Satellite navigation at sea
- simply the best, or simply multi-modal?

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Abstract

This keynote paper introduces the maritime theme in this GPSIC meeting. It questions whether satellite navigation systems for use at sea still have a unique identity in a world of multi-modal systems. In response, it notes the striking differences between marine applications and those in the air and on land. The early realisation by the International Maritime Organisation of the inadequacy of GPS for harbour approach use focussed the minds of the maritime community on the development of augmentations in the early 1990s. The result was the development, international standardisation, and world-wide deployment of a differential system for marine use well ahead of its counterparts in other modes of transport. The future of this system, the IALA beacon system, is then examined in the light of a recent comparative study by the European Maritime GNSS Advisory Forum of its performance in comparison to those of EGNOS and Eurofix. Recent developments in the IALA system are also presented, including a bold frequency re-allocation plan being conducted by IALA throughout the European Maritime Area, and the dramatic spread of this marine system on to land. The conclusion is that the maritime community possesses simply the best current practical realisation of GPS augmentation - and is not simply another user of multi-modal systems!

Introduction

This is a printed, and slightly abridged, version of the presentation given in Monaco.

I have been asked to talk this morning about marine systems in a conference devoted to satellite navigation. Now it may strike you, as it does me, as somewhat anachronistic to talk about *marine* systems at all. There was indeed a time, and not so long ago, when each mode of navigation - sea, air, land - employed completely different technology. A ship’s navigator knew where he stood. He was a master of direction-finding, he used his Decca, or maybe Loran, and he peered at the radar. But he had very little in common with an airborne navigator whose VOR and DME and ILS were completely foreign to him. They would have had little to say to one another.

But all that is supposed to have changed. We are in a new Europe here, a Europe of multi-modal systems, of Trans-European Networks, all based on satellite technology. And a system like EGNOS, for example, is promoted as the satellite enhancement not only for aviation, but also for shipping and land-vehicle tracking; in fact for almost any application that might pick up part of the bill! And yet, maritime navigation *is* different, and we should identify and recognise its differences from the start if we are to ensure that our systems are both suitable for marine applications and likely to be accepted by mariners. For mariners are strange people, with beards, who smoke pipes and marry mermaids! They are away at sea for long periods and this encourages a certain taciturn nature and stubbornness of outlook, a conservatism that informs their decision-making when it comes to navigation systems.

Let us look at the world in they practise their art, at the systems used to navigate ships - at the competition satellite systems have to overcome. There are more than a few of them. The electronic terrestrial - and now satellite - systems are merely the latest in a distinguished and unbroken succession of technologies, starting back with the Pharos of Rhodes! And never forget that most ships are navigated most of the time visually. This is not the world of Instrument Flight Rules. You peer out of the window and see what you can see: coastlines, other ships, and visual aids-to-navigation such as lighthouses, light-vessels, buoys, ships' lights, leading marks and so on. You might even *hear* fog signals. The closer to shore, the more of these traditional aids there are, until docking is usually a wholly visually-controlled manoeuvre.

Visual navigation – “conning the ship” - is enhanced by radar. Radar is universal in larger ships and becoming increasingly common in smaller boats, down the size of cruising vessels. Radar is enhanced by racons on buoys and target enhancers on yachts - devices that receive, amplify and return the radar pulses to give a clear mark on the screen. Radars are now very sophisticated, with all sorts of signal processing to remove sea clutter and track targets.

Visual navigation plus radar is a very powerful, proven, combination that does nearly everything a mariner wants. Satellite systems have to offer something special if they are to compete.

Well, radar plus ECDIS - an electronic chart driven by a precise navigation system, with maybe the radar image actually overlaying the map on the screen - that can compete. That is a powerful combination; it gives a poor mariner a warm glow inside on a dark and stormy night. And the presentation is familiar, pictorial, intuitive – this is how satellite navigation systems compete in the marine field: they co-operate with, rather than replace, what went before.

However, it may shock you to learn that the only electronic navigation system mandatory on any ship currently is direction-finding. And ship-owners do not like to pay where they are not obliged to, or for something that does not make a profit. Their meanness is legendary! Satellite navigation has had to deal with this problem in gaining a foothold in the marine world. However, it has become obvious to ship-owners that differential GPS plus ECDIS lets them reduce the number of officers on the bridge, and so cut their costs.

