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Maritime DGPS: Ensuring the Best Availability and Continuity

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At the 5th GNSS Symposium, held in Seville in 2001, the authors presented a paper entitled 'The Portuguese DGPS network', which began by addressing the current need for a DGPS service, given the removal of Selective Availability (Moore *et al.*, 2001). In that paper, the benefits of DGPS for mariners, namely in terms of accuracy and integrity, were discussed and presented, in order to show that the option to embrace DGPS was, and is, still valid because it can provide the best accuracy and integrity at sea. However, the accuracy advantage afforded and the integrity check performed by DGPS are only useful if the DGPS service reaches very high standards of availability and continuity. It would be almost useless to have a DGPS service with low availability and continuity, because it could mean a ship losing the differential corrections in restricted waters, where the service is most needed. In summary, the level of benefit gained from DGPS is directly proportional to the user availability of the service and to its continuity. Having discussed accuracy and integrity last year, this paper covers issues related to availability and continuity (continuity replaced the previously used concept of reliability). The availability and continuity requirements recently adopted by the International Maritime Organization (IMO) and the International Association of Lighthouse Authorities (IALA) are presented, as well as the ways by which DGPS services can meet the very high requirements for the harbour entrance and approach phase of navigation. The concepts used in the Portuguese DGPS network to minimize downtime and ensure the highest reliability and availability, are presented as an example.

KEY WORDS

1. DGPS. 2. Augmentation. 3. Marine.

1. AVAILABILITY AND CONTINUITY.

1.1. *Standards Adopted by IMO.* Navigation requirements (namely the ones addressed in this paper: availability and continuity) vary significantly between different phases of marine navigation. Generally, three major phases are identified: oceanic navigation (distance to the nearest obstacle greater than 50 miles), coastal navigation (distance to the nearest obstacle between 3 and 50 miles) and harbour entrance and approach, also known as pilotage navigation (distance to the nearest obstacle less than 3 miles).

The requirements for oceanic navigation are very broad because there are no physical constraints. In coastal areas, vessels travelling along the coast and approaching ports demand more stringent requirements because of the need to avoid incidents of collisions and groundings. However, it is in pilotage waters that the requirements are the most demanding because of the close proximity to dangers. For instance, in one of the European Space Agency's Galileo mission definition studies, ship-owners stated that it was essential to have a navigation solution with a maximum availability (no values were mentioned) in harbour approaches, for one-man bridge and remote pilot operations, namely on modern Integrated Bridge Systems where the radionavigation receiver is integrated into the ECDIS (Spaans, 2000).

Since 1983, IMO has been discussing a *Worldwide Radionavigation System*, with the objective of amending regulation V/12 of the SOLAS Convention, in order to include a mandatory requirement for ships to carry a receiver for such systems. In 1995, the 19th session of the IMO Assembly approved Resolution A.815(19) (IMO, 1995), containing in its Appendix the operational requirements for a *Worldwide Radionavigation System*. This Resolution required the system to have a signal availability above 99·8%, calculated over a 30-day period in harbour entrances and approaches and other waters in which freedom to manoeuvre is limited. According to that Resolution, the service reliability should be $\geqslant$ 99·97%, based on a measurement interval of one year.

Some Governments encountered difficulties making their augmentation systems, namely maritime DGPS, comply with these values for availability and reliability, thus prompting a revision of Resolution A.815(19). Therefore, IALA reviewed that Resolution, combining coastal navigation with harbour approaches and entrances, and developing two areas within this combined category, depending on the volume of traffic and/or degree of risk. Additionally, IALA recommended that the term 'reliability' should be replaced by 'continuity'. Where the volume of traffic and/or the degree of risk are higher, the availability and continuity requirements are, naturally, more strict. The proposed values are shown at Table 1.

Table 1. Availability and continuity standards.

