Understanding GNSS availability and how it impacts maritime safety

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BIOGRAPHIES

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ABSTRACT

The General Lighthouse Authorities of the United Kingdom and Ireland (GLAs) provide marine aids-to-navigation (AtoNs) for the benefit and safety of all mariners within their waters. These AtoNs range from traditional lighthouses and buoys through to radionavigation systems, such as marine radiobeacon DGPS. It is widely recognised that Global Navigation Satellite Systems (GNSS), particularly GPS, have become the primary means of obtaining position, navigation and timing information at sea.

Mariners have been conditioned to believe that GPS is infallible, yet this is not the case. This paper reports on recent investigations by the GLAs on three specific threats to GNSS availability; namely the effects of intentional interference and GPS jamming, the impact of a reduced number of available satellites and finally the effect of space weather.

Over the past few years the GLAs have conducted a number of GPS jamming trials, investigating the effect of GPS service denial on a number of GLA vessels, their bridge systems and also on the GLAs' own AtoNs.

The implications of jamming can be severe, particularly when the strength of the jamming signal is comparable to the true GPS signal. During such conditions, hazardously misleading information (HMI) has been observed. Moreover, GPS service denial results in multiple alarms and the simultaneous failure of many bridge systems including the ship's radar, gyro-compass and Automatic Identification System (AIS). It is nowadays taken for granted by mariners that these systems provide accurate situational awareness, and are often regarded as the backup upon which to rely in the event of GNSS failure, and yet they are themselves vulnerable to the failure of GNSS. This paper also considers the impact of the 2009 US Government Accountability Office (GAO) report which predicts 'significant challenges in sustaining and upgrading

widely used capabilities' of GPS due to the struggle to meet launch schedules for GPS IIR replacement and IIF follow-on satellites. The GAO report concluded that the probability of maintaining a constellation of at least 24 useable GPS satellites would fall below 80% by 2011 and that this probability would not return consistently above 95% until 2015. More recent GAO predictions in September 2010 indicate (with 95% confidence) that the number of satellites should not fall below 24 in the medium term, but concerns remain over the effects of satellite ageing and the rate of replacement.

The paper reports on the results of initial investigations into the effects of a reduced GPS constellation on maritime GPS-based navigation. Navigation accuracy performance may be significantly impaired, with the receiver output position being lost or, observed to freeze during prolonged GPS outages. In such conditions there is again the possibility of hazardously misleading information being produced by the ship's navigation system and this could pose a real threat to maritime navigation.

In a time when GPS jamming units are becoming more common, when satellite constellations are changing and as we approach the solar maximum in 2013, understanding GNSS availability and its effects is crucial to maintaining safe navigation.

INTRODUCTION

The General Lighthouse Authorities of the United Kingdom and Ireland (GLAs) comprise Trinity House, The Commissioners of Irish Lights and The Northern Lighthouse Board. Between them, they have the statutory responsibility to provide marine Aids-to-Navigation (AtoNs) around the coast of England and Wales, all of Ireland and Scotland, respectively.

Today, the primary means of Positioning, Navigation and Timing (PNT) being employed in maritime applications is GPS; whether stand-alone or augmented, and the vulnerabilities of GPS are well known [1].

However, many users are conditioned to believe that GPS will always be available, which is simply not the case. GNSS availability can be affected in a number of ways, through events or conditions that affect the constellation health, the signal-in-space or the reception of that signal.

This paper considers three specific threats and reports on how they may affect maritime safety. The three threats considered are:

- GNSS interference and jamming;
- Constellation availability; and
- Space Weather events.

GNSS INTERFERENCE AND JAMMING

There has been a marked increase in both the use, and the availability of GPS jamming equipment in recent years [2]. The implications are that jamming units may find their way onto ferries and around ports/harbours where they will interfere with the many systems utilising GPS; thus affecting maritime safety.

GPS jamming units are widely available on the Internet with current models already capable of jamming L1, L2 and L5 signals, so while this paper reports on the jamming of GPS, all GNSS constellations would be affected in a similar manner.

