pre-computed data was recorded on a CD-ROM. The grouping and frequency assignment algorithm has been implemented on a PC using MATLAB©; it takes a mere five minutes to produce band plan.

12. CONCLUSIONS. The program described in this paper has been developed for optimising the coverage of European DGNSS beacons by re-planning their frequency band to minimise interference. It is based on 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 operation of the new software has been demonstrated by using it to identify an optimum frequency plan for the present 408 radiobeacons. Aeronautical beacons were left on their present frequencies and co-sited pairs of beacons allocated adjacent frequencies. With this new band plan, 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 substantial coverage losses. The new software thus offers much lower levels of interference and more extensive service areas. It is currently being employed by IALA to organise a new band plan in response to widespread changes in the beacon population being introduced by administrations across Europe.

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KEY WORDS

1. Navaids. 2. Marine. 3. Radio Frequencies.