# Enhanced accuracy by regional operation of Europe's new radiobeacon differential system

David Last, Alan Grant and Alwyn Williams, *University of Wales, Bangor, UK*
Nick Ward, *Trinity House Lighthouse Service, UK*

## BIOGRAPHIES

**Professor David Last** has a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He holds the BSc(Eng), PhD and DSc degrees. He is a Fellow and former Senior Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers, a Chartered Engineer, and Vice-President of the International Loran Association. He acts as a consultant to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.

**Alan Grant** received the degree of BSc (Hons) from Staffordshire University in 1999 and is studying for a PhD at the University of Wales, Bangor. He is a member of the Royal Institute of Navigation, the Institute of Navigation, the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

**Alwyn Williams** received the degree of MEng (Hons) from University of Wales, Bangor in 2000. He is currently studying for a PhD at Bangor. He is a member of the Royal Institute of Navigation, the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers.

**Dr Nick Ward** is Principal Development Engineer for the General Lighthouse Authorities of the UK and Ireland, specialising in radionavigation. He is Chairman of the International Association of Lighthouse Authorities' Radionavigation Committee which co-ordinates the development of Differential GNSS. He is a Fellow of the Royal Institute of Navigation and a Member of the ION.

## ABSTRACT

The maritime radiobeacon differential GNSS service in Europe has expanded very rapidly in the last two years. In September 2001, a new frequency plan was brought into effect across the whole of the European Maritime Area (EMA). This resulted in reduced levels of interference and enhanced coverage. There are now 162 maritime differential beacons positioned so that, as far as possible, all critical coastal locations are served by at least two stations.

Along many coastlines, inevitably, three or more beacons can now be received simultaneously. Indeed, by day when coverage is greatest, more than 20 signals are available at some locations. This provides an opportunity to make use of multiple transmissions. With the ending of Selective Availability, spatial dilution of position has come to dominate the accuracy of radiobeacon differential fixes. We have proposed using these multiple sources of pseudorange corrections in a Regional Area Augmentation System (RAAS) to minimise spatial dilution. The approach would be similar to that demonstrated successfully on a larger scale with Loran-C in the Eurofix system.

The paper presents the results of measurements made simultaneously on groups of radiobeacon stations under various receiving conditions. It demonstrates the degree to which RAAS processing of the results enhances position accuracy. In this work, the results from several receivers were combined. The same effect could be achieved with a multi-channel receiver, or by combining the data at a central point and re-broadcasting the result.

Using recently-developed mapping techniques, the paper then analyses the availability of multiple beacon signals across the EMA and maps the areas in which enhanced performance is expected to be available using this new RAAS mode of operation by day and by night.

## INTRODUCTION

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

One of the oldest radio aids-to-navigation technologies, that of marine radiobeacons, is widely employed to transmit DGNSS corrections for maritime users [1,2]. In Europe and North America, the recent expansion of the numbers of beacons in this system has ensured that, at most locations, at least one DGNSS beacon can generally be received [3]. Frequently there is a choice from several. It is customary to use the nearest beacon that provides a signal meeting the appropriate standards, with the second-nearest acting as an alternate.

This paper questions whether that is the best policy. A user who can receive several beacons simultaneously has access to corrections from a number of geographically-separated reference stations. Working satellite-by-satellite, it should be possible to compute a best set of corrections for the user's actual location. This is analogous to the use of a wide-area augmentation system (WAAS), and very similar to the use of a regional area augmentation system (RAAS), such as Eurofix [4]. We explore in this paper the question of whether corrections computed using a number of radiobeacon stations can be more accurate than those from the alternate beacon - or even corrections from the nearest beacon.

## COVERAGES OF BEACONS

The radiobeacon band supports three types of transmission: marine radiobeacons (MB), aeronautical non-directional beacons (NDB) and differential radiobeacons (DGNSS). The area within which the signal of any of these services provides satisfactory coverage is determined by minimum standards laid down by the International Telecommunication Union (ITU), the International Civil Aviation Organisation (ICAO), the International Association of Lighthouse Authorities (IALA) or, in the US, the US Coast Guard [5-9]. Within the European Maritime Area (EMA) of the ITU Region 1 [5], the field strength and signal-to-atmospheric noise ratio of each service must exceed the minima shown in Table 1 [7,8]. The signal-to-interference ratio (SIR) must exceed the appropriate protection ratio in Table 2; these values are derived from the minimum performance standards for receivers [10]. Thus, for a geographical point to be deemed to lie within the coverage of a DGNSS beacon, the beacon's field strength there must be not less than 10µV/m (20dBµV/m), or a higher figure specified by the national administration. The SNR must be not less than 7dB. Finally, no interfering signal may exceed the protection ratios shown in Table 2.

In computing the coverage area of a beacon, we estimate the level of its signal point-by-point throughout an array centred on the station. By day, this strength depends on the radiated power of the station, its distance and the nature of the propagation path. At night, signal components are also received from the beacon via ionospheric propagation. The intensity of these skywave components depends on range, latitude, time of day and season of the year. Skywave will interfere with the groundwave, causing fading. We customarily compute the signal level from the beacon that can be guaranteed for at least 95% of the time at night. This value is weaker than that of the daytime groundwave.

