THE JOURNAL OF NAVIGATION (2002), **55**, 249–262. © The Royal Institute of Navigation
DOI: 10.1017/S0373463302001698 Printed in the United Kingdom

Optimum Choice of Beacon in Maritime DGNSS Systems

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Marine radiobeacons are widely used by the maritime community worldwide as an efficient means of broadcasting differential GPS data to users at sea. In Europe and North America, large numbers of these beacons now serve coastal regions, waterways, and some inland areas. Frequently there is overlapping coverage and a choice of stations. But users receive little guidance as to how to select the beacon that gives the highest quality service. Receivers that choose a beacon automatically generally select either the nearest station or the strongest signal. But the performance of the data-link is optimised by choosing the station received with the highest ratio of signal to either noise or interference. With Selective Availability set to zero, spatial dilution and time-to-alarm have become key factors. This paper compares four beacon selection strategies by means of a computer model based on well-established coverage analysis and system design techniques. We recommend a new 'post-SA' beacon selection method that chooses the nearest station that meets the time-to-alarm requirement. This strategy has been used to identify the 'best beacon' throughout the European Maritime Area, with stations operating in accordance with the new band-plan adopted last September. We also identify the alternate beacon to use if the preferred station should fail.

KEY WORDS

1. GPS. 2. Differential GNSS. 3. Marine Radiobeacons.

1. INTRODUCTION. Differential . Global Satellite Navigation Systems (DGNSS) employ the principle that the main sources of error in satellite navigation are consistent over large geographical areas. These errors can be determined by using reference stations at known locations to measure pseudorange errors. When transformed, these errors can be transmitted as corrections to users' receivers, which adjust their position measurements accordingly. The advantages of DGNSS are improved accuracy and integrity.

One of the oldest radio aids-to-navigation technologies, the marine radiobeacon, is widely employed to transmit DGNSS corrections for maritime users.[1,2] In many areas of Europe and North America, more than one DGNSS beacon is available.[3] With many older beacon receivers, the user must select a station manually, but there is little guidance as to how to make that choice. Many newer types of receiver perform the selection automatically, some choosing the nearest station, others the beacon that provides the strongest signal.

This paper considers the choice of 'best beacon', for both manual and automatic receivers. It compares the results of the commonly used *nearest beacon* and *strongest beacon* strategies. It then introduces two novel approaches: a selection based on signal *quality*, and a strategy tailored to the *post-Selective Availability* (*SA*) world.

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2. INDIVIDUAL RADIOBEACON COVERAGE. The radiobeacon frequency band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and DGNSS radiobeacons (DGNSS). Within the European Maritime Area (EMA) of the International Telecommunication Union (ITU) Region 1, a geographical point is deemed to lie within the coverage of a DGNSS beacon, if the beacon's field strength is not less than 10 μV/m (or a higher figure specified by the national administration) and the signal-to-noise ratio (SNR) not less than 7 dB.[4] In addition, no interfering signal may exceed protection ratios defined by the International Electrotechnical Commission (IEC).[5]

A tool that is widely-used for predicting the coverage of marine radio beacons is the Bangor Coverage Prediction Software.[6] This suite of programs models the coverage areas of single beacons or groups of beacons, taking into account groundwave and skywave propagation, own-skywave fading, and interference, If we are to consider the choice of beacon at a location where more than one signal is available, we need data on all these factors for all candidate beacons simultaneously. Achieving this has required the development of new software that employs a multi-layer array architecture.[7] This new software can still be used to predict the coverage areas of single beacons, as previously. An example is shown at Figure 1 where the outer boundary is the limit of daytime, interference-free, coverage. But in addition, the new software can model the results of various strategies for selecting the best beacon, allowing us to compare them.

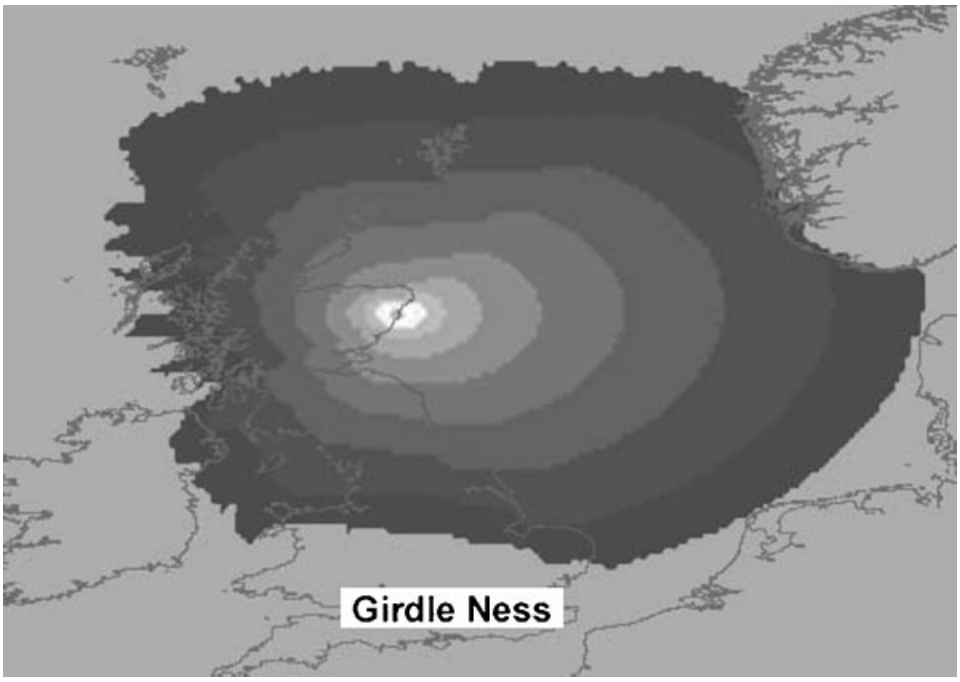


Figure 1. Groundwave field strength contours of a beacon at Girdle Ness, Scotland. Outer boundary is daytime interference-free coverage.

