## Reliable GPS: Interference, Jamming and the Case for eLoran

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## Abstract

The Global Positioning System (GPS) is the primary source of Position, Navigation and Timing (PNT) information in maritime applications, whether stand-alone or augmented with additional systems. This situation will continue in the future with GPS, together with other GNSS, being the core PNT technology for e-Navigation. GPS is vulnerable. Its signals, measured at the surface of the earth, are very weak. As such, the system is susceptible to jamming and unintentional interference, resulting in the possible denial of the service in large geographical areas. The result of such interference could be the complete failure of the mariner's GPS receiver or, possibly worse, the presentation to the mariner of hazardously misleading information depending on how the GPS receiver reacts to the jamming incident.

Recognising this, the General Lighthouse Authorities of the United Kingdom and Ireland (GLAs) in collaboration with the UK Ministry of Defence's Defence Science and Technology Laboratory (DSTL), have conducted a series of sea-trials with the aim of identifying the full effects of GPS jamming on safe navigation at sea.

The full scope of the work aims to perform several important investigations and analyses of the effects of GPS jamming. The following systems were investigated to see how they are affected by GPS jamming:

- Typical marine grade Differential-GPS (DGPS) receivers
- eLoran
- The GLAs' DGPS service including the GLAs' operating procedures when a DGPS station is affected by disruptions to GPS
- Automatic Identification System
- Synchronised lights

This paper presents the key findings of these trials and provides important information on the effect of GPS denial. The GLAs are playing a pivotal role in the establishment of eLoran as an independent source of PNT, taking advantage of eLoran's complementary nature in having dissimilar failure modes to GPS and other the future GNSS. As such, this paper provides information on the performance of an eLoran receiver in an area of GPS service denial.

1. INTRODUCTION. The General Lighthouse Authorities of the United Kingdom and Ireland (GLA) 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 Irelandand Scotland, respectively.

Today, the primary means of Positioning, Navigation and Timing (PNT) being employed in maritime applications is GPS; whether stand-alone or augmented. The vulnerabilities of GPS are well known [1], as the signals are so weak on reception, they are susceptible to interference, whether intentional or not. As such the GLAs are keen to understand the effectiveness of their Aids to Navigation (AtoNs), and the navigation systems being employed by mariners within their waters, under conditions of GPS service denial. The GLAs promote the use of diverse means of navigation and, as such, are playing a pivotal role in the establishment of eLoran as an independent source of PNT, which demonstrates dissimilar failure modes to GNSS [2].

This paper details the approach and results of a trial conducted in collaboration with the UK Government's Defence Science and Technology Laboratory (DSTL). This organisation, which is part of the UK's Ministry of Defence provided and operated the GPS jamming equipment under peacetime regulations. It is important to understand that the effects of GPS jamming identified in this paper are also an indication of the behaviour of navigation systems affected through *unintentional* interference.

**1.1 Context.** It is important to put these trials in context. The GLAs value highly the operational and safety benefits of GPS and it is a vital component in our Radio Navigation Plan [3]. GPS will remain the primary radio navigation means of position fixing from berth-to-berth for at least another ten years, and indeed it is a primary source of Position, Navigation and Time (PNT). However, the introduction of GPS has encouraged mariners to navigate in areas where, and under conditions in which, they had not previously ventured and the introduction of e-Navigation will

further change the way that ships operate. As part of this, we need to understand what happens when key e-Navigation components (e.g. GNSS) are unavailable

**1.2 Issue of Notices.** In order to ensure the safety of mariners during the period of intentional GPS service denial, notice was given to all national bodies in line with the Ministry of Defence (MOD) regulations for the peacetime use of GPS jamming units. In addition, the GLAs issued a Notice to Mariners (NtM) explaining that the service provided by Flamborough Head DGPS reference station would be unreliable for the period of the trial.

2. TRIAL METHODOLOGY. The trial was conducted over several days during April 2008 at Flamborough Head lighthouse, off the North Yorkshire coast of the United Kingdom. DSTL provided a professional low-to-medium power jammer, which was controlled remotely by two VHF transceivers. The jammer transmitted a known pseudo-random noise code, with an effective radiated power (ERP) of approximately 1.5W (2dbW) over the 2MHz bandwidth of the civilian GPS L1 frequency. This unit was used with either a directional antenna or an omni-directional antenna depending on the test being conducted. Figure 1 shows the jammer unit with an omnidirectional antenna attached. Two days of the trial were devoted to dynamic trials onboard a GLA Buoy Tender and one day was devoted to static trials at Flamborough Head. Each trial was designed to test different facets of safe navigation, described next.