**Table 1**

| | Units | Marine (MB) | | Aero (NDB) | DGNSS |
|---|---|---|---|---|---|
| **Min. Field Strength** | µV/m | N of 43°N | 50 | 70 | 10 |
| | | S of 43°N | 75 | | |
| | dB µV/m | N of 43°N | 34 | 37 | 20 |
| | | S of 43°N | 38 | | |
| **Min. SNR** | dB | | 15 | 15 | 7 |

***Minimum field strength and SNR for MB, NDB and DGNSS services in the European Maritime Area of ITU Region I [3,8,11].***

**Table 2**

| **Wanted signal:** | **Marine (MB)** | **Aero (NDB)** | **DGNSS** | |
|---|---|---|---|---|
| **Interfering signal:** | **Any** | **Any** | **MB or NDB** | **DGNSS** |
| ***Separation (kHz)*** | | | | |
| 0 | 15 | 15 | 15 | 15 |
| 0.5 | -39 | 15 | -25 | -22 |
| 1 | -60 | 9 | -45 | -36 |
| 1.5 | -60 | 2 | -50 | -42 |
| 2 | -60 | -5 | -55 | -47 |
| 2.5 | - | -12.5 | - | - |
| 3 | - | -20 | - | - |

***Protection ratios (dB) for minimising interference between interfering and wanted beacons of various types [8,11].***

The intensity of the atmospheric noise is also estimated at each array point; it varies in a random fashion, its mean value over an interval being a function of geographical location, time of day, and season of the year. The values of the wanted signal and the atmospheric noise determine whether or not the point lies within the 'interference-free' coverage of the station.

It is customary to compute the daytime and night-time coverages separately. Daytime coverage is determined by the groundwave signal strength, and night-time coverage by the weaker 95%-ile of the fading signal.

At each point we also estimate the level of any interference from stations on the same frequency as the beacon, or on adjacent frequencies. Interference may be received via either a groundwave or a skywave propagation path, or both. We assess whether the strength of the interference relative to that of the wanted beacon exceeds the protection ratio in Table 2, taking into account both the transmission types of the two stations and their frequency difference. With skywave interference, we use the signal level not exceeded more than 5% of the time. The coverage of the beacon is then that part of the interference-free coverage within which no protection ratio is infringed. These techniques are employed in the widely-used Bangor Coverage Prediction Software for DGNSS Beacons [12-14].

**GROWTH OF DGNSS IN EUROPE**

By 1998, many European administrations had either closed, or were planning to close, their maritime DF services and were introducing new, or additional, DGNSS beacons. This provided an opportunity for designing a completely new frequency plan for the radiobeacon band in Europe. The object was to reduce the very high levels of skywave-borne interference between beacons that share channels, and so maximise range and performance. Without this reorganisation it was clear that this interference – already at unacceptable levels - would increase significantly, since most of the new DGNSS beacons would be of substantially higher power than the old marine beacons they replaced.

In order to co-ordinate this reorganisation, IALA first requested each administration in the EMA to submit details of its future requirements. The result was a list of 427 beacons in total. It contained a massive increase in the number of DGNSS beacons, from the previous 62 to 154, and an equally dramatic cut in marine beacons, from 226 to just 77. The new band-plan would need to pack these 427 stations into the 64 available channels. But among these stations were also 196 aeronautical NDBs which had to be left on their existing frequencies. So, too, would 26 MBs located in countries whose administrations had not responded to IALA's request. The new band-plan would have to accommodate all these stations.

The tool developed for the unique task of fitting these many stations into these few frequencies in such a way as to minimise mutual interference, was a set of Optimisation Software [15,16]. This employed the groundwave and skywave modelling techniques of the Bangor Coverage Prediction Software to estimate the potential for interference between each beacon and every other beacon. It took into account both groundwave and skywave propagation, and in both directions. The software then employed a novel algorithm to find the allocation of beacons to channels that minimised mutual interference, a task that was mathematically NP (Non-deterministic Polynomial)-Complete.

This process was successful. When tested on the population of the band before re-organisation, it produced a dramatic reduction in the level of interference. Whereas previously certain stations had lost 90% of their coverage to interference, with the reorganised band-plan no station lost more than 6%. The software was accepted by IALA and used to generate the new band-plan, which was first published for comment by administrations, and then implemented. Across Europe, beacons changed to their new frequency allocations on 18 & 19 September 2001.

**A CHANGING RADIOBEACON DGNSS SERVICE**

Since the reorganisation, a number of administrations have added further DGNSS beacons. The current population of the band is 461 stations: 162 DGNSS beacons, 143 MBs and 146 aeronautical NDBs [17]. The locations of all these stations are shown in Fig. 1.