In order to understand the effects of jamming and GPS service denial on the safety of maritime navigation the GLAs have, to date, conducted two jamming trials. These trials were conducted in collaboration with the UK Government's Ministry of Defence (MOD) who provided and operated the GPS jamming units. For the safety of all GPS users, and in line with MOD regulations for the peacetime use of GPS jamming units, notice was given to all national bodies. In addition, the GLAs issued Notices to Mariners (NtM) explaining that AtoNs using GPS in the vicinity of the trials location, would be unreliable during the jamming periods.

Flamborough Head Trial

The first jamming trial was conducted off the East coast of the United Kingdom near to Flamborough Head. The aim of this trial was to understand the effect GPS jamming may have on ship-borne and shore-based equipment, GLA AtoNs and also on the crew.

For the trial, the Northern Lighthouse Board vessel *Pole Star* steamed between two known waypoints, through an area affected by the jamming signal. Data was recorded from two typical marine grade GPS receivers which were installed on the vessel, along with an eLoran receiver which was used to provide the true position throughout the trial.

From the results three distinct states were identified, which are defined in Table 1. These states correspond to the manner in which GPS fed equipment responded to jamming conditions. When the jamming signal was sufficiently strong to prevent reception of the signals from the GPS satellites, a large number of alarms sounded on the bridge almost simultaneously, providing a potentially disconcerting and confusing environment for the mariner. However, the effect that represented the highest risk was the provision of erroneous data from some GPS receivers.

Figure 1 provides a comparison of an erroneous position reported by a typical marine grade GPS receiver, with the vessel's true location provided by the eLoran receiver. In this figure, the light blue line shows the path taken between the two waypoints.

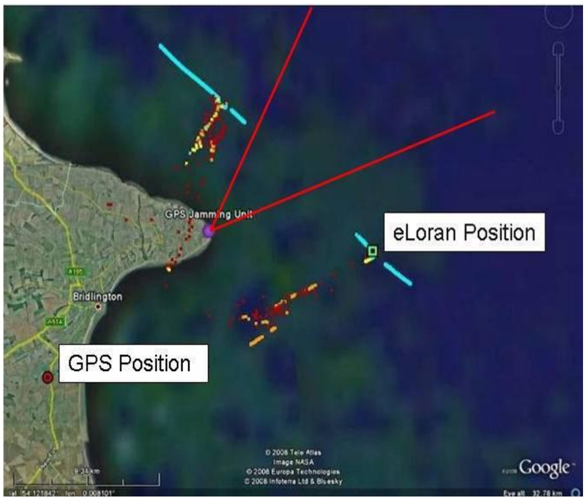

Figure 1: Google Earth™ Plot showing the reported positions from one of the typical marine grade receivers installed on the vessel. An erroneous GPS position (red circle) is compared to the corresponding eLoran position (green square). The GPS position is reported as being inland 22km west from the true eLoran position. (Red lines indicate the boundaries of the main lobe of the jamming unit and position colours indicate reported speed: blue<15knots, yellow< 50knots, orange <100knots and red >100knots).

The colours of the plotted position points in the figure provide an indication of the speed of the vessel. The three states described in Table 1 can be seen.

State 1 is observed at either end of the passage where the solid blue line occurs; this is where the jamming signal strength is much lower than the GPS signal strength and the GPS fed systems are operating normally.

As the vessel approached the main lobe of the jamming signal, indicated by the red lines, it reached an area where the jamming signal was comparable with the received GPS signals, leading to State 2. During this state erroneous data can be observed with the receiver reporting the vessel on land travelling at high speed.

As the vessel entered the main lobe of the jamming signal State 3 was observed. .