But also remember this about the marine world: the number of commercial ships is tiny compared with the number of vessels for leisure. There are well over a million pleasure craft in Europe alone, but fewer than 100,000 vessels over 100 gross tons in the whole world. And these pleasure craft provide substantial markets for equipment manufacturers, fashion-conscious customers willing to spend on new navigation technology. You know, in conferences like this, we often forget that the overwhelming majority of sailors, and indeed aircraft pilots, are amateurs, that these are now large and sophisticated user populations. From the first day we focus on high-category instrument approaches for aircraft. We forget the rest of aviation. We put maritime matters into a ghetto. And yet I will argue that the maritime community, despite its conservative nature and low profile at meetings like this, is actually the most advanced of all user communities in its adoption of differential satellite navigation.

How can that be? Well, a key factor is that the maritime community was the first to recognise the inadequacy of unaugmented GPS, with its poor integrity and limited accuracy. As early as 1990, at a time when most of the world was very gung-ho about GPS, the International Maritime Organisation (IMO) warned that " ... civil GPS alone is not suitable for navigation in harbour entrances or approaches" and that it "doesn't provide simultaneous integrity warning of malfunction." They recommended differential operation. That focussed everyone's minds. And while the aviation and land communities were studying dozens of different differential technologies, the maritime community simply took one technique and implemented it. By now they have quietly standardised it, got it recognised by the international bodies, and installed it around the world. It is – as the title of this paper and the song say - simply the best!

I am talking, of course, about differential GPS using the good old marine radiobeacons at lighthouses to carry the corrections. They were there, their radio transmissions were internationally approved and protected, it was straight-forward to extend those approvals to include the new DGNSS, and since no-one uses them any more for direction-finding, it was a kindness to give them a new role in the autumn of their days!

This system, often called the "IALA beacon system" (IALA is the world body that coordinates marine aids to navigation) is right at the heart of two current major issues in the marine field that I want to talk about this morning.

IALA beacons, EGNOS or Eurofix?

The first is the question is which differential technology is best suited to augment GPS and GLONASS until Galileo might become operational. The contenders, apparently, are IALA beacons, EGNOS and LORAN-C plus Eurofix. They are compared in a recent, important, very detailed, report by the European GNSS Maritime Advisory Forum for the European GNSS Secretariat. You and I might take issue with the report in certain respects: it talks about the need for such systems " ... operating in the relatively short-term before Galileo becomes operational." That implies that it will "become operational", which it may well, "in the relatively short term", which it may, and that then alternatives and differential enhancements will then no longer be required, which is yet to be demonstrated! Nevertheless, the report is required reading for the European maritime navigation community and it contains a fascinating comparison for marine users of these important technologies. So we will spend a little time on it now.

In case some of this is new to you, the IALA system transmits differential corrections and integrity information as additional, MSK, modulation on the coastal radiobeacons. These operate in a frequency band around 300kHz. They have ranges up to several hundred kilometres. They were originally established for ships to take direction-finding bearings on - some of them as long ago as the First World War, incidentally. So now the oldest marine navigation technology has converted itself into the newest! For typically 500 Euros you can buy an add-on receiver for a differential-capable GPS; a combined receiver costs about 800. The resulting accuracy is required to be better than 10m, to meet the harbour-harbour approach standards of the IMO; in practice, it is generally a couple of metres, 95% of the time. Note that this is a Local Area Augmentation System (LAAS); it carries corrections for the satellites visible from a single reference station at the beacon site. There will soon be 154 of these things across the European Maritime Area, with the coverage shown in Fig. 1.