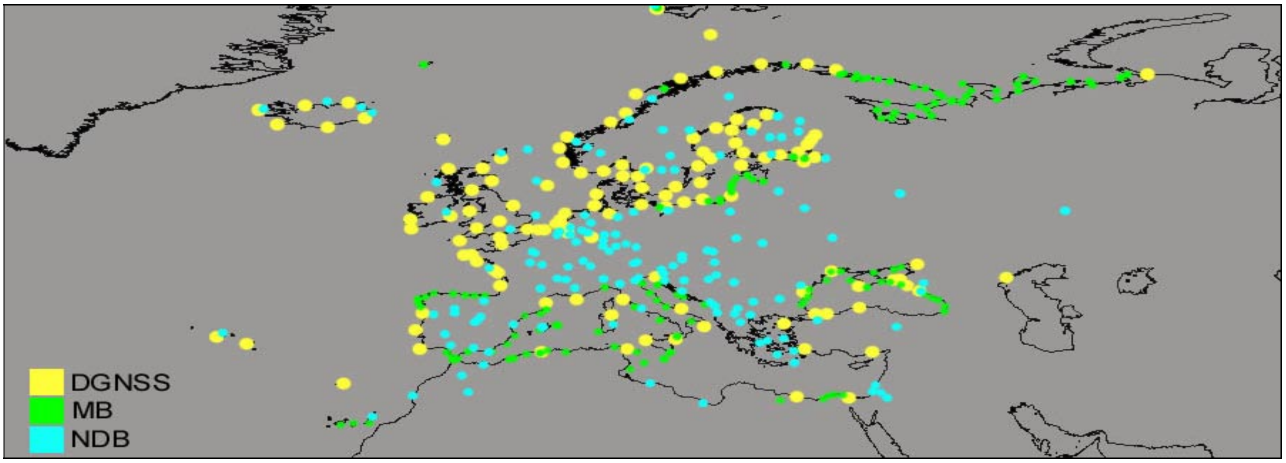


***Fig. 1: The 461 beacons of the European Maritime Area radiobeacon frequency band***

The development of this large number of new stations has fundamentally changed the nature of the DGNSS service in Europe. In most coastal locations, and over large inland areas, several beacons can now be received simultaneously. This has raised the question for users: which is the best beacon to use. The present authors have developed a further software model that answers this question [18,19]. At all locations across the EMA, it identifies the best beacon, and also the best alternate should that beacon not be available. We have shown that, in general, the best beacon at any location is the nearest beacon that meets international standards: specifically, that has a sufficiently-high signal-to-atmospheric noise ratio, and signal-to-interference ratio, to meet the time-to-alarm requirement. Identifying this beacon is a complex matter that requires analysis point-by-point. The software designed for this process employs a more advanced architecture than that for determining coverage. It is capable of giving access to the groundwave and skywave field strengths of all beacons simultaneously, since this is necessary for identifying the best beacon.

In this paper, however, we question whether using the best beacon guarantees the most accurate position fix. The reason for choosing the *nearest* beacon (provided it meets the time-to-alarm requirements) is that the accuracy of radiobeacon DGNSS fixes is now dominated by spatial dilution of precision of the corrections. The degree of dilution increases with the distance of the receiver from the reference station. This dominance of spatial dilution is in marked contrast to the traditional situation: in the days of selective availability (which was a major factor driving the growth of the radiobeacon DGNSS system) it paid to use the beacon with the highest SNR and SIR, thus minimising the error rate of the messages and so the latency (ie delay) of the corrections. In that way, the effects of the rapidly-changing errors due to SA were minimised by differential operation, and the accuracy of the fixes thus maximised.

But, if we truly wish to minimise spatial dilution of precision could we not do better than using the nearest station - or the next nearest, if the nearest is unavailable? If, as a result of the growth in the numbers of stations, we now have access to multiple sets of correction data, could we not compute the best set of data for the receiver's actual location? After all, that is essentially what happens in a wide-area augmentation system such as WAAS [20] or EGNOS [21]. It is also the basis of Eurofix [4]; as with radiobeacon DGNSS, Eurofix employs a series of independent Local Area Augmentation (LAAS) reference stations, each co-sited with its own transmitter - a Loran station. The Eurofix user receives a number of these stations simultaneously and computes the corrections at his location using these multiple sets of data. In Eurofix, this is called a RAAS – a Regional Area Augmentation System [4].

Let us explore whether we can turn our radiobeacon DGNSS LAAS system into something better? And even if users would not have sufficient stations everywhere, where could we expect improved accuracy from doing so? We also sought to know whether there are snags, such as clock bias differences between the stations, that would prevent this idea succeeding?

We decided first to identify the areas in which users enjoy the benefits of multiple stations; that could be done using our new-architecture software. Then we would try out the idea using off-air signals. We would attempt to answer the questions: is the concept feasible; is it worthwhile; and, if so, where will it work?

## NEW SOFTWARE ARCHITECTURE

The Bangor Coverage Prediction Software was designed to identify the coverage area of a single beacon. By computing the coverage of each member of a group of beacons in turn, it can also generate their combined coverage. But if we are to consider the use of multiple beacons at a point where more than one signal is available, we require simultaneous access to data on all those beacons at that point. Achieving that goal required the development of a new and different software architecture that will now be described briefly.

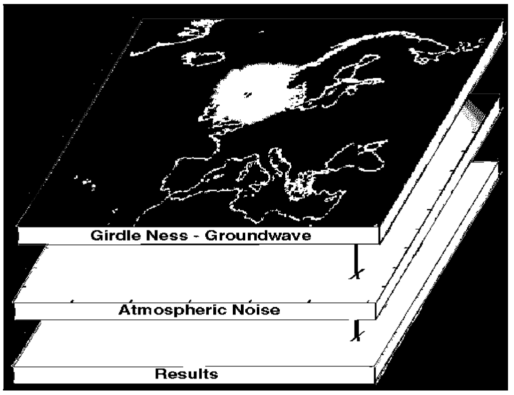


***Fig. 2: New software architecture employs a three-dimensional array. This simple example has just three layers. They hold the groundwave strength of a single beacon, the atmospheric noise, and (in the results layer) coverage computed using the first two.***

The factors that determine the coverage of a beacon have been identified as the field strengths of: the beacon's groundwave and skywave, atmospheric noise, and the groundwave and skywave components of all potential interferers. The groundwave and skywave field strength distributions of each beacon are first pre-computed at every point in a very large array, spaced by 0.1$^{o}$ of latitude by 0.1$^{o}$ longitude. This array covers an area exceeding that of the European Maritime Area (EMA).