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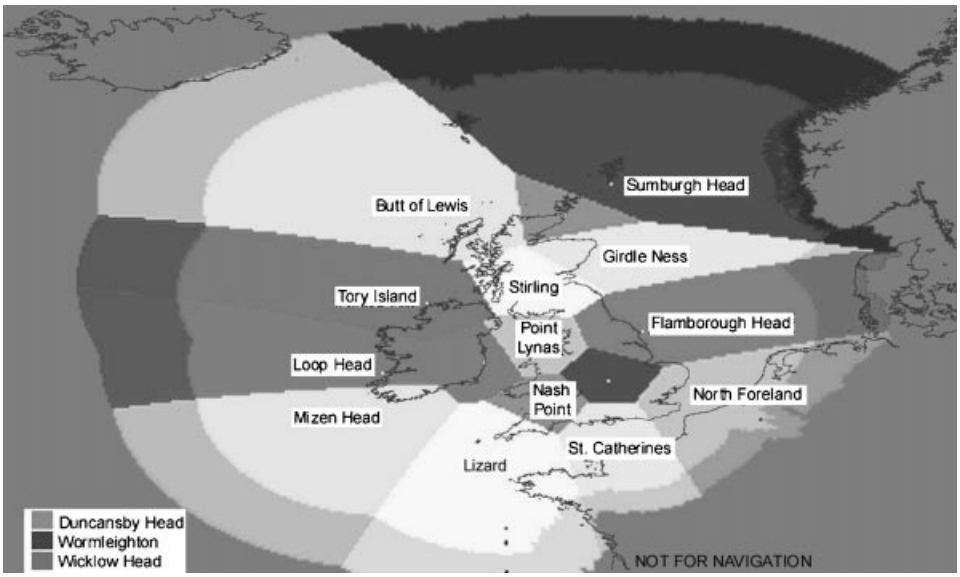


Figure 2. Beacon selection using *nearest beacon* strategy, for the 16 United Kingdom and Ireland DGNSS stations only. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent. (This and later similar charts are also published in colour.)

3. MODELLING BEACON SELECTION STRATEGIES. Currently, two strategies for selecting the beacon to use are commonly employed in DGNSS receivers: the *nearest beacon* and the *strongest beacon* strategies.

When a receiver employs the *nearest beacon* strategy, it ignores all attributes of the beacon's signal. Thus it will sometimes select a nearby weak station – possibly one whose signal has arrived via a land path of high attenuation – and ignore a more powerful signal from a beacon a little further away received via a sea-water path. In this case, the more distant beacon's signal would have a higher SNR than the nearest one. So choosing the nearest signal in this way could result in more data errors and thus greater delays in receiving correction updates.

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

We will first employ our software to map the choices of best beacon made by these two strategies, and then examine whether they generate significantly different choices. We will do so using the system of 16 beacons designed to serve the United Kingdom and Ireland. Note that the sets of British Isles and EMA beacons used in this paper, and the frequencies they employ, are taken from the new band-plan introduced in September 2001.[9] Coverage by beacons outside the UK is omitted in these examples.

3.1. *Modelling the nearest beacon strategy*. The process starts by computing the coverage areas of each of the 16 beacons. Then, point-by-point throughout these areas, we identify the nearest beacon. When all points have been examined, we produce an output plot (Figure 2), with a different colour (though here a level of grey) to distinguish the area within which each beacon has been chosen.

Figure 2 also distinguishes between the extent of coverage available by day (outer boundary) and at night (inner, lighter, region). The night-time coverage is less than

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the daytime because of fading due to skywave cancellation of the wanted beacon's signal. This form of diagram is designed for navigators who must input the choice of beacon into their receivers manually. It tells them which beacon to use by day or night, where on a voyage they should change beacon selection, and where they should cease to rely on coverage from the system.

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

3.2. *Modelling the strongest beacon strategy*. The same process was then employed to model the *strongest beacon* strategy; this time the beacon with the strongest signal at each point was identified. The result is shown in Figure 3.

