Is DGPS Still a Good Option for Mariners?

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The International Maritime Organisation (IMO), in its Sub-Committee for the Safety of Navigation, has recommended the acceptance of GPS as a component of the *World-Wide Radionavigation System*. However, the Sub-Committee highlighted that GPS accuracy is not sufficient for harbour entrances and approaches and that it does not provide instantaneous integrity to alert users of any malfunction. The Sub-Committee considered that DGPS could improve both the accuracy and the integrity of GPS. In practice, the use of differential corrections to GPS signals allows elimination of most of the errors of GPS and improves the integrity of the service significantly. While GPS does not provide instantaneous integrity, the use of DGPS reference stations, which continuously monitor the signals of the visible satellites, enables the timely warning (under 15 seconds) of any malfunction or failure. However, the recent discontinuation of Selective Availability (SA), which led to an improvement in stand-alone GPS accuracy, has changed some of the premises that justified differential services. This paper presents the needs of mariners in terms of radio positioning, with the aim of evaluating the ability of unaugmented GPS and DGPS to comply with marine navigation requirements. The impact of the removal of SA on DGPS and its benefits for mariners will also be discussed in order to show that DGPS is still adequate and useful for mariners.

KEY WORDS

1. DGPS. 2. Maritime. 3. Augmentation.

1. RADIONAVIGATION REQUIREMENTS FOR MARITIME OPERATIONS.

There are no universally accepted navigation requirements for marine navigation; the accuracy and integrity requirements vary significantly between the different phases of a voyage. 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 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 hazards. Therefore, only these requirements will be discussed in this paper.

Requirements also differ between different countries and organisations. For this evaluation, in which the focus is mainly on accuracy and integrity requirements, the following sources are used:

(a) the requirements adopted by IMO in the definition of a future Global Navigation Satellite System (GNSS);
(b) the requirements proposed by the European Maritime Radionavigation Forum (EMRF) and;
(c) the US government requirements, contained in the 'Federal Radionavigation Plan' – 1999 (FRP-1999).

1.1. *Requirements adopted by IMO for a future GNSS.* Since 1983, IMO has been discussing a *World-Wide Radionavigation System*, with the objective of amending regulation V/12 of the SOLAS Convention to include a mandatory requirement for ships to carry a GNSS receiver. In 1995, the 19th session of the IMO Assembly approved Resolution A.815(19) (IMO, 1995), which contains in its Appendix the operational requirements for a *World-Wide Radionavigation System*. This Resolution specified operational requirements relevant to the first generation GNSS, commonly referred to as GNSS-1. Two years later, during its 20th Assembly, IMO updated its policy for a future GNSS, approving Resolution A.860(20) (IMO, 1997), which specifies top-level maritime requirements more appropriate to the second generation GNSS (GNSS-2). Appendix 2 to this Resolution is a 'list of minimum maritime user requirements for a future GNSS' and contains the following requirements:

(a) absolute accuracy: $\leqslant$ 10 metres;
(b) integrity (time to alarm): $\leqslant$ 10 seconds.

Additionally, Resolution A.815(19) had already stated that 'for ships with operating speeds above 30 knots more stringent requirements may be necessary'.

1.2. *Requirements proposed by the European Maritime Radionavigation Forum* (*EMRF*). The EMRF unites those representing both users and national and international providers of maritime radionavigation services. Its main objective is to provide the primary focal point for maritime radionavigation development in Europe. The EMRF (and one of its predecessors, the European GNSS Maritime Advisory Forum) has been developing a review of requirements for a large number of maritime applications, and these were presented in a report entitled 'Applications and User Requirements' (EMRF, 1999). Although it contained useful information, this report did not specifically identify the changes that should be made to update and introduce new material into IMO Resolution A.860(20). Therefore, the IMO Sub-Committee on Safety of Navigation prepared a draft revision of that Resolution (NAV 46/7/3, 2000) incorporating relevant parts of the EMRF report. In terms of maritime requirements, the main changes proposed to Resolution A.860(20) are a revision of the list in Appendix 2 (whose proposed title is 'table of minimum maritime user requirements for general navigation') and the introduction of a new Appendix 3 relating to the maritime user requirements for non-general navigation and positioning. Regarding navigation in pilotage waters, the proposed requirements are:

Port Approach and Restricted Waters:
(i) predictable accuracy: 10 metres,
(ii) integrity (time to alarm): 10 seconds.