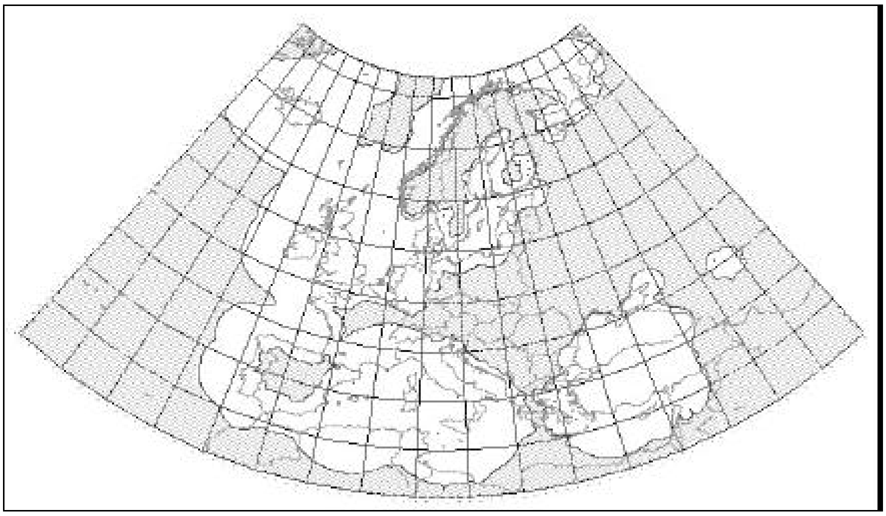

Fig. 1: IALA DGNSS beacon coverage in Europe, after [1]

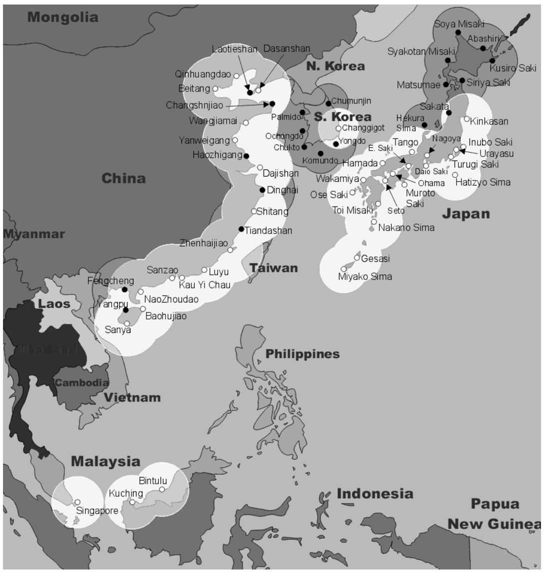

Fig. 2: IALA DGNSS radiobeacons in the Far East, after [1]

The system is world-wide. Fig. 2 shows the Far East coverage. In the US it covers both coastlines, plus the Great Lakes and the Mississippi. International standards for the transmissions are now issued by the IMO, by the International Electrotechnical Commission (IEC) and by the International Telecommunication Union (ITU). So you can see that it is well entrenched in coastal areas, and expanding fast.

EGNOS should need less introduction to this group of experts. It is a Europe-wide system, essentially compatible with the WAAS in the US and MTSAT in the Far East. Correction and integrity information, measured at multiple reference stations using wide-area techniques, are distributed on a GPS frequency via GEO satellites that also provide an additional ranging signal. The claimed accuracy is of the order of 3.5m. But there is a good deal about EGNOS that is still uncertain: the final coverage, the time-scales, the costs, and the prices of receivers.

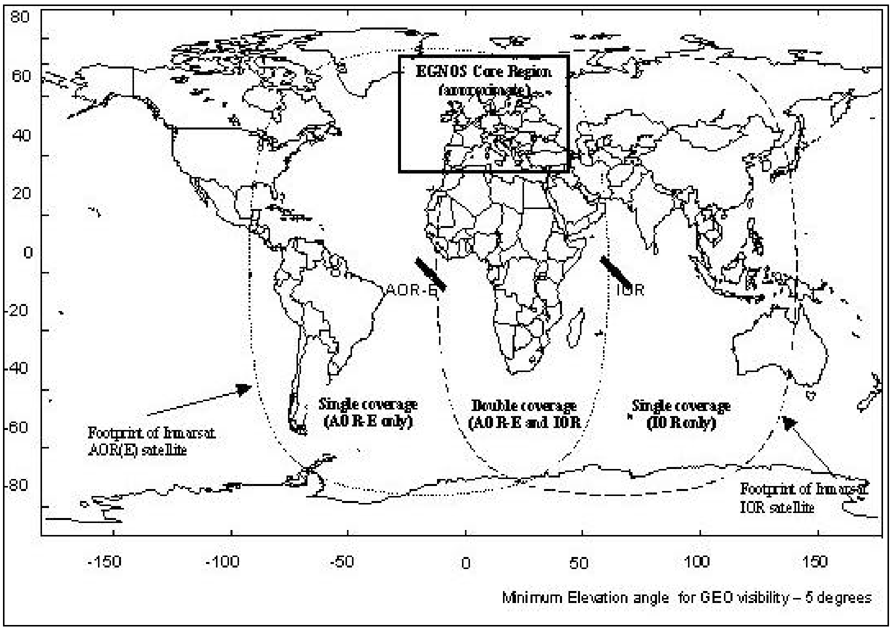

Fig. 3: Proposed EGNOS coverage, after [1]