The array structure (Fig. 2) is three-dimensional. The computed groundwave distribution of each beacon is stored in a single level (the top level in this figure). Since there are hundreds of beacons in the EMA, the structure must be capable of accommodating hundreds of such levels. The skywave distributions are stored in a further such set of levels. The atmospheric noise distribution across the area is contained in a single additional level (the middle one in this figure).

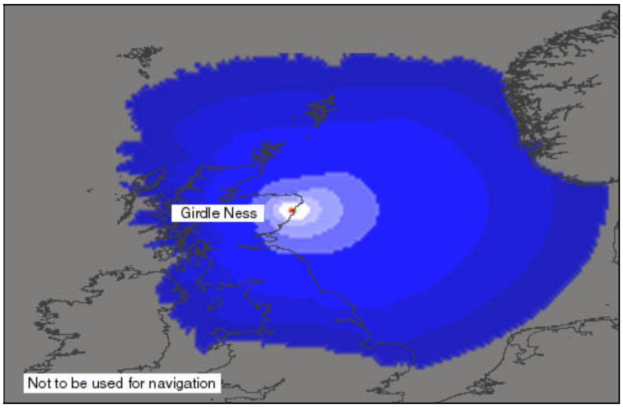


***Fig. 3: Groundwave field strength contours of a beacon at Girdle Ness, Scotland. The outer boundary is the limit of daytime interference-free coverage computed using data from top two layers in Fig. 2.***

We can choose to extract and plot the data from a single layer - as in Fig. 3, which shows contours of the ground-wave field strength of a beacon, taken from the top layer in Fig. 2.

Likewise, by accessing point-by-point the groundwave, skywave, atmospheric noise and interference relevant to a single beacon, we can plot its coverage. For example, the top two layers in the figure contain sufficient data for producing a plot of the simple interference-free groundwave coverage. In Fig. 3, the region within the outer boundary of the contour plot is that coverage. At all points within it, both the field strength (top layer) and signal-to-atmospheric noise ratio (top and second layers) meet the international standards.

This three-dimensional, multi-layer, structure is the tool we need to help us identify the number of beacons that provide coverage simultaneously at any point.

## SERVICE FROM MULTIPLE BEACONS

We ran the software analysing at each location in the array, and for each beacon, whether all criteria for coverage were met. That is: whether the field strength exceeded its minimum, including taking fading into account at night; whether the signal-to-atmospheric noise was adequate; and whether all signal-to-interference ratios exceeded their appropriate protection ratios. This latter check involved analysing the groundwave signals from every other beacon, plus at night the skywaves too. In this way, we established beacon-by-beacon whether the array point lay within the beacon's service area. Finally, we totted up how many beacons provided service simultaneously at that point.

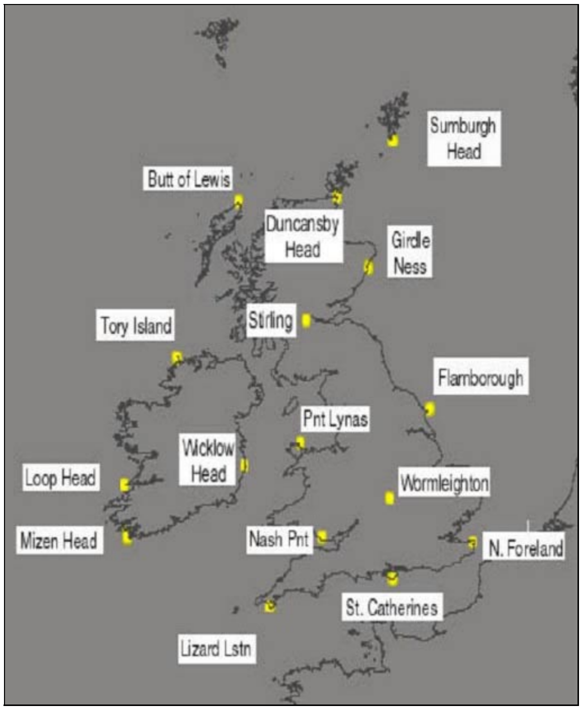


***Fig. 4: The 16 DGNSS beacons that serve the British Isles (Duncansby Head and Wicklow Head are planned but not implemented)***

This computation was first carried out using just the system of 16 beacons designed by the General Lighthouse Authorities (GLAs) to serve the United Kingdom and Ireland (Fig. 4). Of these beacons, 14 are now on air and two are yet to be installed. The result of the computation is shown in Fig. 5. The number of beacons simultaneously available varies from just one, in regions close to the edge of coverage, to 7. A large proportion of the critical coastal areas, and of the land areas, are served by at least three beacons. Whilst not all beacons are available everywhere all the time, we have shown recently that availability levels of individual beacons generally exceeds 99.5% [22]. Thus, there is a very high probability in practice of these numbers of beacons' signals being available simultaneously.

We now extended the analysis to the whole of the European Maritime Area, with its 162 DGNSS beacons. Fig. 6 shows the result by day when, in many areas, there are large numbers of beacons with overlapping coverage. The greatest concentration - in the North Sea - is 23! By night, of course, many fewer signals that meet the minimum standards are available because of fading of the beacons' signals, and an increase in skywave-borne interference from distant co-channel stations. Nevertheless, there are still many areas with simultaneous coverage from multiple beacons.