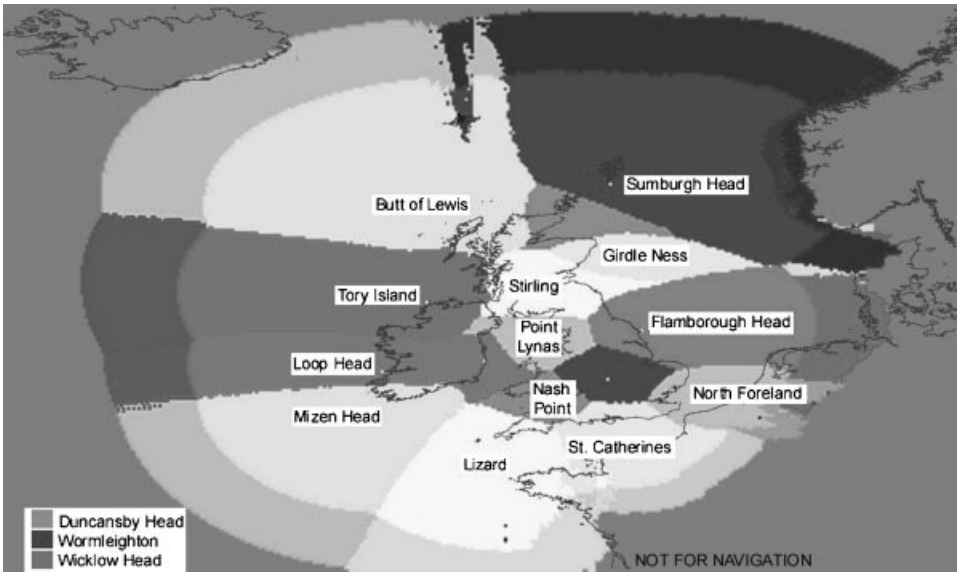


Figure 3. Beacon selection using *strongest beacon* strategy, for the 16 United Kingdom and Ireland DGNSS stations. Outer boundary: daytime interference-free coverage. Inner boundary: night-time equivalent.

The beacons this strategy chooses appear to be significantly different from those chosen by the *nearest beacon* strategy (Figure 2). The lighter areas in Figure 4 are the regions in which the two strategies produce different results; they constitute 15% of the total daytime coverage.

To understand the reasons for these areas of difference, consider the large sector west of Ireland along the Tory Island/Loop Head boundary. Here the signal from Tory Island is the stronger, despite its not being the nearest station. The reason is simply that Tory Island is a more powerful beacon than Loop Head. But even where two stations of equal power do compete, the *nearest beacon* strategy frequently selects the weaker signal. For example, the Stirling/Tory Island boundary up the west coast

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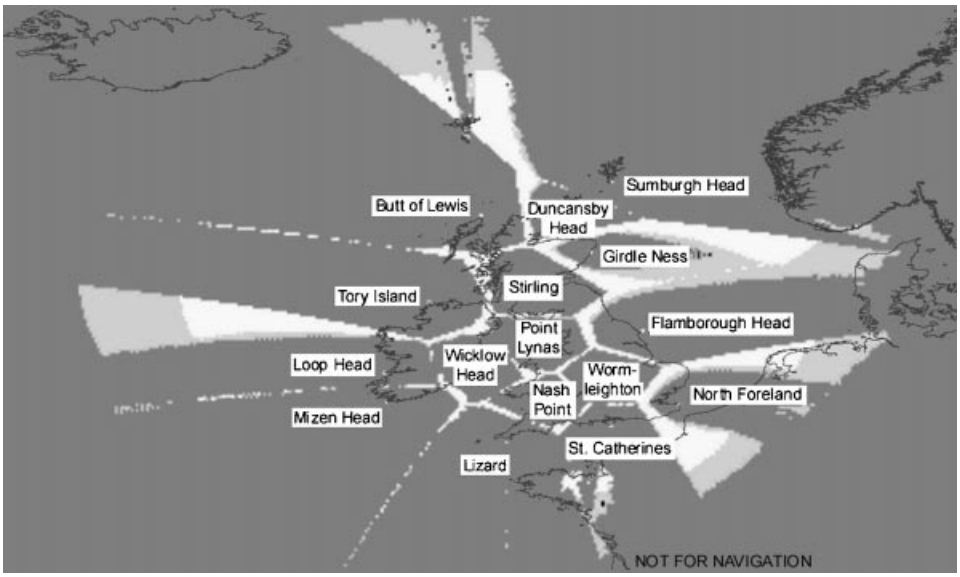


Figure 4. The lighter areas identify regions in which the *nearest beacon* and *strongest beacon* strategies select different beacons.

of mainland Scotland lies much closer to Stirling than to equally powerful Tory Island. But the Stirling signals arrive via land paths of high attenuation, while the signals from Tory Island signal come via longer paths, but over the sea, and are stronger.

In these, and other fairly extensive regions, the *nearest beacon* strategy fails to select the station with the strongest signal. The consequences are a lower SNR, a higher message error rate, and greater message latency, than the *strongest beacon* would offer. With SA active, latency was the major constraint: the greater the latency, the greater the pseudo-range error that built up before the next correction was received, and so the greater the resulting position error.

4. BEACON SELECTION BY SIGNAL QUALITY. The logical conclusion of the previous argument is that we should always choose the beacon whose signal has the highest signal-to-noise ratio. There are two sources of noise – firstly, atmospheric noise; its level at any time is essentially the same on all channels across the radiobeacon frequency band. Thus, choosing the *strongest beacon* automatically gives the highest signal-to-atmospheric noise ratio. The same is not true, however, for interference – the dominant noise source for radiobeacon coverage in Europe at night.[8] One beacon might suffer strong interference from a distant station on its frequency; another beacon of equal strength, but on a different frequency, might have much less interference, and so a higher SNR. Thus, in selecting our beacon, we should take into account not only atmospheric noise but also interference. And we should use as our measure of quality the overall SNR. That is, the ratio between a beacon's signal strength and either atmospheric noise or interference, whichever is the greater. This is our *quality strategy*.