Port:

(i) predictable accuracy: 1 metre,
(ii) integrity (time to alarm): 10 seconds.

It is interesting to quote also the proposed accuracy requirements for some non-general navigation applications, namely hydrography: 1–2 m; aids to navigation management: 1 m; and offshore exploration and exploitation: 1 m. In terms of integrity, the Sub-Committee on Safety of Navigation anticipates that 'more stringent requirements may be necessary for ships operating above 30 knots' (NAV 46/7/3, 2000).

1.3. *Requirements contained in the Federal Radionavigation Plan.* The FRP is the official document, which defines policies and plans for radionavigation services provided by the US government, and is jointly developed by the US Departments of Defense and Transportation. Chapter 2 of the latest Plan (FRP, 1999) contains the civil marine radionavigation requirements for the different phases of navigation, based on a combination of requirements studies, user inputs and estimates. FRP-1999 divides pilotage navigation into two phases: inland waterways and harbour entrance and approach.

For the inland waterway phase of navigation, the predictable accuracy requirements (2 drms) are 5–10 metres for recreational boats and smaller vessels and 2–5 metres for other ships. For the harbour entrance and approach phase, the predictable accuracy requirements (2 drms) are 8–20 metres for all ships and 1–5 metres for resource exploration. The FRP also warns that 'special radionavigation requirements may arise from new environmental laws and regulations designed to reduce marine vessel casualty events'.

2. PERFORMANCE OF GPS (WITHOUT SELECTIVE AVAILABILITY).

2.1. *Removal of Selective Availability.* A US Presidential Decision Directive of 1996 specified that Selective Availability (SA) would be removed from GPS within 10 years. It specified also that initial consideration for its removal would occur in the year 2000 and that the President would make an annual determination on the continued use of GPS SA, beginning in 2000. The pressure, from GPS users, to end SA was very high and only military concerns about losing their GPS positioning advantages stopped it from being discontinued in 1996. During the following four years, the military community evaluated the implications of removing SA, realizing its declining value for security purposes, mainly due to the following:

(a) SA had been overtaken by augmentation systems, such as maritime DGPS networks, which were already installed in more than 30 countries, providing a service of high accuracy and integrity; and
(b) US military had developed the capability to negate GPS signals in case of growing tension or conflict: *Selective Denial*.

This capability to deny GPS signals on a regional basis was achieved at the beginning of 2000 (final NAVWAR tests were completed in February 2000), thus paving the way for discontinuing SA, which was announced by President Bill Clinton on the 1st of May 2000 (PDD, 2000).

2.2. *Stand-alone GPS accuracy.* With SA turned off, stand-alone GPS accuracy has improved significantly from the previously specified 100 metres (95%). US

Table 1. Requirements for the various phases of navigation in pilotage waters.

Source	Phase of navigation	Accuracy required (metres)	Integrity required (secs)
IMO	World-wide	10 (95%)	10
EMRF	Port approach & restricted waters	10	10
	Port	1	10
FRP-1999	Inland waterways	Recreational boats and smaller vessels: 5–10	—
		Other ships: 2–5	—
	Harbour entrances and approaches	All vessels: 8–20 (2 drms)	—
		Resource exploration: 1–5 (2 drms)	—

authorities have not yet updated the Standard Positioning Service (SPS) Signal Specification since the removal of SA, but using the performance parameters contained in the 2nd Edition of that document, single frequency receivers could be expected to obtain an accuracy of the order of 25 metres (95%). However, that document was published before the system reached Initial Operational Capability and does not reflect improved constellation performance. Furthermore, some manufacturers have developed innovative techniques to use portions of the encrypted P(Y) code. These dual frequency civil receivers can compensate for the ionospheric errors, thus ensuring a better accuracy. However, they require a very high Signal to Noise Ratio, which precludes their use in dynamic applications, such as marine navigation.

According to a presentation made at the Civil GPS Service Interface Committee Meeting, in September 2000 (Shaw, 2000), the draft performance standards in the new Signal Specification, not including ionospheric/tropospheric errors or receiver noise, are as follows (considering all satellites in view and a 5° mask angle):

(a) Global average horizontal accuracy: 5 m (95%),
(b) Global average availability: 99·5% at 15 m (95%),
(c) Worst site horizontal accuracy: 15 m (95%),
(d) Worst site availability: 92% at 15 m (95%).