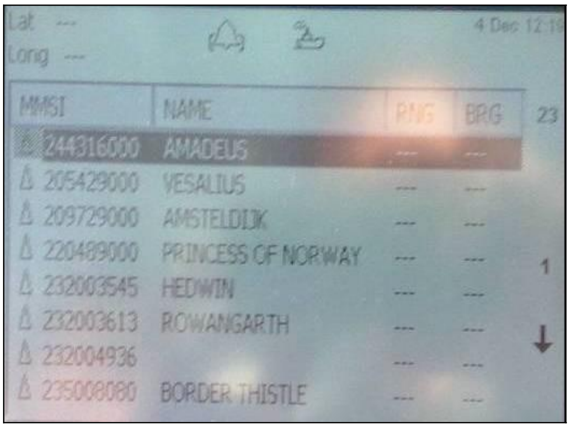

Figure 2: The effect of GPS denial on a typical AIS unit. The loss of the vessel's position prevents the unit from calculating a range (RNG) or bearing (BRG) to near-by vessels. This greatly affects the situational awareness of the crew.

This is where the GPS signals were swamped by the jamming signal and the receivers failed to provide an output. Then, as the vessel continued the passage out of the jamming area, one can observe the change in states as the ratios of jamming to GPS satellite signals decrease and GPS is reacquired.

In the worst case, during this particular passage, the GPS receiver reported a position some 22km away from the true location. The GPS receiver nevertheless declared the position valid. This position was made worse by the fact it was reported inland at a speed of over 100knots while the trial vessel steamed steadily at 10knots. Depending on how the resulting GPS positioning data is used, it could feasibly result in vessels changing course, through the use of an autopilot, and it could also affect the vessel's reported position to the outside world. This would then not only affect the vessel's situational awareness but also the situational awareness of vessels in the vicinity.

The errors observed in Figure 1 were also seen on the vessel equipment fed by the onboard GPS receivers. Erroneous positions were observed on the vessel's Electronic Chart Display and Information System (ECDIS), on the Automatic Identification System (AIS) positions (Figure 2) and on the vessel's Radar (Figure 3).

State	Ratio of signal strengths	Observed result
1	Jamming signal << GPS signals	Normal operation
2	Jamming signal ≈ GPS signals	GPS fed equipment provides erroneous information, some of which is hazardously misleading.
3	Jamming signal >> GPS signals	GPS denied and equipment fails to provide PNT information.

Table 1: Table describing the effects observed for the three states identified from the results of the 2008 trials.

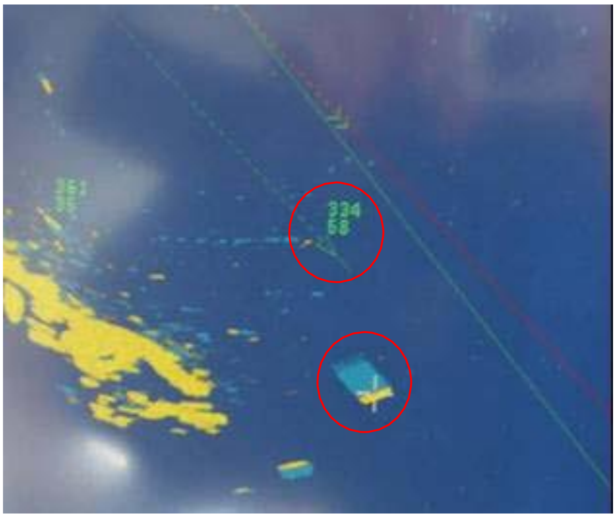

Figure 3: Erroneous AIS positions reported on the radar onboard NLV *Pole Star*. The bottom circle highlights the radar return for a nearby vessel, while the top circle highlights the reported AIS position for that vessel, which is clearly reporting an erroneous GPS position caused by jamming.

The results observed during these trials gave an important example of what can happen to onboard equipment as well as the impact it can have on the mariner during periods of GPS jamming and service denial. It is clear that GPS denial caused by jamming can not only prevent PNT information from being calculated, it can also result in erroneous data being presented to the mariner.

Newcastle Demonstrations

Following the success of the 2008 trials, a series of demonstrations was conducted off Newcastle-upon-Tyne, on the North East coast of England.

These demonstrations were held to communicate the importance of resilient PNT to a selected audience. The audience included a number of key decision makers from European and UK Governments, maritime industry, mariners and other aids-to-navigation service providers and the demonstrations allowed them to observe the effects of GPS jamming first hand. The demonstrations took place onboard the Trinity House Vessel *Galatea*.