Our software provides all the information we need to assess beacons' SNRs in this way: the groundwave and skywave strengths of the wanted beacon, the atmospheric

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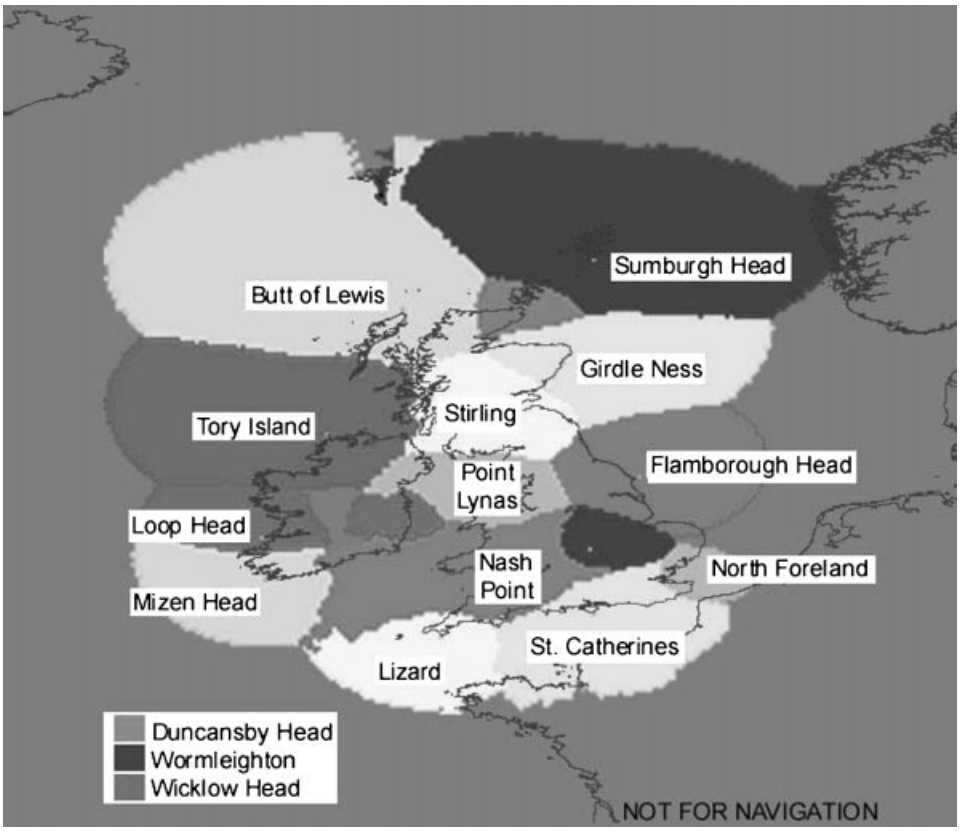


Figure 5. Beacon selection using the *quality strategy* for the 16 beacons of the UK and Ireland, under night-time conditions with interference.

noise level, and the strengths of all interfering components on all channels. Thus we can compute the SNR of each beacon's signal at any point and so identify the best beacon according to this *quality strategy*. Figure 5 shows the results for the British Isles beacons. This figure is plotted under worst-case conditions: that is, at night when interference capable of reducing coverage can be received via sky-wave propagation from other beacons up to 4200 km away. In consequence, not only is night-time coverage smaller than by day, but the effect of interference on the choice of beacon is greatest then.

In contrast, the *nearest beacon* strategy ignores all interference. In the lighter areas of Figure 6, which total 14% of the night-time service area of the system, the new *quality strategy* has chosen beacons of higher SNR than did the *nearest beacon* strategy. Clearly, the *nearest beacon* method fails to provide the user with the highest quality signal over substantial and important areas.

5. THE ENDING OF SELECTIVE AVAILABILITY. In May 2000, SA was set to zero. What effect does this have on beacon selection strategy? Now the dominant position error sources in GPS become ionospheric and tropospheric delays. Both