These figures are not very useful because they do not consider three important GPS error sources (ionospheric and tropospheric delay, and receiver noise). Therefore, to have a coarse indication of GPS accuracy, without SA, a brief trial was conducted in Lisbon at the end of 2000, recording simultaneously unaugmented GPS positions and DGPS positions, at the Portuguese Hydrographic Office building. The total time of observations was 115 hours and the final results of stand-alone GPS were:

(a) 95% error: 14·3 m, and
(b) 99% error: 18·8 m.

These results clearly indicate that the accuracy of GPS, without SA, has improved significantly, making it sufficient for many applications and groups of users. The accuracy improvement gained after the end of SA is amplified by the current over-specification of the constellation, which was composed of 27 satellites at the time of this experiment and increased to 29 by the beginning of 2001. However, it must be noted that in May 2001, 18 of these satellites had exceeded their design life (7·3 years)

Table 2. Evaluation of the capability of GPS for navigation in pilotage waters.

Source	Phase of navigation	Accuracy required (metres)	Met by GPS	Integrity required (secs)	Met by GPS
IMO	World-wide	10 (95%)	X	10	X
EMRF	Port approach & restricted waters	10	X	10	X
	Port	1	X	10	X
FRP-1999	Inland waterways	Recreational boats and smaller vessels: 5–10	X	—	—
		Other ships: 2–5	X	—	—
	Harbour entrances and approaches	All vessels: 8–20 (2 drms)	✓	—	—
		Resource exploration: 1–5 (2 drms)	X	—	—

and 16 of them were already working in single-string failure mode, meaning that a single failure in the wrong system would leave the satellite unusable. This means that some of the oldest satellites are expected to begin to fail in the near future, and there is no guarantee that the current number available in the constellation will be maintained.

Furthermore, better accuracy is still essential in some maritime applications, such as dredging, hydrographic surveying, buoy positioning, safety of life applications and, particularly, some phases of pilotage waters navigation, including harbour manoeuvres. Table 2 evaluates how stand-alone GPS met or failed the requirements for pilotage waters navigation, during the trial period. This was confirmed by the IALA Radionavigation Committee in a note issued in September 2000: 'the accuracy advantage afforded by DGNSS remains essential for meeting the IMO requirements for harbour entrance and approach phase of navigation' (IALA, 2000).

2.3. *GPS integrity*. Aside from accuracy, the removal of SA does not overcome the main issue for mariners, integrity. Poor integrity is still the most important vulnerability of GPS, from a mariner's perspective. The reception of timely warnings indicating 'when the system should not be used for navigation' (FRP, 1999) is essential for ships navigating in critical waters, and GPS can provide erroneous information for relatively long periods without having the capability to warn users. Real-time monitoring is performed at the Master Control Station (Schriever Air Force Base), which uses data collected by six GPS Control Segment stations distributed around the globe: Hawaii and Kwajalein – in the Pacific Ocean; Diego Garcia – in the Indian Ocean; Ascension – in the Atlantic Ocean and Colorado Springs and Cape Canaveral – in continental USA. However, these six stations do not provide 100% tracking coverage. This means there are gaps in the monitoring network, and the satellites are unmonitored for some periods each day. Furthermore, these ground stations have a slow reaction time (up to 1 hour) and, as a consequence, navigators could be using incorrect positions for a considerable period without any warning. In recent years, several mechanisms have been developed to improve GPS integrity, namely Receiver Autonomous Integrity Monitoring (RAIM) and the use of DGPS reference stations. However, RAIM is not always available because at least five satellites need to be tracked to detect a failure and six are required to identify the faulty satellite and remove it from the positioning solution. Furthermore, good