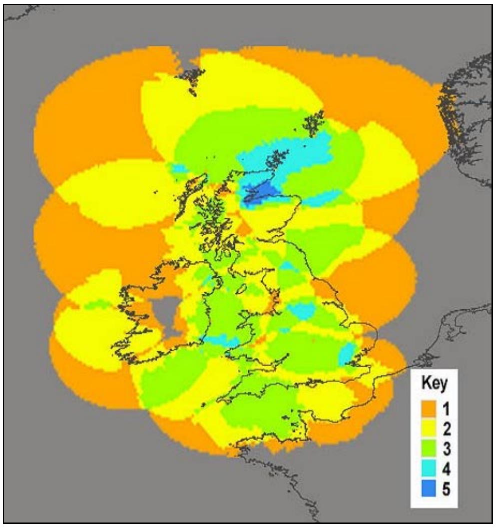


*Fig. 5: Number of GLA beacons available simultaneously (worst case, at night), including stations at Wicklow and Duncansby Head that are planned but not implemented*

These analyses have shown that over large areas of the EMA at least three signals are available with a quality that will ensure a high availability of correction messages. We will now employ the signals at one such location to explore the degree to which the use of these multiple signals is both possible and advantageous.

**TEST RESULTS**

Tests were carried out at our laboratories in Bangor, North Wales (N53°13, W004°08). The nearest DGNSS station is Point Lynas, at just 23km range. By day, Bangor lies within the coverage of 7 stations: Point Lynas (primary), Nash Point (alternate), Flamborough Head, Lizard, Tory Island, Stirling and Wormleighton (Fig. 4). At night, only Point Lynas meets all coverage criteria. The strongest of the other beacons just fails to meet the 95% skywave-borne interference criterion. As we will see, this does not prevent these other beacons being used in a regional area augmentation system.

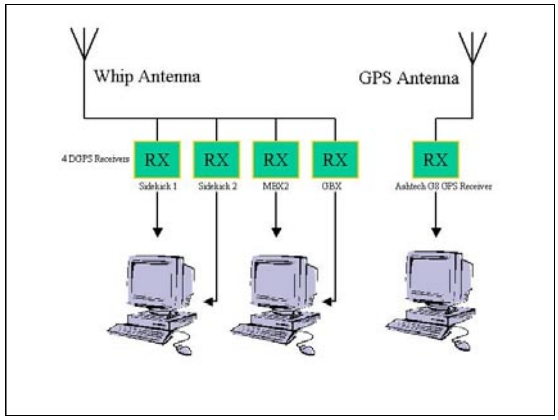


*Fig. 7: Experimental set-up for testing RAAS concept*

We set up the equipment shown in Fig. 7: four DGNSS radiobeacon receivers (two Cambridge Engineering Sidekick receivers, a CSI MBX2, and a CSI GBX). We also installed an Ashtech G8 GPS receiver. We allocated one beacon receiver to the nearby station of Point Lynas and the others to Wormleighton, Stirling and Loop Head (Fig. 4). Each of these stations is equipped with Trimble 4000MSK Reference Station equipment and transmits Type 9-3 messages at a data rate of 100 bps. We recorded the RTCM data from the beacon receivers, and the full data output stream of the GPS receiver, for 24 hours. The tests were conducted in August 2002.

The RTCM data sets from the four beacon receivers were converted to text format. The results, in the form of pseudo-range corrections (PRCs) and range rates (RRs) were entered into a Microsoft Excel spreadsheet for processing. Since the reference stations are not synchronised in such a way that they broadcast the PRCs of a given satellite simultaneously, we first processed the data so as to enable us to compare PRC values that were as close to simultaneous as possible. The time-skews were less than 10s. Post-SA, PRCs vary very slowly; our measured average range rate was only 0.027m/s; thus, the errors resulting from using PRCs that were not precisely simultaneous should have been less than 0.3m, even with the maximum time-skew.

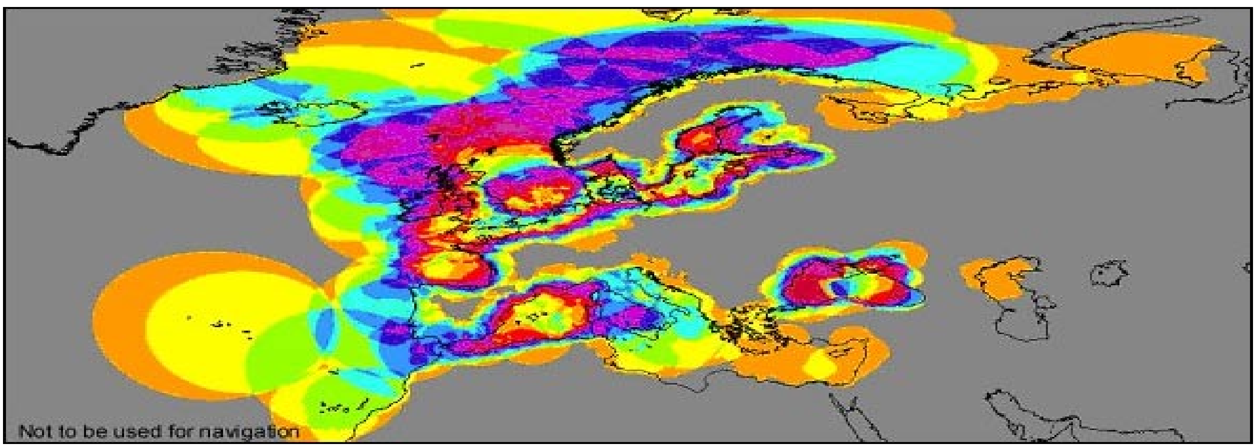


*Fig. 6. Numbers of beacons available throughout the EMA under daytime conditions [22].*

We were concerned about clock bias differences between the reference stations. A clock bias error results in an equal shift of all PRCs from the station. They are of little significance when radiobeacon DGNSS is used in its conventional way, with all corrections being taken from a single station, since the result is a small error in the time output of the navigation solution, not in the position. In the same way, when we come to combine PRCs from multiple stations, clock bias errors should not matter provided we use the same proportions of each station's PRC for all satellites. But such bias errors could mask the small differences in PRCs between stations that we wish to investigate in this study.