Area	Absolute horizontal accuracy	Availability	Continuity	Augmentation
Ocean	$\leqslant$ 100 m	> 99·8% over 30 days	N/A	None
Coastal/harbour with low level of risk	$\leqslant$ 10 m	> 99·5% over 2 years	$\geqslant$ 99·85% over 3 hours	Single station
Coastal/harbour with high level of risk	$\leqslant$ 10 m	> 99·8% over 2 years	$\geqslant$ 99·97% over 3 hours	2 or more stations

IALA has included these values in its draft 'Recommendation on the Performance and Monitoring of DGNSS Services in the Band 283·5– 325 kHz' and also in a document reflecting the later views on availability and continuity standards in relation to IMO Resolution A.815(19). This draft revision of the *Worldwide Radionavigation System* Resolution was approved at the 47th Session of the Sub-

Committee on Safety of Navigation that invited the Maritime Safety Committee to approve it with a view to submission for adoption at the 23rd session of the Assembly, in November 2003.

The Portuguese continental coast does not present a high level of risk, because shallows are uncommon and there are no reefs. However, the volume of traffic is relevant because of the many ships that sail to/from Gibraltar, most of which travel along the Portuguese coast. The number of ships involved is around 30000 per year (80 ships per day). Along the west coast, the number decreases a little to something nearer 25000 ships per year (65 ships per day). These values may be considered high and will determine the standard to be used for the Portuguese DGPS network on the mainland coast (bottom row of Table 1) requiring two or more DGPS transmitting stations to augment the satellite transmissions simultaneously.

In the archipelagos of Azores and Madeira the risk is also low, but the maritime traffic is substantially lower. Therefore, the goal in the Archipelagos will be to comply with the less stringent requirements contained in the middle row. This represents the situation when a single DGPS transmitting station is required to augment the satellite transmissions.

1.2. *Definitions of Availability and Continuity*. Before analysing how the availability and continuity standards will be met both on the mainland coast and in the archipelagos, it is important to review the definitions of availability and continuity.

Availability is defined in IMO Resolution A.915(22) (IMO, 2001) – previously A.860(20) (IMO, 1997) – as 'the percentage of time that an aid, or systems of aids, is performing a required function under stated conditions. Non-availability can be caused by scheduled and/or unscheduled interruptions'. By definition, availability refers to the availability of the signal in space, or *signal availability*. But there is also the availability at the user, known as *system availability*. Although the latter is beyond the responsibilities of national administrations, we will discuss it superficially in paragraph 4. *Signal availability* is defined as 'the availability of a radio signal in a specified coverage area' (IMO, 2001).

Reliability was defined in IMO Resolution A.860(20) as 'the probability that a service, when it is available, performs a specified function without failure under given conditions for a specified period of time' (IMO, 1997). Recently, IMO has replaced the term 'reliability' by 'continuity', the definition of which is included in IMO Resolution A.915(22) (IMO, 2001) as 'the probability that, assuming a fault free receiver, a user will be able to determine position with specified accuracy and is able to monitor the integrity of the determined position over the (short) time interval applicable for a particular operation within a limited part of the coverage area'. Therefore, continuity is more or less the same as reliability, but over a shorter term; reliability used to be based on a measurement interval of 1 year and continuity is usually expressed over 3-hour periods. The intent of having a parameter like continuity is to provide guidance for continuity of service during a specific manoeuvre, such as port entry, anchoring or docking. These manoeuvres usually take less than 3 hours and therefore IMO expressed continuity over a 3-hour calculation period.

2. MEETING AVAILABILITY AND CONTINUITY STANDARDS OFF THE PORTUGUESE COAST.

As already stated, the standards to be

met off the coast of continental Portugal, due to the relatively high volume of traffic, are: availability: $> 99{\cdot}8\%$ over 2 years, and continuity: $\geqslant 99{\cdot}97\%$ over 3 hours.