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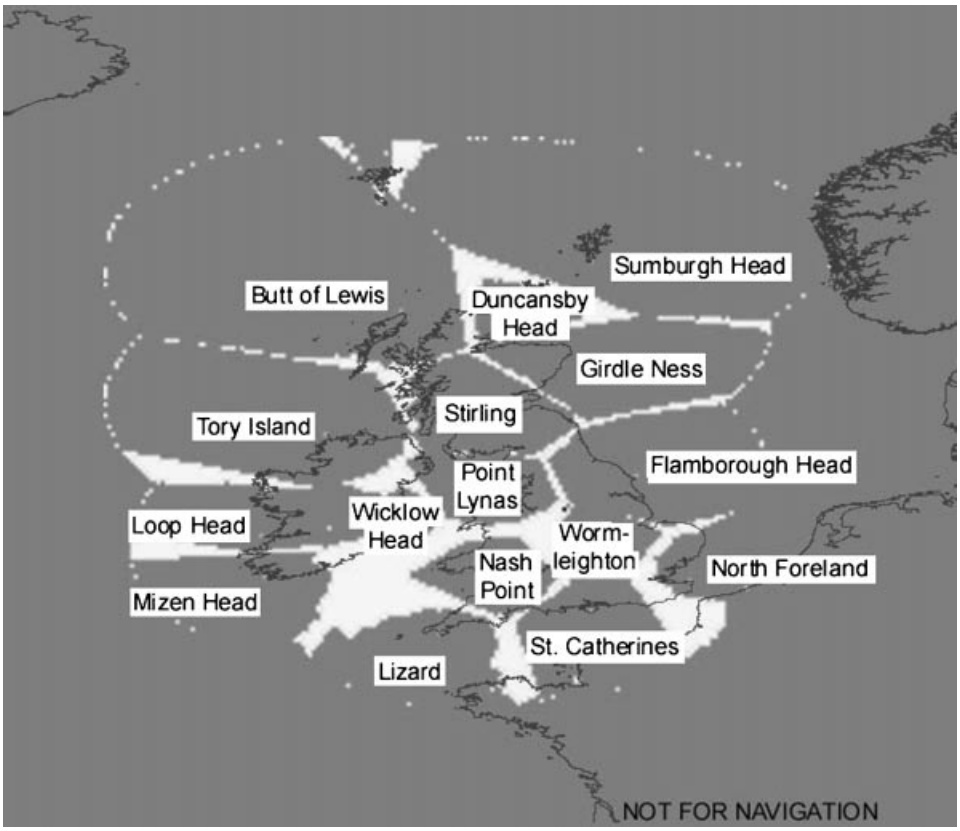


Figure 6. The lighter areas identify regions in which different beacons are selected by the *nearest beacon* and *quality* strategies.

types of error change much less rapidly than did the previously dominant SA. Therefore, correction messages remain valid for longer periods of time; indeed, they may be usable for tens, or even hundreds, of seconds. So the effect of latency on the reception of corrections is markedly reduced, and much lower beacon SNR values can be tolerated than before. Receiving the station with the highest SNR, or even the strongest one, would appear to be much less important than before.

On the other hand, as the separation between reference station and receiver increases, the dominant error source soon becomes spatial dilution of precision. These errors result from the user and the reference station experiencing different ionospheric and tropospheric delays. So it would appear that a simple *nearest beacon* selection strategy is all that is now required.

But the situation is complicated by a third factor! Correction messages also carry alarms to warn the user of unhealthy satellites or failures of reference stations. Indeed, enhancement of integrity is now a much more important benefit of differential operation for many users than enhancement of accuracy. So it may not, in fact, be acceptable to choose a nearest beacon with minimal spatial dilution but low SNR, since this would result in increased message latency and, possibly, an excessive time-to-alarm.

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Table 1. Time-to-alarm definitions and specifications. Italics show discrepancies and ambiguities.

Authority	Statement regarding time-to-alarm (TTA)
IMO (A.815)[10]	A warning of *system malfunction* should be *provided to users* within *10 seconds*.
IMO (A.860)[11]	Time-to-alarm is *the time elapsed between the occurrence of a failure in the system and its presentation on the bridge*. Time-to-alarm $<= 10$ *seconds*.
IALA[12]	A warning of *system non-availability or discontinuity* should be provided to users within *10 seconds*.
IEC[5]	While in manual mode and the manually *selected station is unhealthy*, *unmonitored*, *or signal quality is below threshold*, then an alarm shall be activated.
USCG[13]	1. (*Time-to-alarm is*) the time from when *a protection limit is exceeded* to when the user equipment suite/user is alarmed by the broadcast. (It shall be) less than 2 seconds for 200 bps transmission rates, *4 seconds* for 100 bps transmission rates and 8 seconds for 50 bps transmission rates. 2. Time-to-alarm: The maximum allowable time between the appearance of an error outside the protection limit at the integrity monitor and the broadcast of the alarm.
FRP[14]	Integrity of the Maritime DGPS service operated by the USCG is provided through an integrity monitor at each broadcast site. Each broadcast site is remotely monitored and controlled 24 hours a day from a DGPS control centre. *Users will be notified* of *an out-of-tolerance condition* within *6 seconds*.

6. TIME-TO-ALARM SPECIFICATIONS. Recognising this issue led us to study the time-to-alarm (TTA) specifications in the published radiobeacon DGNSS international, and US national, standards. Table 1 shows the requirements set by five authorities: the International Maritime Organisation (IMO);[10,11] the International Association for Marine Aids to Navigation and Lighthouse Authorities (IALA);[12] the International Electrotechnical Commission (IEC);[5] the United States Coast Guard (USCG);[13] and the US Federal Radionavigation Plan (FRP).[14] The ambiguities in the statements and discrepancies between them, both shown in italics in the table, are significant.