For this trial, the GPS jamming unit was installed onboard the *Galatea* and configured to jam GPS within a small area around the vessel. As before, two typical marine grade GPS receivers were installed along with an eLoran receiver; however for this trial a modified electronic chart display was also installed. This electronic chart display was altered to enable two position inputs to be displayed at the same time and was used to compare the reported GPS and eLoran positions in real-time.

Figure 4: The vessel's VHF transceiver provides an audible and visual alarm when GPS is not available.

Throughout the demonstrations differential Loran (dLoran) corrections were provided using a transportable reference station installed on the shore at South Shields

The reference station was used to mitigate the impact of temporal variations on the eLoran position. Differential-Loran corrections were generated by the reference station, which were sent to the GLAs' eLoran transmitter in Cumbria for inclusion in the eLoran Loran Data Channel (LDC) broadcast. The eLoran receiver on the vessel received the broadcast and was able to extract and apply the corrections in order to obtain an eLoran position within 9m (95%).

Demonstration Scenarios

Two scenarios were used in the demonstrations. The first was the sudden effect of a strong jamming signal, designed to simulate a jamming unit being brought onto a ferry or other vessel. This took the vessel's equipment directly to State 3; the complete loss of GPS information with a large number of alarms sounding on the bridge. The loss of GPS information prevented the *Galatea's* AIS and VHF units (Figure 4), amongst other systems, from operating correctly.

Before the second scenario was conducted, the jamming unit was stopped and all of the GPS receivers integrated into the bridge equipment were allowed to reacquire satellites and fully recover. The second scenario was designed to reflect a vessel steaming towards a jamming source. The field strength of the jamming signal was slowly increased until State 2 was observed, with erroneous and often hazardously misleading information reported.

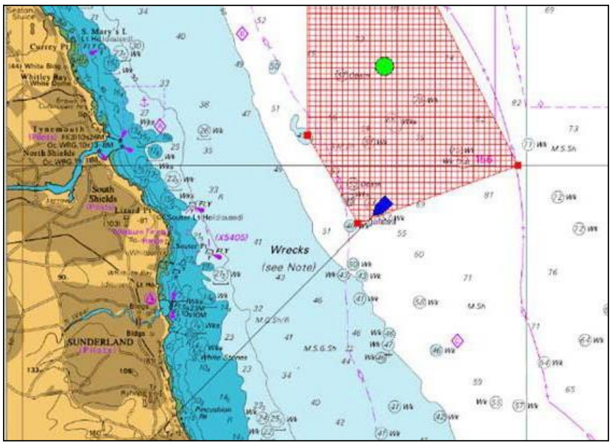

Figure 5: A screen shot of the modified electronic chart showing two positions reported from the demonstration vessel. The green dot is the eloran position and shows the true location of the vessel within the jamming area (red hatched box). The blue vessel icon is the erroneously reported GPS position. The line emerging from the icon is an indication of the reported speed, which was given as over 700 knots.

As with the trials in 2008, erroneous GPS positions reporting unfeasibly high speeds were observed as shown in Figure 5. However, significantly more subtle errors were seen; errors where the vessels reported position differed *only very slightly* from the true location and wandered around slowly. It is these subtle changes, with believable positions which result in hazardously misleading information (HMI). While the overall result of GPS jamming on the *Galatea* was consistent with that observed on the *Pole Star*, there were a few marked exceptions.

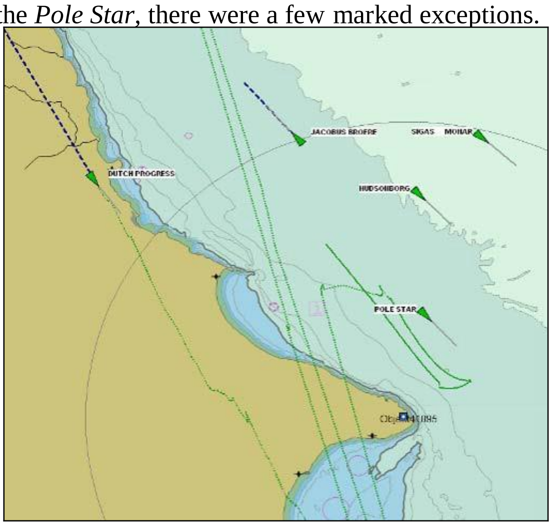

Figure 6: Vessel traffic image from AIS monitored by the Maritime and Coastguard Agency (MCA) AIS station at Flamborough Head during the 2008 trial. The effect of GPS jamming can be seen on the erroneous positions reported by the trial vessel *NLB Pole Star* (centre right) and also on the vessel *Dutch Progress* (top left).