These standards could not be achieved by single coverage of DGPS, as stated in Table 1. Therefore, two Broadcast Stations will be installed: one on the south-western tip of Portugal, in *Sagres*, and the other on the middle of the western coast, in Cape *Carvoeiro* (see Figure 1). With the installation of these two stations, together with the

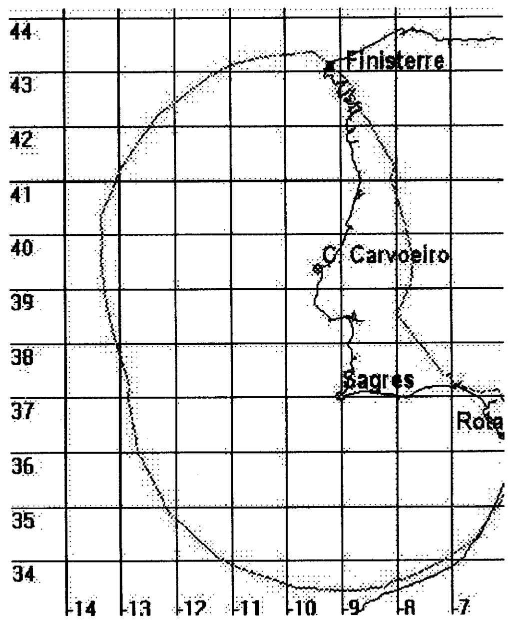

Figure 1. Coverage prediction diagram for continental Portugal showing Broadcast Stations at *Sagres* and Cape *Carvoeiro*.

Spanish Broadcast Stations of Cape *Finisterre* and *Rota*, all points in Portuguese waters will be covered simultaneously by at least two stations. Thus, if any station has an outage, no point on Portuguese waters will lack the reception of DGPS corrections: if the Portuguese southern station (to be installed in *Sagres*) fails then the Portuguese south coast will remain covered by the Spanish station of *Rota* and the western coast will be covered by the Portuguese northern station, installed approximately in the middle of the western coast: Cape *Carvoeiro*. Additionally, the northern half of the occidental coast will also receive the signal from the *Finisterre* station; if the Portuguese northern station (to be installed in Cape *Carvoeiro*) has an outage then the south coast and the southern half of the occidental coast will remain covered by the Portuguese southern station and the northern half of the occidental coast will receive the signal from the *Finisterre* station.

This architecture enables overlapping coverage and ensures that all points in the mainland coastline will receive simultaneously two DGPS signals. The signal availability standard of $99{\cdot}8\%$ over 2 years, implies that each of the two Broadcast Stations must be available for $95{\cdot}5\%$ of the time, which is perfectly attainable because it allows for approximately 32 hours of unusable time every month. This allowed average of 32 hours off-air time seems sufficient to accommodate all scheduled maintenance and unscheduled failures. Access to the mainland Broadcast Stations is easy and can be done in less than 3 hours, by car. Bad weather is unlikely to delay significantly the response to unplanned outages.

Nevertheless, to reach a 95·5% availability at each mainland Broadcast Station, all essential components will have redundant units running in hot-standby mode, because redundancy of major functions is fundamental to ensuring that the operation of the stations will continue uninterrupted in case of a hardware failure. The most critical components are the Reference Station (which is the heart of a Broadcast Station), the transmitter (which is the indoor component more likely to fail) and the transmitting antenna (which is very exposed to weather and to corrosive salty environments). The duplication of these critical components will ensure, not only a high availability, but also a high continuity.

Each Broadcast Station will have two Reference Stations, each one directly linked to one of the transmitters, forming a fixed pair. The pair actually generating and transmitting the corrections will be referred to as the active one and the other as passive. If the error of the position calculated with the differential corrections generated at the active Reference Station exceeds an acceptable tolerance, then the system switches automatically to the passive pair Reference Station + transmitter. In this process, other parameters are checked, namely Message Error Ratio (MER, which is an indicator of the quality of the broadcast, expressing the number of bad bits divided by the total number of bits.), broadcast signal strength, broadcast SNR, number of healthy satellites, HDOP, Pseudo-range residuals, Range Rate residuals, User Differential Range Error (UDRE, which is a one-sigma estimate of the Pseudo-range correction error due to ambient noise and residual multipath. UDRE is broadcast by each Broadcast Station, providing for overall error estimates.) and age of corrections. If the active Reference Station has any of these parameters exceeding the specified thresholds, then the system switches over between pairs automatically and without interrupting the DGPS broadcast.