The first ambiguity is as follows: IMO A.815[10] and IALA[12] speak of a warning being 'provided to users', and the FRP[14] states that 'users will be notified' within the TTA. Does this mean that the user's receiver will *display* a warning within the TTA, as users might reasonably expect? Or does it mean simply that the reference station will *transmit* that warning, as some administrations appear to believe? The difference is very significant: it is the time the warning takes to pass through the transmission system and for the receiver to respond to it. This delay may be several seconds. Also, its magnitude depends in part on a latency determined by the SNR, and hence on the beacon selection strategy employed. The USCG document appears to define TTA in both ways: in Chapter 4, the TTA lasts until 'the user equipment suite/user is alarmed'; but in the *Definitions* section, the TTA lasts until 'the broadcast of the alarm'.[13] As far as IMO is concerned, and IALA which bases its document on IMO,

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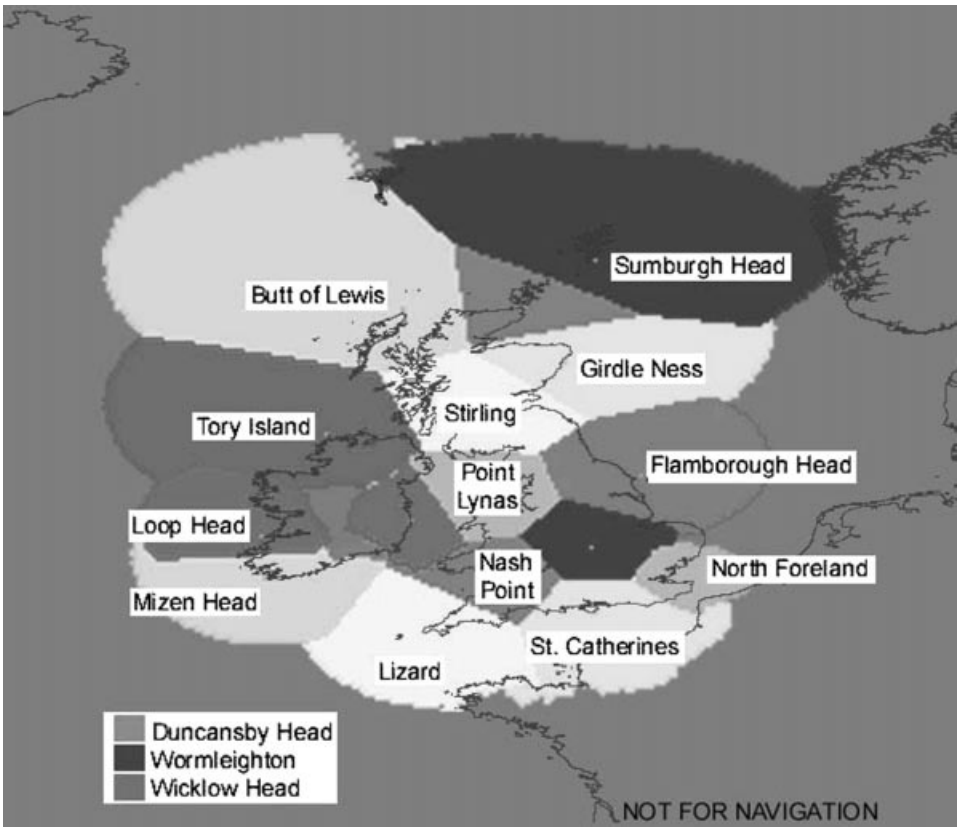


Figure 7. Beacon selection using the new *post-SA* strategy for the 16 beacons of the UK and Ireland, under night-time conditions with interference.

this ambiguity can be resolved by IMO A.860.[11] This defines time-to-alarm as 'the time elapsed between the occurrence of a failure in the system and its presentation on the bridge'.

The second ambiguity is whether the 'system malfunction' in IMO A815[10] means precisely the same as IALA's 'system non-availability or discontinuity',[12] or the IEC's 'selected station is unhealthy, unmonitored, or signal quality is below threshold',[5] or the USCG's 'protection limit is exceeded',[13] or the FRP's 'out of tolerance condition'.[14] The IEC offer yet another statement that applies just to automatic receivers. These multiple ambiguities concern the causes of alarms only and so have no implications for the choice of beacon selection strategy. The resulting confusion could, however, be significant for administrations operating marine radiobeacons.

A major quantitative discrepancy is the time-to-alarm limit itself. For 100 bps transmission, IMO A.815[10] and A.860[11], and IALA[12], all specify 10 seconds. The USCG[13] specify 4 s, the FRP[14] 6 s, while the IEC[5] give no specification. Clearly, the USCG's 4 s, measured from when the protection limit is exceeded to when the user's equipment (or the user) is alerted, is the most stringent of the TTAs and so demands the highest SNR. Finally, only the USCG specify a maximum range (300 statute miles) at which a radiobeacon's signals should be used without warning.