The EGNOS "core coverage area" is essentially Europe (Fig. 3) - although there are serious limitations of satellite visibility at the high northern latitudes. There's no operational coverage yet; EGNOS is still at a relatively early stage, with the exciting developments yet to come, including the potential of being extended across Africa and the Middle East.

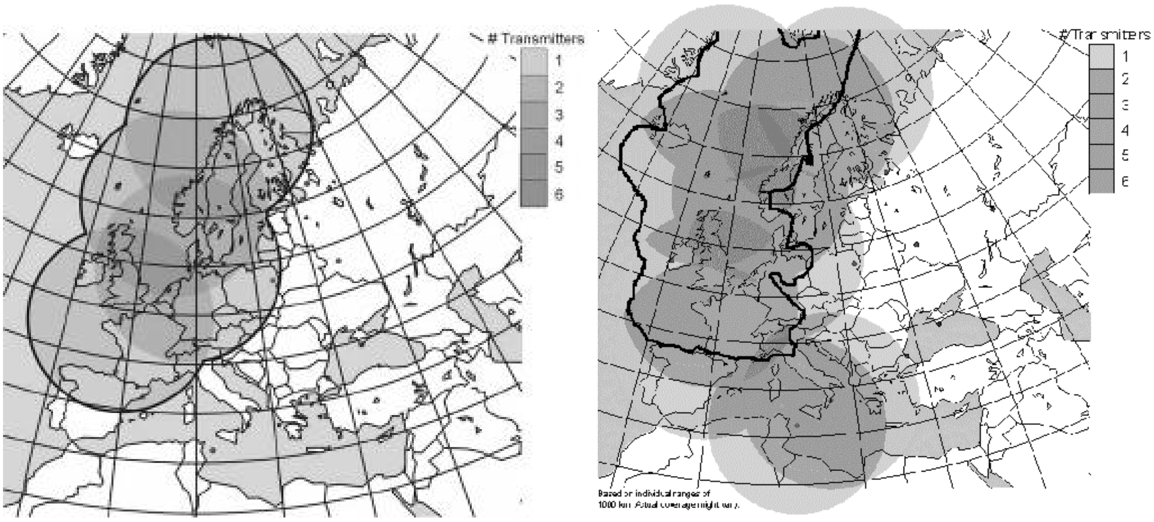

Fig. 4: (Left) Current Eurofix coverage,(Right) potential future coverage, both after [1].

Loran and Eurofix are well-known to some of you and, I guess, hardly known to others. Loran has been the most widely-used terrestrial precision electronic marine aid to navigation, the aid of choice throughout the US Coastal Confluence Zone. It operates at a low radio frequency - 100kHz - where propagation is remarkably stable. So its repeatable accuracy is very high, often better than GPS was before SA was "set to zero"; its absolute accuracy is lower. Eurofix is a technique for broadcasting GPS and GLONASS corrections and integrity information over these very high-powered Loran stations. The resulting DGPS accuracy is better than 5m, usually much better. But Eurofix is different from the other candidates: if GPS signals cannot be received, as often happens in cities, Loran takes over and navigation continues. Also, you can generally receive several Loran stations in most places, and if you interpolate corrections you get a Regional Area Augmentation System (RAAS), intermediate between a LAAS and a WAAS.

Eurofix is now available, on an experimental basis from the four stations and with the coverage shown in Fig. 4 (left). This includes a good deal of the sea and the land areas of Western Europe, including high latitudes. In fact, GPS augmentation via Eurofix is now available to a population greater than that of the United States. And there are various schemes, of uncertain time-scale, for expanding it, possibly to all the transmitters of the North-West European Loran system, even to cover the whole continent eventually.