Additionally, in each site there will be a dual transmitter, composed of two identical and interchangeable LF/MF transmitters. Under certain conditions (low output power and high reflected power) the system automatically performs a change of the transmitters. The duplication of Reference Stations and transmitters enables the system to sustain any failure in one of them, by automatically switching to the passive pair Reference Station plus transmitter.

Transmitting antennas are probably the least reliable equipment in a Broadcast Station, because they are exposed to bad weather (extreme temperatures, condensation, strong winds, rain, snow, ice, etc) and to corrosive salty environments. Problems in transmitting antennas are not uncommon. For instance, in Spain, during the year 2000, the antennas of two Broadcast Stations had problems: one of them (at *Estaca de* bares) was destroyed by strong gusts, leaving the Broadcast Station off-air for approximately one and a half months; another antenna (at *Finisterre*) had problems and was unusable for approximately one week (Rebollo, 2001). Apart from these unscheduled failures, the antennas also require periodical maintenance. In the Portuguese DGPS network the requirement is to have antennas with maintenance intervals of at least 3 years, but it is difficult to reach this goal because the antennas need frequent inspections and minor repairs.

To cope with these situations (unplanned outages and periodical maintenance) and reach the highest signal availability, two broadcast antennas will be available at each site of the Portuguese DGPS network: a primary antenna and a stand-by one, to be used during maintenance periods or other malfunctions of the primary antenna. On the mainland, existing antennas will be used as the stand-by ones. If the primary (new) antenna on one of these sites breaks down or fails then it will be possible to switch locally to the stand-by ones, ensuring an available signal in the coverage area. The primary antennas will be required to have an efficiency of 2·5% in the worst environmental conditions, while the stand-by antennas on each site will have a lower efficiency, but enough to cover the intended maritime area from the coastline to a range of 50 nm.

Considering these factors, the mainland Broadcast Stations shall consist of the following components: two Reference Stations, one Integrity Monitor, two transmitters, one Local Control Unit, and two broadcast antennas. Besides duplicating the essential components, other options were taken to reach the highest availability, namely in terms of power supply and in terms of communications between the Control Station and the Broadcast Stations.

2.1. *Power Supply*. Each Broadcast Station will have an emergency diesel generator with sufficient capacity to supply the Broadcast Station, in the unlikely event of a main power failure. Additionally, a few batteries will be installed to keep the station working during the few seconds it takes for the emergency diesel generator to start feeding the Broadcast Station. The capacity of the batteries will be at least one hour. Thus, if the emergency diesel generator does not start, that one-hour supply capacity will allow the station to keep working for the time necessary to broadcast a Navigational Warning notifying that the station will stop broadcasting.

2.2. *Communications Network*. Broadcast Stations are expected to operate autonomously, without intervention, for many years. Nevertheless, the Portuguese DGPS network will have a Control Station, located at the headquarters of the Portuguese Lighthouse Authority and staffed 24-hours a day. The purpose of the Control Station will be to provide timely monitoring and control of the remote Reference Stations, Integrity Monitors and transmitters, installed in each Broadcast Station, via the exchange of appropriate messages over a communications network. Effective monitoring and control of all Broadcast Stations requires a very reliable communications network. Therefore, two communications links will be established; the primary link will be an existing telephone line and the secondary link will be a GSM network (mobile communications). If the primary link fails, then the secondary will provide the necessary back-up.

2.3. *Advantages of Duplication and High Reliability*. For the mainland, the service continuity goal is 99·97% over 3 hours, which means that, assuming the DGPS service is available at a certain time (beginning of a manoeuvre or operation), then the probability that it is still available 3 hours later must be above 99·97%. This definition excludes scheduled outages, because they are notified and then the manoeuvre or operation should not commence. With such a service continuity requirement, it is necessary for each Broadcast Station to have a continuity of at least 98·3%, which allows for approximately one unplanned interruption, in each Broadcast Station, every week.