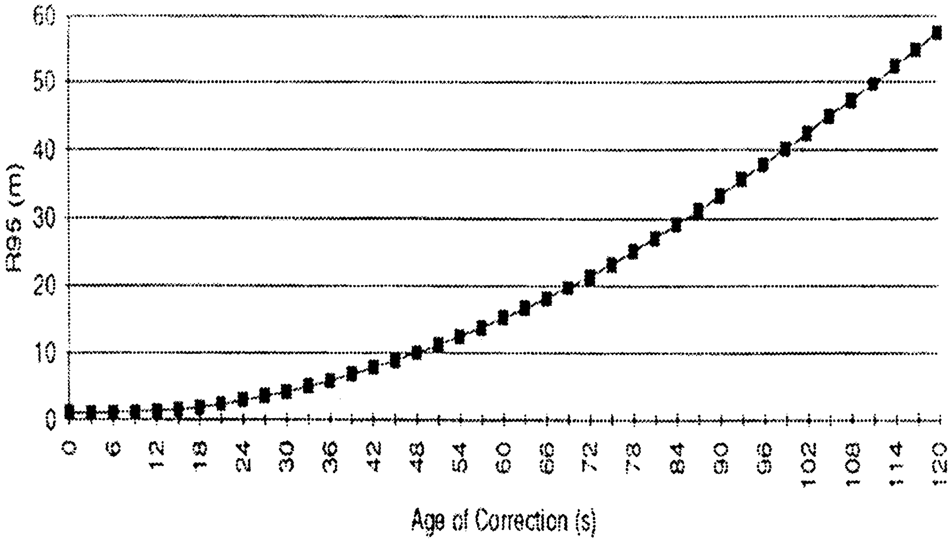

Figure 1. Age of corrections analysis with SA.

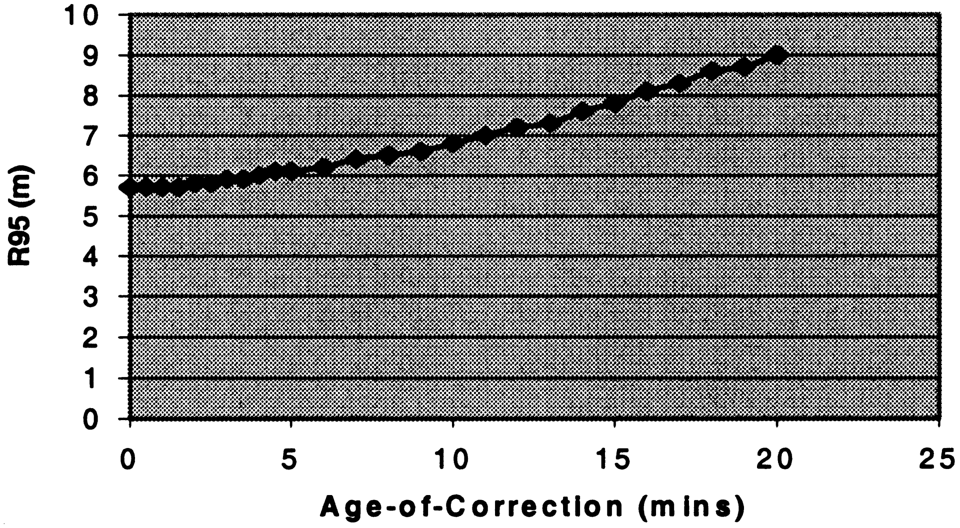

Figure 2. Age of corrections analysis without SA.

satellite geometry is required, as poor geometry makes RAIM much more difficult. Therefore, one of the best ways to provide an independent assessment of the health of GPS satellites is the use of differential stations.

3. DGPS PERFORMANCE.

3.1 *Effect of discontinuing SA on DGPS.* The transmission of differential corrections to the GPS signals allows the elimination of most of the errors of GPS, improving its accuracy to only a few metres. The removal of SA has also enabled improved results using DGPS. SA errors were completely compensated by the differential technique, but the corrections lost their validity after a period of time because SA was a random, fast changing, error, see Figure 1. Therefore, to obtain good DGPS results, corrections had to have a low latency and had to be transmitted very frequently (with a total age of corrections of < 10 seconds), thus placing a considerable strain on DGPS systems, particularly on the communication channel used to broadcast the corrections to the users.

With the end of SA, the remaining GPS errors have a slower changing rate. Tropospheric/ionospheric delays and errors in the satellite ephemeris and clocks do not change as quickly as the random shifts generated by SA. In fact, satellite ephemeris and clock errors change very slowly.

As can be seen in Figure 2, without SA, there is almost no degradation of the accuracy of the computed position in the first 5 minutes (R95), due to the increasing age of corrections. Only after 15 to 20 minutes is a small drift of 3 to 4 metres in the pseudo-range accuracy noted. Therefore, if DGPS corrections are broadcast every 10 seconds, as they were before SA was discontinued, then good results may still be obtained when DGPS corrections are lost (due to interference or other reasons) for periods of up to 15 minutes. This results in *increased robustness* of the DGPS service and *reduced susceptibility to interference*.