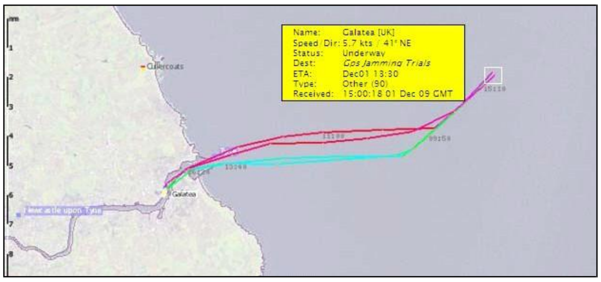

Figure 7: Reported AIS positions of THV *Galatea* from one day of the GPS jamming demonstrations in December 2009. The trace shows the reported positions in and out of port but shows that the vessel's AIS unit failed safe and did not report any erroneous positions. (Image from www.shipais.com)

The ECDIS onboard the *Pole Star* reported erroneous positions and ultimately failed with the complete denial of GPS. However the ECDIS on the *Galatea* continued to track the vessel's position due to an additional position feed from the vessel's gyro, making it more resilient to jamming, but only in the short term until the gyro requires re-calibration. This is carried out with its built-in GPS receiver!

In addition, the AIS transceiver on the *Pole Star* reported the vessel's position erroneously due to jamming, and this was observed at shore based traffic monitoring stations. Figure 6 shows a screenshot of a vessel traffic monitoring system provided by the Maritime and Coastguard Agency (MCA) during the 2008 trials and clearly shows the erroneous positions reported by the *Pole Star's* AIS transceiver.

During the demonstrations on the *Galatea*, the AIS transceiver did not provide any erroneous position information, as can be seen in Figure 7. These differences show that the impact of GPS jamming will be different for each vessel and depends on the model, installation and configuration of the onboard systems.

EFFECT OF JAMMING ON SAFE NAVIGATION

In order to navigate safely, the mariner needs to have reliable, clear and trusted information about where they are and what is going on around them so that any threat can be located and identified. While consideration is often given to threats such as areas of shallow water, obstacles or other vessels; consideration is not generally given to the loss of positional information, timing or situational awareness.

Loss of GPS derived PNT information at sea results in the loss of the vessel's ECDIS, AIS, GPS and DGPS receivers preventing the mariner from being able to position themselves and those around them through what are nowadays regarded as the normal means. In addition, the systems one would normally expect to be independent from GPS, and as such available for use in GPS denied conditions, are also affected; namely the vessel's radar and gyro-compass.

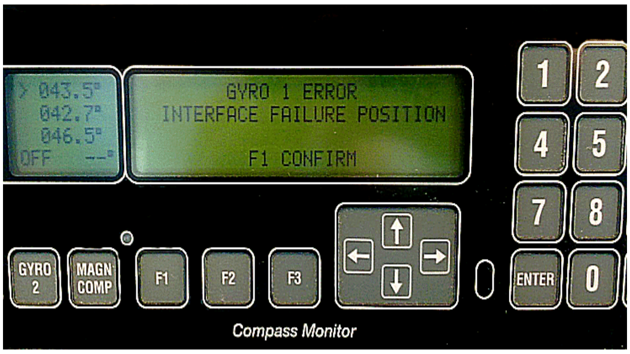

Figure 8 : Photograph of the gyro-compass in an alarm mode following the loss of GPS.

The radar takes a GPS input to provide a "North-up" setting and the gyro-compass uses GPS to stabilise drift error. Under GPS denial conditions these units also enter an alarm state and should not therefore be used (Figure 8).