Duplication of essential components is the most efficient way, not only to maximize the availability, but also to ensure the best continuity. Another way of improving the system continuity is to choose the most reliable pieces of equipment. For instance, the computers chosen for the Local Control Units are industrial grade PCs that are required to withstand harsh environmental extremes and which have a much higher Mean Time Between Failures (MTBF). Additionally, the existence of a watchdog timer in these industrial computers makes stand-alone unmanned operations much more reliable and easy to manage because they can automatically trigger resets or reboots. A watchdog timer is a device or electronic card that performs a warm boot (restarting the system), after a certain period of time, if something goes wrong with the computer and it does not recover on its own. A common problem is for a computer to lock up if two parts or programs conflict. In some cases, the system will eventually recover on its own, but this may take an unknown and perhaps extended length of time. A watchdog contains a digital counter that counts down to zero at a constant speed from a preset number. If the counter reaches zero before the computer recovers, a signal is sent to designated circuits to restart it.

3. MEETING AVAILABILITY AND CONTINUITY STANDARDS IN THE ARCHIPELAGOS.

As stated in paragraph 1, the standards to be met in the archipelagos are:

(a) availability: $> 99{\cdot}5\%$ over 2 years,
(b) continuity: $\geqslant 99{\cdot}85\%$ over 3 hours.

These standards are lower than for the mainland coastal region, because of the lower volume of marine traffic, and can be achieved by a single DGPS station. The installation of two Broadcast Stations would bring obvious benefits, ensuring dual coverage in a substantial part of the archipelagos and improving signal availability significantly; DGPS users would not experience an interruption in service even if one of the sites experienced an outage. However, this option would also increase the costs of the network unnecessarily because one Broadcast Station is able to cover all the intended area. Moreover, in most of Madeira coastal waters, it is possible to receive the DGPS signal transmitted from the two DGPS Stations installed in the Canary Islands (which are part of the Spanish DGPS network). Therefore, although the requirement for Madeira is a single station, there will be dual coverage in significant parts of the archipelago, thanks to the Canary Island DGPS Stations. Furthermore, the problem of lack of national dual coverage can be minimised by ensuring total redundancy of all the equipment of the Broadcast Station, so that any single and individual failure does not compromise the operation of that station.

From the availability requirement, the total time out of service for a single Broadcast Station over the 2-year period must not exceed 3 and a half days. The average out of service time per month for a typical DGPS is 3·6 hours; therefore, all pieces of equipment at the Archipelagos Broadcast Stations must be duplicated to ensure full redundancy of all equipment and minimize down-time, and so keeping within the limits imposed by IALA and IMO. This means that, as well as the duplication of Reference Stations, transmitters and broadcast antennas, all other pieces of equipment will be duplicated at the archipelagos, namely Integrity Monitors and Local Control Units.

There are mainly two differences between the mainland and the archipelagos, which justify the option of installing two Integrity Monitors in the latter: on the mainland, considering the Spanish Broadcast Stations of Cape *Finisterre* and *Rota*, all points on continental Portuguese waters will be covered simultaneously by, at least, two Broadcast Stations. Thus, if any station starts transmitting in an 'unmonitored' mode, users will continue to receive a DGPS 'monitored' signal from another Broadcast Station. In the archipelagos, if the Broadcast Station started transmitting in an 'unmonitored' mode (due to Integrity Monitor failure), then there would be no alternative Broadcast Station for the user. The period of time needed to repair or replace a damaged Integrity Monitor will be much higher in the archipelagos than in the mainland due to flight connection restrictions, and thus the availability and continuity standards could be compromised. Broadcast Stations on the mainland will be located at a relatively short distance from the headquarters of the Portuguese Lighthouse Authority, and it will be possible to repair or even replace a damaged Integrity Monitor in a very short period of time; typically within 6 hours. In the archipelagos, in case of bad weather, flights may be delayed or even cancelled, further delaying repairs.

This option, to install two Integrity Monitors, has also been adopted by the United States, Canada, United Kingdom and Republic of Ireland, whose authorities interpreted 'availability' as the availability of the *monitored signal*. They required two Integrity Monitors in each site of their DGPS networks so that if one fails the other continues to monitor the quality of the broadcast signal. With that second Integrity Monitor their Broadcast Stations are able to reach the availability standard with a *monitored signal*.