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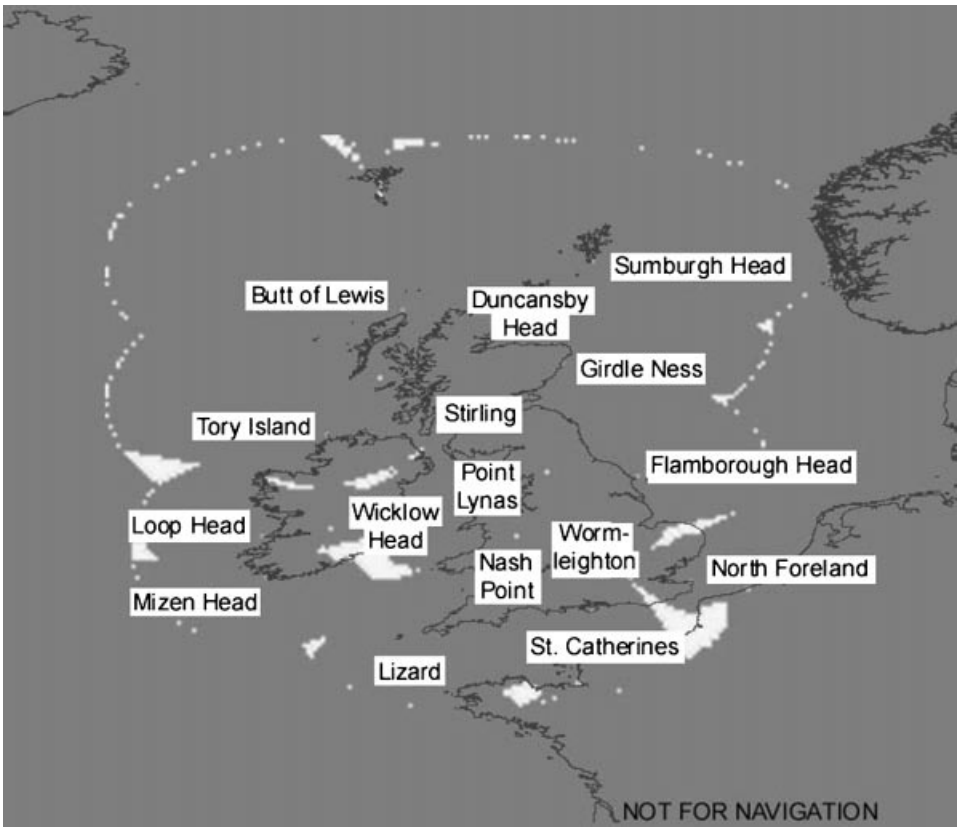


Figure 8. Lighter areas identify regions in which the *post-SA* and *nearest beacon* strategies select different beacons.

We have chosen to interpret these confusing specifications as follows. We have assumed that the maximum TTA is that experienced by the receiver, in accordance with IMO A.860.[11] This is the most conservative assumption, but also the common-sense one! It means that the TTA must include latency delays due to noise and interference. Secondly, for assessing beacon selection strategies and making coverage predictions in Europe, we have adopted the IMO/IALA 10 second TTA requirement. Different values would be required for USCG systems that meet the FRP requirements. Finally, we decided to seek to minimise spatial dilution of precision.

7. BEACON SELECTION BY THE *POST-SA* STRATEGY. A simple *nearest beacon* strategy would not guarantee that the TTA requirement was met. A quality strategy would not minimise spatial dilution. So we propose a post-SA strategy based on the following principle: the beacon to be selected is the nearest one that can meet the quality measure required for a 10 second TTA.

Measurements relating the signal word error rate to SNR have established that a signal of 7 dB minimum *signal-to-noise-or-interference ratio* will have sufficiently low latency to give a high probability of successful message reception within 10 seconds.[6] Indeed, this minimum SNR was included in the specification of beacons originally in order to ensure the 10 s message updates required to achieve acceptably-low position

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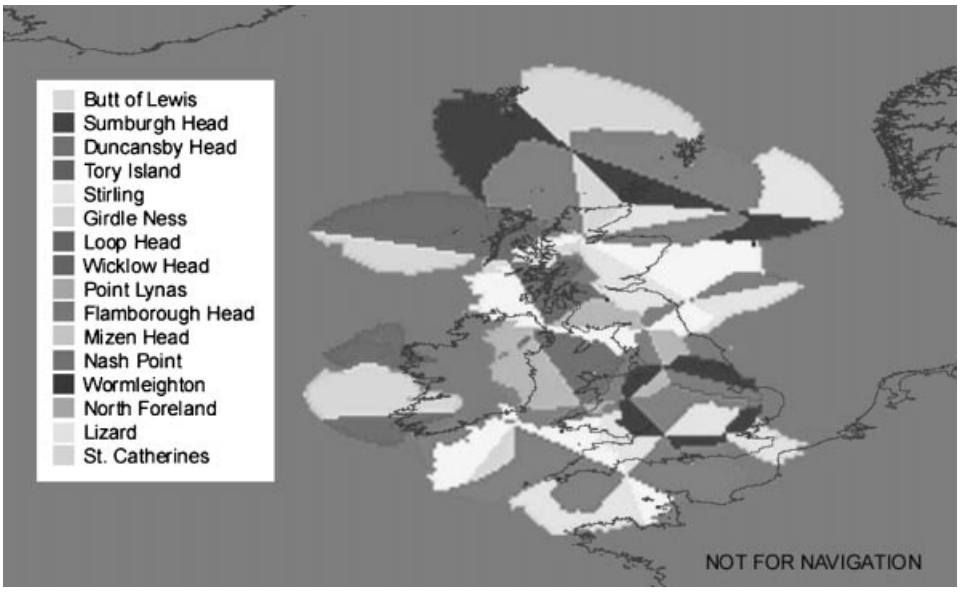


Figure 9. Choice of alternate beacon – the one to use if the best beacon should be unavailable.

errors when SA was in operation. So our post-SA strategy retains this minimum SNR.