Clearly GPS jamming can significantly affect the safety of mariners. From these trials it can be seen that the extent of the impact varies from vessel to vessel depending on the equipment installed and the configuration selected.

SATELLITE CONSTELLATION

From the users' perspective, GNSS availability is the percentage of time they can receive usable data from sufficient satellites in order to calculate their position. The reduction in the number of available satellites in the constellation will have a direct impact on the system's availability.

A report from the US Government Accountability Office (GAO) in 2009 predicted *"significant challenges in sustaining and upgrading widely used [GPS] capabilities"* due to delays in launching modernised GPS satellites. They reported the probability of maintaining a constellation of at least 24 useable GPS satellites could reduce to 80% or less by 2011, and not return to 95% probability consistently until 2015, as shown in Figure 9. This could lead to reduced satellite numbers causing coverage "windows" where less than 4 satellites could be observed and as such reduced GPS availability [3].

A later report by the GAO [4] indicates that the probability of maintaining a constellation of at least 24 operational GPS satellites is now expected to be 95% for the foreseeable future. This figure is based on the current launch schedule and although the US Air Force Space Command (AFSPC) have provided reassurances, the satellite launch programme has in recent years experienced delays and therefore the risk of reduced satellite availability still remains.

Following the 2009 report, the GLAs commissioned a study to investigate the impact a reduced GPS constellation would have on users in their waters [5].

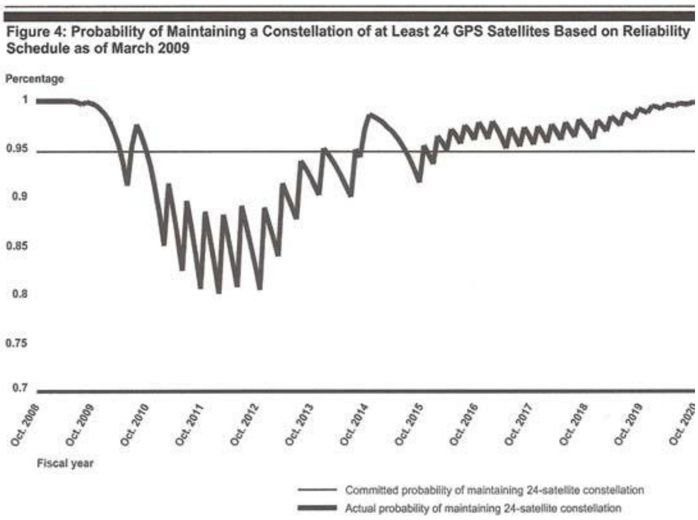

Figure 9: *GAO Probability of Maintaining a Full GPS Constellation [3]*

This study was conducted by the GNSS Research and Applications Centre of Excellence (GRACE) and was split into two parts. The first part was to analyse the impact theoretically and found that with a 21 satellite constellation, GPS coverage "windows" (e.g. <4 satellites) could last for several minutes and cover a large proportion of the UK and Ireland (Figure 10). This can cause reduced GPS availability and therefore increased likelihood of position errors affecting maritime safety.

The second part of the study investigated the effects further through a dynamic simulation, investigating the effects should a vessel be positioned off the coast of Belfast during one of the coverage "windows'. For this a marine grade GPS receiver and a simulator were used to observe the effects. The study found that the number of available satellites fell below four for several minutes and the reported position data from the receiver appeared to freeze for up to 10 minutes.