However, the majority of the countries did not require the use of a second Integrity Monitor because these are very reliable pieces of equipment, which, according to the experience of several countries, rarely fail. Additionally, if the single Integrity Monitor fails, then the Broadcast Station will continue to transmit in an 'unmonitored' mode, informing the users of this state. Even with only one Integrity Monitor, as will be the case in continental Portugal, it will be possible to reach the availability standards, despite the possibility of the signal being 'unmonitored' for some periods – when the Integrity Monitor fails.

Local Control Units consist generically of one computer and everyday experience shows us that computers are susceptible to failures. Therefore, two of them will be installed, in parallel and both fully configured, in the Broadcast Stations of Azores and Madeira. If one of them fails, the other will be able to replace it, performing all the necessary tasks. This is the best way to ensure the highest availability, particularly in sites located far from the Control Station.

Another difference between the Broadcast Stations to be installed in the archipelagos and on the mainland is that in Madeira and the Azores both broadcast antennas will be similar, in order to allow a remote switching from the Control Station. They will be required to have an efficiency of 2·5%, in the worst environmental conditions.

Table 2 shows a comparison of how the availability and continuity standards will be met in continental waters and the archipelagos.

4. SYSTEM AVAILABILITY.

The role of national administrations is to ensure the highest availability and continuity for their radionavigation services, meeting or exceeding the international standards. However, the availability of a navigation solution for the mariner (*system availability*) is often lower than the *signal availability*. *System availability* can also be called *user availability* because it refers to the availability at the user's receiver. It is difficult to quantify because it depends on unpredictable factors (intentional and unintentional interference) and is

Table 2. Meeting availability and continuity standards in the Portuguese DGPS network.

Area	Volume of traffic	Signal availability standard	Continuity standard	No. of stations	Availability of each station	Continuity of each station	Constitution of each Broadcast Station
Continental Portugal	High	> 99·8% over 2 years	⩾ 99·97% over 3 hours	2	> 95·5% over 2 years	⩾ 98·3% over 3 hours	2 Reference Stations; 1 Integrity Monitor; 2 Transmitters; 1 Local Control Unit; 2 broadcast antennas.
Azores and Madeira archipelagos	Low	> 99·5% over 2 years	⩾ 99·85% over 3 hours	1	–	–	2 Reference Stations; 2 Integrity Monitors; 2 Transmitters; 2 Local Control Units; 2 broadcast antennas.

influenced by extremely variable issues (atmospheric noise and performance of the DGPS receiver).

Atmospheric noise is generally considered by national administrations, which overcome its influence on availability and continuity, by properly determining the transmitted power and siting the DGPS Broadcast Stations accordingly. Interference, particularly intentional interference (jamming), is a major problem of GPS, and consequently of DGPS, because if the basic GPS signal is lost then the augmentation service is useless. Performance of the DGPS receiver is a factor that depends uniquely on the mariner, who must understand that different receivers have different signal processing, which affect the resulting accuracy, integrity, availability and continuity.

The US Coast Guard claims that quantitative analysis has shown a *user availability* 'somewhat higher than 98%' in their DGPS network. However, 'empirical data with the latest MSK receiver technology needs to be collected over a period of several years in order to ascertain a more exact number' (US DOT).

5. CONCLUSION. DGPS is a service that contributes significantly to the reduction of navigation related incidents, because of improved accuracy (less dramatic than with SA on, but still important) and also because of the integrity check provided (giving mariners an extra-assurance that their position is correct). However, the level of benefit gained from DGPS is directly proportional to the *user availability* of the service and to its continuity. Though *user availability* depends on unpredictable factors (interference) and other extremely variable factors (atmospheric noise), national administrations must try to provide the highest possible availability and continuity. The best way to do this is by redundancy (duplicating the essential components in a DGPS Broadcast Station) and by reliability (choosing always those pieces of equipment with highest MTBF). The Portuguese DGPS network was been designed bearing in mind this need to provide a highly available and reliable service, in order to maximize the benefits derived from DGPS, namely reduction of navigation related casualties and better protection of the environment.

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