To estimate the magnitudes of any such clock bias components, we first computed for each station the average of all PRCs, for all satellites, over the 24 hours. The reasoning was that, with stations located relatively close together like these, the effects of location on these averages should be very small and differences between averages would be due principally to clock bias discrepancies.

**Table 3**

| Station | PRC average | Distance from Point Lynas (km) | Weighting factor |
|---|---|---|---|
| Wormleighton | -11.08 | 219 | 0.45 |
| Stirling | -10.90 | 336 | 0.29 |
| Loop Head | -11.14 | 385 | 0.26 |
| Point Lynas | -10.92 | | |

Table 3 lists the "PRC average" values of the first set of stations investigated. Happily, each of these four average values lay within 0.13m of the overall mean value (-11.01m). These are negligible differences; we concluded that we could safely proceed with comparing the PRCs between these stations.

We first looked at the discrepancies between the PRCs for a given satellite measured at Point Lynas, and those from each of the other three stations: Stirling, Wormleighton and Loop Head (let us call those the "outstations"). We asked: how much error would there be in the PRCs if a user at Point Lynas employed corrections from each of these outstations? We first computed, satellite-by-satellite the correlation coefficients of each outstation's PRCs with those at Point Lynas. These correlation values ranged from 0.852 for Satellite 10 at Wormleighton, to 0.990 for Satellites 11 and 20 there. We then averaged the correlation coefficients for each station across all satellites. The results are shown in Table 4 in the column headed "Correlation coefficient". The average correlation coefficient was 0.963 at both Wormleighton and Stirling, and a lower 0.940 at more distant Loop Head.

We now calculated a set of PRCs for Point Lynas by interpolating between the PRCs at the three outstations. This RAAS interpolation was weighted by the reciprocals of the ranges from the outstations, so favouring the nearest. Table 3 shows these ranges and the weighting factors: Wormleighton 0.45, Stirling 0.29 and Loop Head 0.26. The "interpolated PRCs" for Point Lynas were then compared, satellite-by-satellite, with the PRCs actually recorded there. The correlation, 0.982 (Table 4), was much better than that at any of the individual outstations; the degree of de-correlation was between 30% and 49% of that at the outstations. It appears, therefore, that RAAS interpolation offers a significant benefit.

**Table 4**

| Station | Correlation coefficient | PRC difference (m) |
|---|---|---|
| Wormleighton | 0.963 | 1.05 |
| Stirling | 0.963 | 1.06 |
| Loop Head | 0.940 | 1.40 |
| ***Interpolated*** | ***0.982*** | ***0.66*** |

Computing the correlation coefficients in this way measures the agreement between the variations in the PRCs. We separately assessed the situation by examining the discrepancies between the actual PRC values. We computed the average of the modulus of the errors between each outstation PRC and the corresponding PRC at Point Lynas. The results, averaged across all satellites, are in the columns of Table 4 headed "PRC difference". These average discrepancies vary from 1.05m at Wormleighton to 1.40m at Loop Head. When we then compared the *interpolated* PRCs for Point Lynas with the values *measured* there, the average difference fell to 0.66m; this error is between 47% and 63% of those for the individual outstations. Again, we see a marked improvement.

We conclude that, in this case, a user would obtain PRC values much closer to the correct ones by interpolating the PRCs from these three outstations than by simply using the PRCs from any one of them, even Wormleighton the recommended night-time alternate.

The complete test was now repeated using Wormleighton with Tory Island (358km) and Mizen Head (417km). The two new stations are a little further away than Stirling and Loop Head. There was a larger discrepancy between clock bias values, with maximum differences of approximately 0.5m. But, again, the interpolated PRCs for Point Lynas proved much closer to the PRCs actually measured there than did the PRCs from any individual outstation. In other words, the results confirmed those from the first group of stations.

Finally, using this second group of beacons, we also checked the position results at Bangor over a total of 24h. Table 5 shows the 2-d and 3-d errors with respect to an antenna position established by long-term code-differential GPS measurements. Using corrections from the nearby station, Point Lynas, reduced the 2-d mean error from 5.3m to 2.5m. Corrections from the individual outstations also reduce the error, but by less. But interpolating their PRCs gave 2.6m, a value within 0.1m of that of Lynas itself. The 3-d results followed the same pattern. We conclude that interpolating the PRCs from these three outstations, even including one as distant as 417km, gives results almost indistinguishable from those provided by the local beacon.

**Table 5**

| Station | Distance from Bangor (km) | Mean error (m) | |
|---|---|---|---|
| | | 2-d | 3-d |
| No differential | | 5.3 | 15.2 |
| Wormleighton | 219 | 2.6 | 2.7 |
| Tory Island | 358 | 3.4 | 3.5 |
| Mizen Head | 417 | 4.9 | 5.0 |
| Lynas | 23 | 2.5 | 2.5 |
| *Lynas interpolated* | | 2.6 | 2.7 |

## WHERE RAAS PAYS OFF

Our analysis of these test results suggests that it pays to use a RAAS solution, rather than any of the possible alternate beacons, where three beacons contribute to that solution and the receiver lies within the triangle they form. Interpolating between three beacons in this way takes into account the gradients of the PRCs, of course.