The report compares these three systems in a wide variety of marine applications - navigation, operations, traffic management, search-and-rescue and so on - in a way that is not often done. And the conclusions make interesting reading. Regarding accuracy, there is little to choose between them; they are all differential code GPS systems. They all meet most general navigation and positioning requirements. None of them meets the very precise requirements that require carrier phase positioning. They all provide, or promise, the excellent *coastal* coverage that mariners need. With IALA beacons, it is there already, except for the eastern Mediterranean where another 10 stations are needed. EGNOS and Eurofix, of course, could give much better *inland* coverage than IALA. But neither does so yet; one is betting on the future. All three systems have good integrity: they tell the mariner promptly when something goes wrong. There are subtleties: a WAAS system like EGNOS, or a RAAS like Eurofix, use more reference stations than a LAAS like IALA, which enhances integrity. But the overall message is that, in terms of performance, there is not a lot to choose between them.

	Investment costs (MEuro)			**Annual O&M (MEuro)**
System	**Already made**	**Future**	**Total**	
IALA	12	16	28	5
EGNOS	25	290	315	28
Eurofix	24	50	74	10

Table 1: Comparison of costs of three systems, after [1]

The differences are in the costs and the risks. Table 1 shows the estimated costs of the three systems (I have rounded the figures a little and summed the totals). There are dramatic differences between them: EGNOS costs many times more than the other two. Its coverage may be greater than that of IALA beacons, of course, but it is not much more than that of Eurofix; indeed, it cannot work in the far north where Eurofix can.

When it comes to balancing the risks, essentially you are judging whether in the future users will prefer EGNOS or Eurofix to IALA beacons, and so drive them out of their present dominant position. But before that happens, they will need to be built, standardised, and made attractive to mariners, with affordable receivers.

So which of the three will become the future satellite navigation augmentation for marine use? The debate is going to be interesting!

A quart into a pint pot – the frequency allocation problem

I want to focus for my final few minutes on some exciting developments in the IALA system in which I have been involved recently. Keynote speakers are allowed that indulgence;

though do not think that I am biassed, I am also deeply into Loran and have an EGNOS receiver in my lab, which not many can claim! But the IALA system is the one the marine industry actually uses right now, so developments there are very important. It is an excellent system within its limitations, technically simple, low-cost, easily deployed by individual administrations. A bit like fax when it first appeared, I always think: a simple technology, just right for its time, perhaps a stepping-stone to greater things. But its very success has lead to problems.

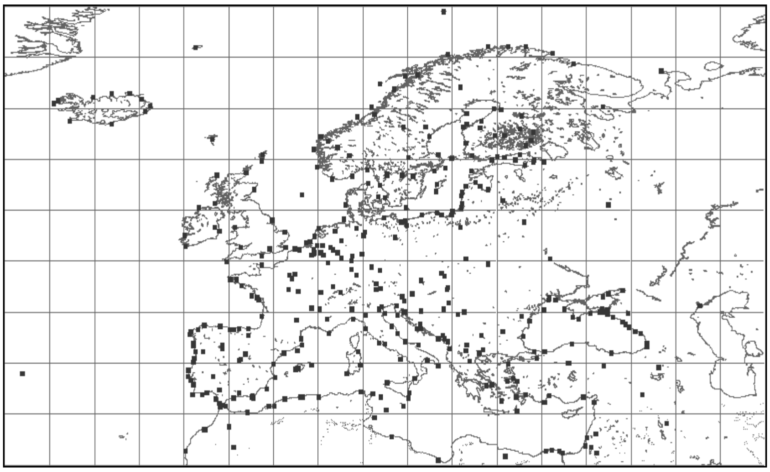

Fig. 5: There are now more than 400 radio-beacons within the European Maritime Area

Europe now has too many beacons (Fig. 5) crammed into the frequency bandwidth, with just 64 radio channels shared by more than 400 old marine DF beacons, plus some aeronautical ones, plus all the new differential beacons. The situation has been getting steadily worse. The result is high levels of interference; channels are shared by up to 15 European stations with interference from powerful beacons a problem to others up to 2000km away.