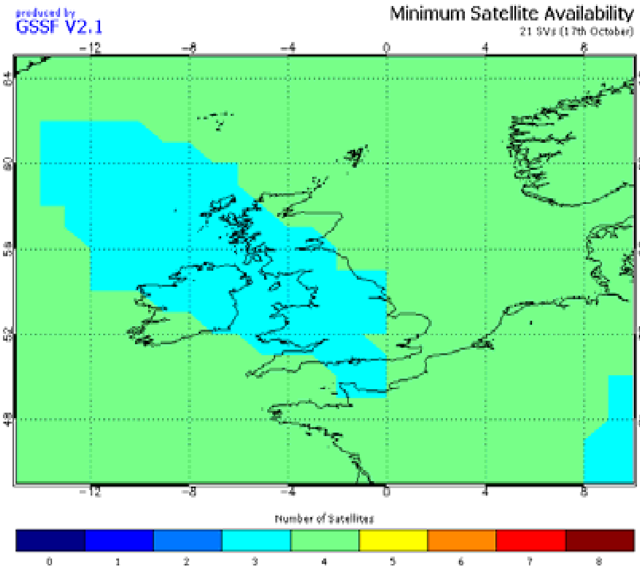

Figure 10: *Three-satellite window over Belfast (October 2009, 21-satellite constellation) [5]*

If a mariner was traveling at a speed of 35 knots when the position input froze, their reported position would be in error by 10km from an outage lasting 10 minutes. These outages are significant and mariners need to be informed of such risks to GPS (and GNSS in the future) before they occur, so they are prepared for any disruptions.

SPACE WEATHER

Space weather events are a particular concern to GNSS availability due to their random nature. It is known that GNSS signals are delayed proportionally to the number of free ions as they propagate through the Earth's atmosphere en-route to the receiver. The amount of ions in the ionosphere is referred to as the Total Electron Count (TEC). TEC is dependant on time of day, latitude and solar activity, among other factors [6]. During high solar activity the number of ions in the atmosphere is much higher than at any other time. The greater the signal delay, the larger the errors are in the satellite's pseudorange and hence the position error can be significant.

Variation in electron density along the GNSS signal path causes signal refraction which produces *'phase scintillation'*, introducing group delay that may cause large errors in the pseudorange measurement. Diffraction of the signal wave front induces *'amplitude scintillation'* - variations in signal amplitude – with strong fades possible leading to a GNSS receiver losing signal tracking and at worst the GNSS navigation solution may be lost.

Solar activity is cyclical, peaking at a maximum approximately every 11 years, during which periods GNSS performance can be severely degraded, especially at equatorial, auroral and polar latitudes. The next solar maximum is predicted to occur during 2013, as depicted by National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) forecast in Figure 11 [7].

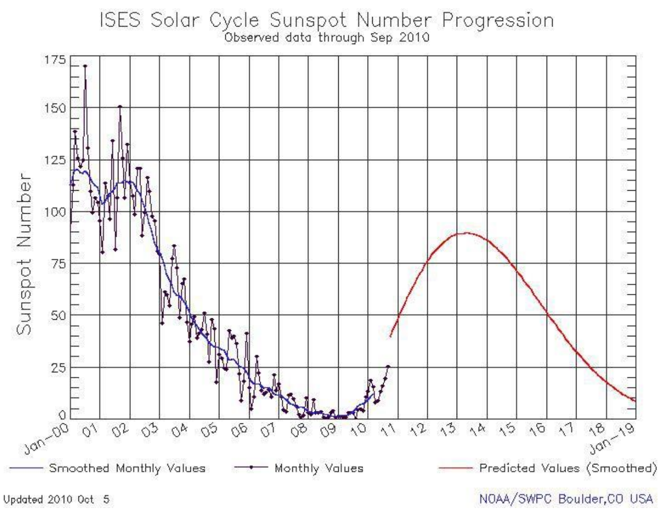

Figure 11: *Predicted solar sunspot activity using observed data up to September 2010. The solar maximum is forecast to occur in May 2013 [7].*

During quiescent periods of solar activity, ionospheric effects on GNSS can be managed such that the residual errors caused by the ionosphere do not generally pose a problem to maritime navigation performance.

The GLAs' DGPS corrections significantly reduce common mode errors, including the effects of the ionosphere. However, at the peak of the solar cycle with high levels of sunspot activity, solar storms and flares, the application of ionospheric models and differential corrections may be less effective and this could increase position errors and introduce an integrity risk to maritime navigation.

Maritime navigation systems and services that rely on GNSS are at greatest risk of disruption from the ionosphere during the period from 2011 to 2015. Even during a quiet solar maximum, the occurrence of individual sun spots could give rise to significant effects for discrete events. The effects vary with latitude, season and time of day (the hours soon after sunset being most affected).