Before SA was switched-off, many countries used a data rate of 200 bits per second (bps) in their DGPS transmissions, because these relatively high data rates allowed increased accuracy due to a more frequent update of the corrections. However, they also caused a reduction in coverage, as the energy was spread over a greater bandwidth. Without SA, it will be possible to use lower data rates, perhaps 100 bps or even 50 bps whilst still maintaining very good accuracy, and so increase the coverage provided before SA was removed.

Another benefit for the DGPS service is that, by reducing the amount of correction data to broadcast, it will be possible to transmit crucial safety of navigation information using a special message (RTCM-SC 104, type 16) that accommodates up to 90 characters. This additional information could include Navigational Warnings and meteorological/hydrographic data and other information useful to the mariner, such as information on the status of the local DGPS service and limited information on service outages in adjacent coverage areas. Additionally, the spare datalink capacity may be used, in the near future, to broadcast RTCM-SC 104 messages containing phase corrections. Carrier phase corrections are similar to pseudo-range corrections and are computed using the carrier-phase measurements made at the DGPS Reference Station. The Radio Technical Commission for Maritime Services is preparing version 3 of RTCM-SC 104 to include a recommended format for this high-accuracy DGPS, which is capable of giving sub-metre accuracies in real-time.

3.2. *DGPS accuracy*. Extensive tests were performed with two trial stations, installed in Portugal in 1999. The accuracy of the DGPS positions, at 9 reference points scattered throughout the Portuguese coastline, was better than 3·5 m (95%) and in the order of 4 m (99%). Another trial was conducted in October 2000 (i.e. after SA was discontinued) recording simultaneously stand-alone GPS positions (whose results have already been presented) and differentially corrected positions, for approximately 115 hours. The trial DGPS station was installed for a brief period in Lisbon, and the positions were recorded at the Portuguese Hydrographic Office building. The final results of this very small trial were: 95% error: 1·8 m and 99% error: 2·4 m.

Table 3. Evaluation of the capability of DGPS for navigation in pilotage waters.

Source	Phase of navigation	Accuracy required (metres)	Met by DGPS	Integrity required (ses)	Met by DGPS
IMO	World-wide	10 (95%)	✓	10	✓
EMRF	Port approach & restricted waters	10	✓	10	✓
	Port	1	X	10	✓
FRP-1999	Inland waterways	Recreational boats and smaller vessels: 5–10	✓	—	—
		Other ships: 2–5	✓	—	—
	Harbour entrances and approaches	All vessels: 8–20 (2 drms)	✓	—	—
		Resource exploration: 1–5 (2 drms)	✓	—	—

As expected, these results are very good and conform to the values stated in the FRP: 'user equipment may achieve accuracies better than 3 metres' (FRP, 1999). Table 3 shows that DGPS trial results met almost all accuracy requirements for pilotage waters navigation, including the most demanding ones. Only the 1 m accuracy requirement proposed by the Sub-Committee for the Safety of Navigation for ports was not met during this small trial. This is a very stringent requirement, only achievable with carrier-phase corrections, likely to be incorporated in DGPS services in the near future.

The accuracy improvement provided by DGPS is more significant when measuring Speed Over Ground (SOG) and Course Over Ground (COG), especially when the radionavigation receiver (GPS or DGPS) supplies position, velocity and heading inputs to ECDIS, AIS, Integrated Bridge Systems or autopilots. These automatic systems require better positioning accuracies that are difficult to meet with unaugmented GPS. Aside from the extra accuracy of DGPS, which may not be required for some applications, the most important benefit of DGPS is the extra assurance it gives that a positioning solution is correct.

3.3. *DGPS integrity*. DGPS stations permanently monitor the signals of the visible satellites and, if they detect any malfunction or failure in a satellite declared to be healthy, then they eliminate it from the navigation solution and flag that satellite's number in the appropriate RTCM-SC 104 message. Detection of bad data from a healthy satellite takes approximately 10 seconds, and broadcast of the appropriate warning is done in 5 seconds at 100 bps or 2·5 seconds at 200 bps. DGPS mobile receivers may be configured not to use uncorrected (or unhealthy) satellites in their differentially corrected positioning solutions, thus incorporating an inherent integrity check and giving users a high degree of confidence in the position.

The IALA Radionavigation Committee warned that 'the cessation of SA does not remove the integrity issue: GPS can give erroneous information for periods of up to a few hours without warning'. (RNAV/14/5/3, 2000).