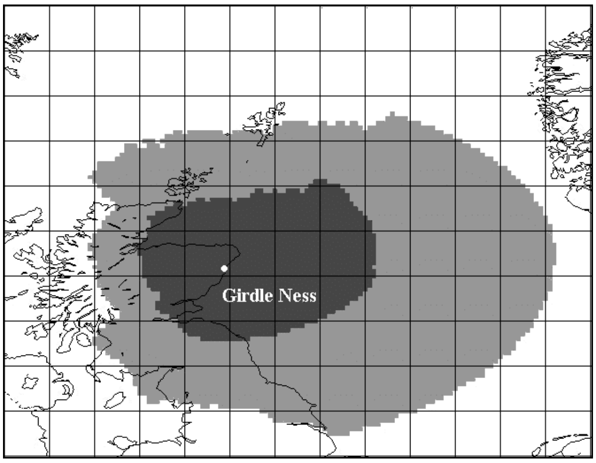

Fig. 6: (Outer contour) Coverage of Girdleness DGNSS beacon without interference, (Inner) reduced coverage due to interference

The beacon in Fig. 6, on the north-east coast of Scotland, should serve every ship across the North Sea almost to the Norwegian coast, and every sheep in the Scottish Highlands! But, because of interference, it can only be used reliably in the inner, much smaller, region shown.

Some European beacons are losing up to 90% of their potential coverage. It is a scandal! What is to be done?

Well, just now, across Europe, maritime administrations are introducing new differential GPS beacons in unprecedented numbers, the total soon to be increased from 63 to 154. At the same time they are reducing the number of the old direction-finding ones from 226 to just 77. With 196 aeronautical beacons sharing the band, there will be 427 stations in all. IALA has seized this unique window of opportunity, this time of change, to optimise the frequency band, re-allocating channels to beacons so as to help them live together in peace. And the tool they have used to achieve this is a software package we have just developed with the General Lighthouse Authorities of the UK and Ireland. It is a wonderful problem for an academic - an example of the infamous travelling-salesman mathematical conundrum. But, we have solved it well enough to shoehorn all the beacons into the available channels. We have taken into account interference between every beacon and all the other, 170,000 pairs of stations, interference across the earth's surface and via the ionosphere at night.

The result is a new band-plan that accommodates these 427 beacons efficiently (Fig. 1). And even though the number of beacons has actually *increased*, even though high-powered, long range, DGPS stations have replaced short-range marine DF beacons, the loss of coverage to interference has been cut from 90% to less than 20%. IALA and the European administrations have accepted the new band plan, and beacons across Europe will change to their new channels on 31 March next year. And now IALA are looking to apply the same techniques across the Far East and the South American continent.

The marine system comes ashore

Fig. 7: British Isles night-time DGNSS land coverage from maritime radio-beacons

With the new IALA service the coastlines of Europe will have more than 150 differential stations, with coverage in most places from at least two stations. And there is a curious side-effect to all this. In the comparison of systems I presented earlier, EGNOS and Eurofix had been planned to cover most of the continent of Europe, while the IALA beacons covered the coastal regions only. Well, it is no longer that simple!

Fig. 7 shows the night-time (ie worst-case) DGNSS coverage provided by the present British Isles IALA system: excellent in the sea areas. But inevitably, the service also covers much of the land. And because it is a low-frequency signal, it even penetrates deep into the city areas, just as Eurofix does so well - and EGNOS does not. Except in the four regions shown, there is already a differential GPS service, accurate to a metre or so, and with high integrity, for any land user with a 500 Euro receiver, free of charge and with no restriction as to its use. This marine system is actually available to all, and being used in an increasing number of applications. At present, this land coverage is a side-effect of the marine coverage.

But strange things are happening to maritime systems. In the US, the Department of Transportation are intentionally extending their marine system to serve the whole land area of the continental US - the lower 48 - with coverage from more than one beacon everywhere. The system will be used for numerous purposes, many of them in land transportation or farming, but even including some aeronautical applications. And they are well down the road to implementation.

Conclusions

I started this keynote paper by saying that it was perhaps anachronistic to consider marine satellite navigation in isolation in a world of multi-modal thinking. I went on to show that the maritime community has developed augmented satellite navigation further and faster than any other mode of transport, to a point where there is a standardised system world-wide in routine daily use. We have seen that, with two other excellent systems looking to knock it off its perch, it is having to go on developing fast. And now we have finished up with the multi-modal use on land of our marine system, a system that is based on radio-beacons, the oldest, most traditional, form of radio-navigation, now as it approaches its centenary, in a new millennium, giving us the most up-to-date marine and land navigation technology.

[1] *Potential of radionavigation systems to augment GPS and GLONASS*, European GNSS Maritime Advisory Forum Draft Working Paper, Marfor/WP5/V0.1, 23 Nov 1999.

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