Space weather events have the potential to affect GNSS availability, either by affecting the performance of the satellites themselves or by preventing signal reception.

MITIGATION

In general there are a number of steps that can be taken to help reduce the impact of these threats:

- Increase awareness of GNSS vulnerabilities,
- Detecting incidents and warn the mariner when they occur.
- Prevent incidents from occurring, where possible, through legislation and enforcement
- Reduce as much as possible the effects of incidents when they occur, through the 'hardening' of GNSS technology.
- Have alternative means of PNT, independent of GNSS.

Understanding that these threats exist and knowledge of what disruption they may cause is the first step to mitigating their effect, but this does not stop it happening. Being able to identify that an event is occurring and that the data being received from the receiver may not be true is an important part of mitigating the effects.

For jamming issues specifically, the use of GPS jamming units is illegal in the UK and Ireland, however preventing them from being used is very difficult to achieve. Jamming units are small and easily hidden; however port side security and vessel security procedures should prevent jamming units from being used in these locations. It is a different case, however, to prevent a jamming unit from being used at a coastal location or headland due to the remote nature of these areas.

Mitigating the effect of jamming can be achieved in a number of ways; by limiting the effect within the receiver by using anti-jamming techniques, or by hardening GNSS receivers [8, 9]. Ultimately the best mitigating activity is to not rely on GNSS PNT once the integrity of the data has been compromised.

For space weather events or cases of reduced satellite numbers, there is very little action the mariner can take to remedy the problem or stop it happening. The mitigating action here is one of awareness, information forewarning the mariner that such a condition is imminent for example.

Monitoring and detection networks can assist in providing such notifications and real-time information on GNSS problems. The need for such a network across the UK and Ireland is the subject of a different GLA publication [10], but the GLAs support the discussion on a body to monitor GNSS performance and to take the lead in the dissemination of key information.

For periods where GNSS availability has been affected by mutual interference, jamming, space weather events or constellation issues, the best mitigating action is to use PNT information from a second source, one with dissimilar failure modes.

Mariners need to be prepared for GNSS failures and have access to PNT information through dissimilar systems. In addition, procedures covering what to do in the case of GNSS unavailability should also be provided and rehearsed. It is with this view that the GLAs firmly promote the use of all available means of navigation.

CONCLUSIONS

This paper has reviewed three threats to GNSS availability and concluded that all three could affect maritime safety.

The GLA jamming trials have shown that GPS jamming can significantly affect the safety of maritime navigation. The two trials observed the presentation to the mariner of erroneous data, some of which could be considered hazardously misleading along with the degradation of crews' situational awareness.

The main effects observed were:

- The presentation of random errors leading to hazardously misleading information (HMI) which could, depending on installation, cause a vessel to move off course.
- The presentation of erroneous and potentially misleading data to other vessels and shore based infrastructure.
- The sheer number of alarms on the bridge of the vessel could be disconcerting and distracting for the mariner.
- The loss of GPS fed systems, which can create an unfamiliar bridge situation and remove safety critical systems from operation.
- The identification that a large number of bridge systems are integrated with GPS and enter an alarm state during periods of GPS outage.

The loss of GPS or a lack of integrity in the reported information leads to an unfamiliar situation on the bridge. The crews of the *Pole Star* and the *Galatea* were expecting to lose GPS, were well-trained and had primed other systems so they could navigate safely. In real life there would be no advance notice and the impact on the crew would be more severe.

The impact of low satellite numbers, as predicted in the 2008 GAO report, could result in poor constellation availability and a loss of PNT information for a considerable period of time. This could result in the same outcome as observed in the GPS jamming trials when entering State 3, where many systems on the bridge failed and entered an alarm condition.

Space weather events are difficult to predict both in terms of when they may occur and their severity. Events could affect satellite positions, their operation and the reception of their signals by the user and are clearly a threat.

The GLAs strongly support the need for a resilient PNT solution, one that could continue to provide reliable information during such threats for the safety and benefit of all mariners.

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