But if the receiver were to lie outside the triangle, we would still have knowledge of those gradients and it would be reasonable to apply them, at least in regions close to the triangle. Then, a different way of calculating the PRCs at the receiver would then be required, since the process would be one of extrapolation, not interpolation. This option has not so far been explored.

Similarly, if only two beacons were available, the gradient in one direction would be known. This should also provide a limited benefit. It would be interesting to explore where, and for how far, a two-beacon solution would provide more accurate PRCs than either beacon alone.

But even if extrapolation and the use of two beacons are excluded, we can employ our computer model to identify those areas in which the receiver lies within a triangle of beacons each of which meets the full coverage criteria. In such regions, it should pay to use a RAAS solution. Fig. 8 shows the area in which these fairly conservative criteria are met by day when the British Isles beacons are used. Fig. 9 shows the (much smaller) area at night. The equivalent results for the entire EMA are presented in Figs. 10 and 11.

## FURTHER BENEFITS OF RAAS OPERATION

There are fundamental differences between a three-beacon RAAS solution and the traditional single-beacon LAAS approach. We have seen that RAAS should be more accurate then LAAS in many cases. But, with the ending of SA, the key reason for using radiobeacon DGNSS is not its greater accuracy but the enhancement of integrity it provides [18,21]. And, of course, a receiver that can take advantage of multiple beacons will enjoy at least as great an integrity benefit as a traditional single-beacon receiver. Indeed, provided the receiver marks a satellite as unhealthy as soon as it is flagged by any of the reference stations being received, the degree of integrity improvement afforded by differential operation will actually be increased.

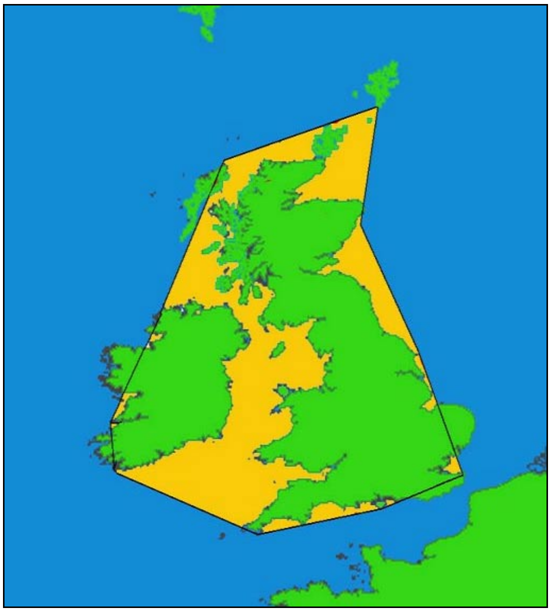

***Fig. 8: Orange highlights the region in which it pays to use RAAS: ie we are within a triangle of three stations, each of which meets full coverage criteria by day.***