4. OTHER PROBLEMS OF GPS AND POSSIBLE BENEFITS OF DGPS.

The benefits of DGPS discussed so far have been mainly in terms of accuracy and integrity. However, the benefits of DGPS for mariners are not restricted to just better accuracy and integrity. DGPS offers more advantages, overcoming or attenuating other problems of GPS, namely bad visibility of satellites in certain areas and susceptibility to solar disturbances.

4.1. *Visibility of satellites.* The current GPS constellation (May 2001) is composed of 29 operational satellites, but in certain areas at certain times, insufficient satellites will be in view to ensure low Dilution of Precision (DOP). The number of visible satellites may be restricted in coastal waters by mountains and when in harbour by large structures and buildings, which can reduce stand-alone GPS performance below acceptable levels. Periodic maintenance and manoeuvres, namely maintenance of the caesium clocks and repositioning manoeuvres, may also reduce the number of available satellites for periods of some hours, with the resulting gaps extending over large geographical areas. In restricted and congested areas, vessels need frequent and highly accurate position information, particularly large vessels, given their inability to manoeuvre quickly. Therefore, temporary loss of satellites may degrade positioning accuracy.

With few Lines of Position (LOP), each one has a larger contribution to the positioning solution and the accuracy of the individual LOPs becomes more critical. With 8 or more satellites visible, if 1 or 2 LOPs have larger than expected errors, they are smoothed by the weighted positioning solution. With only 3 or 4 satellites visible, which may well be the case inside harbours, the errors of each LOP have a larger impact on the positioning accuracy. Therefore, if a reduced number of satellites is visible, then the application of differential corrections to their pseudo-range measurements improves the quality of each LOP resulting in a much better quality fix.

Maritime DGPS networks comply with RTCM standards, which require that Reference Stations have pseudorange correction accuracy better than 35 cm (rms). Thus, each individual differential LOP is highly accurate (better that 35 cm, ignoring spatial decorrelation), which means that it will be possible to have good quality fixes even with a small number of DGPS LOPs. Therefore, the accuracy improvement of DGPS is more apparent in areas of low visibility of satellites.

4.2. *Ionospheric disturbances.* The ionosphere is a shell of electrically charged particles, which owes its existence primarily to ultraviolet radiation from the sun. It causes a delay in the propagation of GPS signals, which varies continually in response to changes in solar radiation. With the termination of SA, ionospheric delay is the major source of GPS errors, introducing range errors varying from less than one metre to tens of metres, depending on time of day, season, location of the receiver and solar activity.

While some geodetic GPS receivers employ mathematical models (generally the Klobuchar model) to correct for the ionospheric delay, marine navigation receivers do not compensate for it. The situation may be particularly significant during the peaks of the solar cycle, as is the case now, when increased sunspot activity augments the number of energetic particles on the upper atmosphere causing abnormal delays and, consequently, range errors that may reach 100 metres (IALA, 2000). Ionospheric disturbances can occur on occasions other than peaks of the solar cycle and can increase the propagation delay suffered in the ionosphere significantly, causing relatively large positioning errors on single frequency GPS receivers, such as the those used for marine navigation.

Ionospheric errors are almost completely compensated by the differential technique for users near the DGPS Reference Station, because the respective signal paths from the satellites are sufficiently close. Even during solar maxima, when the positioning errors are the highest, the compensation is almost complete. Therefore, maritime DGPS avoids, or at least attenuates, the impact of solar disturbances on marine navigation.

5. CONCLUSIONS.

In terms of accuracy, it is clear that DGPS no longer has the dramatic benefit that it used to before SA was discontinued. Nevertheless, and despite the significant improvement in its accuracy, stand-alone GPS is not yet sufficient to comply with some accuracy requirements, namely for navigation in pilotage waters. The main benefit of DGPS for mariners is the integrity, which gives mariners the assurance that the position they are using is correct. Stand-alone GPS does not offer adequate built-in integrity to its users and the use of DGPS stations enables the timely warning of any satellite anomalies.

With the termination of SA, DGPS broadcasts will also be able to improve their services by reducing the susceptibility to interference, increasing the coverage and transmitting safety of navigation and meteorological messages. In the future, the addition of new messages containing phase corrections will allow sub-metre accuracies to be achieved.

While integrity is now the main justification for DGPS, there are some occasions when the accuracy improvement of DGPS is more apparent and significant, namely when few satellites are visible, due to terrain shading, and during ionospheric disturbances (peaks of the solar cycle, severe magnetic storms, etc).

Thus, DGPS is still very useful aid for mariners and certainly the best available option.

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