The result of applying this strategy to the 16 British Isles beacons is shown in Figure 7. This figure is again plotted under the worst-case conditions of night-time, with interference. The results are strongly influenced by the differences of interference levels on the various beacons' channels. For example, the coverage of North Foreland is reduced by skywave interference from a distant station in the Mediterranean region. As a result, St. Catherine's is selected as the best beacon to use when following sections of the busy sea-lanes in the English Channel, even though North Foreland is the nearest beacon.

This point is clearly illustrated in Figure 8 in which the lighter areas are those where the *post-SA strategy* and the *nearest beacon* strategy give different results. Within these regions the nearest beacon should not be used at night since its signal fails to meet the time-to-alarm criterion.

Our new post-SA strategy happily turns out to be very similar to one recently proposed by the IEC.[5] However, whereas the IEC take only the signal-to-*atmospheric* noise ratio into account, our strategy ensures that *interferers* also do not exceed the minimum protection ratios.

7.1. *Alternate beacons.* This paper has presented strategies for identifying the best beacon to use at any location. But, if that beacon should be unavailable because of a scheduled or unscheduled outage, it is far from obvious to the user which station to select as the alternate. Our new software also allows us to answer that question. We run the same process as for choosing the best beacon, but this time select the second best. The alternate beacon results from the *post-SA* strategy are presented in Figure 9.

7.2. *Data in tabular form.* The maps shown in Figures 2, 3, 5, 7 and 9 are in a

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Table 2. Part of a tabulated data set of beacon selections made using the *post-SA* strategy.

60 -	NASH_POINT
61 -	WICKLOW_HEAD
62 -	POINT_LYNAS
:	
:	
Lat: 53·2 Long: - 4·1	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 4·0	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·9	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·8	Primary - 62 Secondary - 61
Lat: 53·2 Long: - 3·7	Primary - 62 Secondary - 61

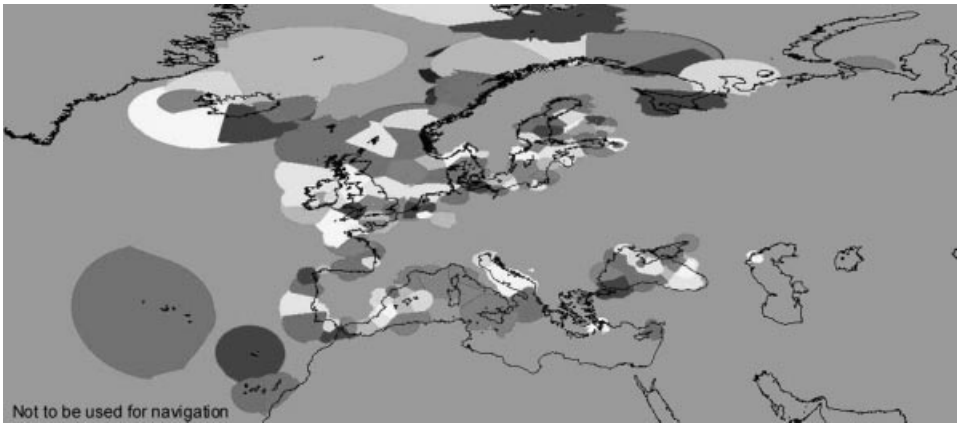


Figure 10. Beacon selection using the new *post-SA* strategy for the whole European Maritime Area (daytime, with interference).[8]

format designed to be convenient for users who are obliged to enter beacon selections into their receivers manually. To allow 'automatic' receivers to employ the same information, we have produced it in a tabular form that manufacturers can store within their receivers. Table 2 shows part of this data set: it lists at each location specified by latitude and longitude the best beacon computed using the *post-SA strategy* (Primary), and the alternate (Secondary).

7.3. *Beacon selection across the EMA*. In Figure 10, we show the result of using the new *post-SA* strategy to identify the best beacon everywhere throughout the entire European Maritime Area (30–72°N, 30°W–55°E).[8] The figure shows, for the first time, the combined coverage of all 158 differential GNSS radiobeacons in the EMA, identifying point-by-point the radiobeacon with the lowest spatial dilution whose signal meets the time-to-alarm criterion.

8. CONCLUSIONS. This paper has compared competing strategies for selecting the radiobeacon to be used where more than one is available. In addition to the *nearest beacon* and *strongest beacon* strategies commonly employed by current-generation receivers, a *quality strategy* has been studied in which the best beacon is deemed to be the one with the highest ratio of signal-to-atmospheric noise, or interference.

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With the ending of SA, however, the constraints on beacon selection have changed dramatically. We have proposed a new strategy in which the best beacon is the nearest one (i.e. with least spatial dilution) whose signal quality meets the time-to-alarm requirements. Since there are multiple ambiguities in the TTA specifications of different international and national bodies, we have judged it most appropriate to interpret the requirement as being that the user is made aware of a fault within 10 seconds of its occurring. Happily our new post-SA strategy turns out to very similar to one being considered by the IEC.

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

Finally, we strongly recommend that steps be taken to eliminate the discrepancies between the specifications published by the various authorities, and the ambiguities within them.

ACKNOWLEDGEMENTS

The authors acknowledge financial support for this work from the UK Engineering and Physical Sciences Research Council and from the General Lighthouse Authorities of the UK and Ireland.

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