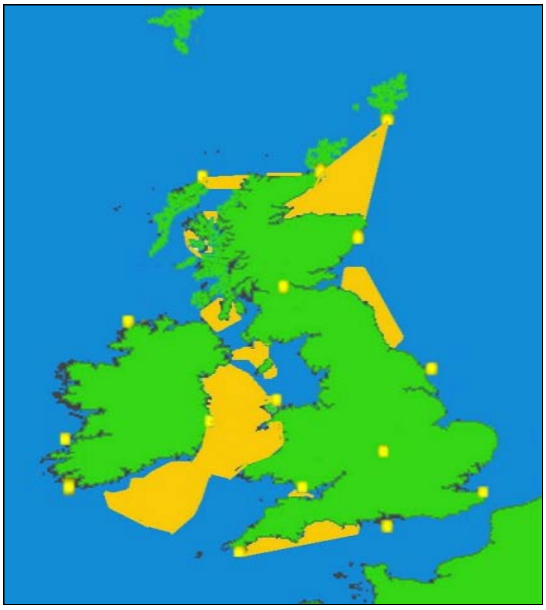

***Fig. 9: As Fig.8, but at night***

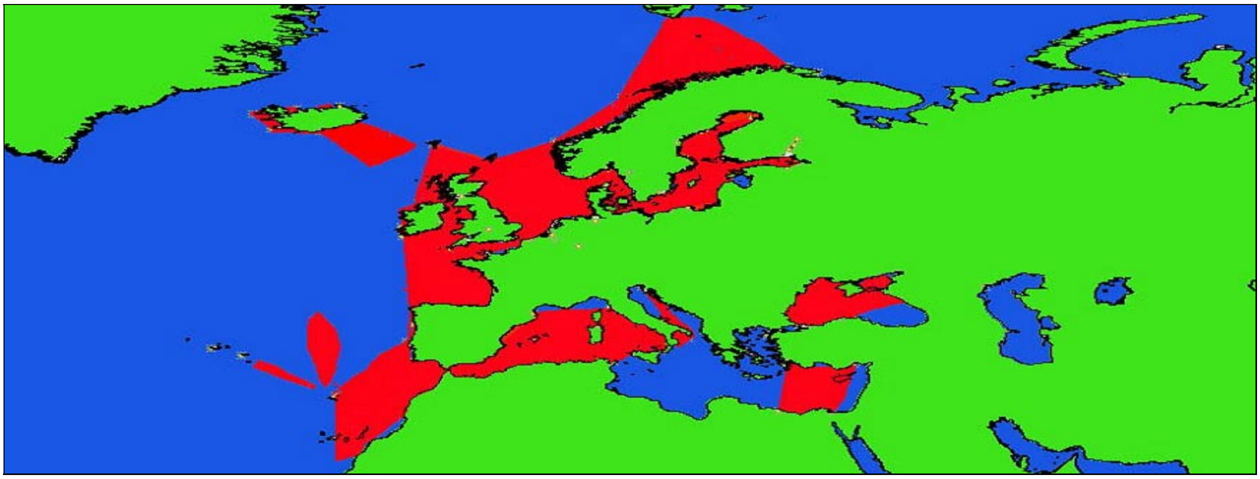

***Fig. 10: Red highlights the region in which it pays to use RAAS: ie we are within a triangle of three stations, each of which meets full coverage criteria by day.***

A further benefit of RAAS operation is that it should extend the area over which high-quality differential reception is available. We have seen that, with the ending of SA, the need for rapid updates of PRCs has gone. In principle, delays of many tens of seconds between PRC updates would lead to little degradation of position accuracy. Thus, we could make use of weaker signals from more distant radiobeacons. The 24-hour test data analysed above actually employed two groups of three beacons outside the area in which their coverage *at night* fully meets the international standards. Yet these beacons clearly provided accuracy benefits. The factor that requires us to continue to employ tight specifications in stating the coverage of radiobeacons post-SA is the time-to-alarm [18]. Indeed, we show in another paper in this session that no easing of standards can be permitted if this specification is to be met [21]. But if the receiver now has access to multiple beacons, the probability of receiving an alarm message will be greatly enhanced, and that is likely to extend substantially the area within which the TTA specification can be met.

In that case, multiple beacon operation – even employing beacons outside the standard coverage limits - is likely to provide both accuracy and integrity benefits.

It remains to explore this aspect of multiple beacon operation fully. We would also wish to investigate the degree to which even better results than those demonstrated above could be achieved by the use of other algorithms than simple weighted interpolation. We envisage exploring at the same time the dependence of accuracy on the geometry of the outstations, including the use of extrapolation to areas outside the region bounded by the outstations.

That done, we will be in a position to set formal criteria to be met if a RAAS solution is to be better than a LAAS one. We will then go on to prepare coverage plots according to those criteria; we anticipate that these will be more extensive than the plots presented above, especially at night.

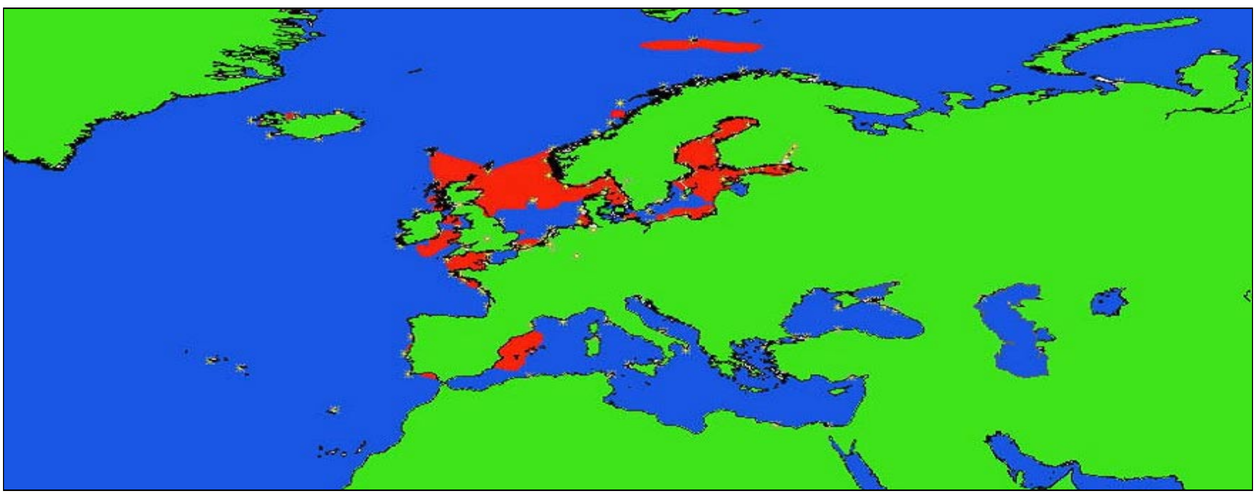

***Fig. 11: As Fig. 10, but at night***

## CONCLUSIONS

This paper has presented a preliminary exploration of the benefits of receiving multiple beacons from a radiobeacon DGNSS network. It has shown that the feasibility of doing so is now commonplace, especially by day, given the recent substantial increases in the numbers and ranges of European beacon systems. We have demonstrated that PRCs calculated by interpolating the values from three stations at ranges of approximately 200-400 km from the receiver are more accurate than the PRCs from any single such outstation. Thus, when a local station fails, interpolation is a better option than the use of a simple alternate.

We go on to argue that the benefits of a RAAS solution over a conventional LAAS one include not only higher accuracy but also a greater degree of integrity. We propose exploring whether these benefits are available, at least in part, outside the area within which the PRCs of three stations can be interpolated. Indeed, we show good reason to believe that RAAS operation could even extend the use of the radiobeacon service beyond its present boundaries.

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