**2.1 Facets Tested.** The trial was designed to test multiple facets of safe navigation, and was split into dynamic trials and static trials.

The *dynamic* trials took place aboard the Northern Lighthouse Board vessel *NLV Pole Star* and included investigations of the effects of GPS jamming on:

- DGPS based navigation
- eLoran performance
- Shipborne Automatic Identification System
  (AIS) equipment
- VHF Digital Selective Calling unit
- Vessel crew and bridge workload

The *static* trials took place at Flamborough Head lighthouse and included the following investigations of the effects of GPS jamming on GLA AtoN provision:

- Radiobeacon Differential-GPS service
- Synchronised lights

Section 3 and 4 discuss the dynamic trials and results, while Section 5 presents the static trials and results.



Figure 1: Main GPS jammer unit at Flamborough Head, shown with an omni-directional antenna



Figure 2 - A simple 10Nm long route between two waypoints.



Figure 3 : Coverage area of the GPS jamming unit at 25m above ground level on maximum power of 1.58W ERP. (Image courtesy of DSTL)

**3. DYNAMIC TRIAL SETUP.** A simple sailing route was designed as shown in Figure 2. Its length was 10Nm and it was designed so that the vessel's passage dissected both the main lobe of

the GPS jammer and two side lobes. The vessel steered a course back and forth between the two waypoints travelling at 10kt, meaning each run along the route had a duration of 1 hour. The waypoints were positioned beyond the jamming region to enable the various GPS enabled units aboard the ship to reacquire GPS satellites. Figure 3 shows the modelled coverage of the main lobe of the signal from the GPS jamming unit, and Figure 4 shows a navigation chart with the approximate coverage regions of the side-lobes (grey hashed area) and main lobe (red hashed area) overlaid. The eLoran receiver output was fed into charting software displaying this chart on a laptop PC during the trials. This served as visual confirmation of eLoran's performance during the trial, and served as a "ground truth" system during periods of GPS jamming.



Figure 4 - Approximate regions encompassing main lobe (red) and side lobes (grey).

For the duration of the dynamic trials the jamming unit was set on a constant power, although it was disabled when not required for example between jamming runs. A total of 8 runs were performed over two days of dynamic trials.

3.1 Navigating Without GPS. During the dynamic trial it was planned that the vessel would lose its GPS positioning capability and in order to maintain a true, repeatable, passage the vessel's crew employed radar navigation using the parallel indexing technique. Parallel indexing is an advanced navigation technique mainly used to keep a safe distance from a navigational hazard, for example shoreline, rocks. and other geographical features represented on the radar screen. The navigator draws a line on the screen that is connected to several conspicuous radar returns and is parallel to the ship's intended course but offset to the left or right by a certain distance.

The navigator maintains course by manoeuvring to keep a constant distance from this line. Parallel indexing fixes the position in only one dimension, and its accuracy is dependent on the radar calibration, the radar range scale in use, and the radar conspicuity of the selected targets. A skilled mariner should be able to maintain a cross-track error of about 30m using this technique [9].

As already mentioned, the eLoran input to charting software was separate to the vessel's navigation system and this served as confirmation of the vessel's location during jamming periods.

**4. DYNAMIC TRIAL RESULTS.** This section presents the details and results of the dynamic trial, discussing the dynamic trial facets outlined in Section 2.2.

**4.1 GPS and Differential GPS Receivers.** For the purposes of the trial three additional receivers were installed on the Pole Star. Two of these were typical marine grade differential GPS receivers, the third was a more expensive dual-frequency surveying receiver (configured to operate on GPS L1 only). Due to a lack of space on the vessel's mast, the antennas for the three receivers were installed on the handrail of the main deck. This meant that there was a certain amount of sky obscuration due to the vessel's superstructure. Each receiver was connected to a laptop PC and National Marine Electronics Association (NMEA) data were recorded from them throughout the jamming trial.

Over the course of the dynamic trials the receivers were monitored and all of them lost GPS lock. The two differential receivers maintained lock on the medium frequency broadcast from the nearby Flamborough Head DGPS reference station. However, this reference station was also affected by the jamming signal. Because of this there were no DGPS corrections to apply, and their position solution was derived from stand-alone GPS.

When processing the recorded data from the three receivers the NMEA GPRMC (Recommended Minimum Content) sentence was used as this provides the reported position, speed and time. This sentence also provides an indication of the validity of

the data, setting or clearing a flag to indicate 'valid' or 'invalid'. The decision to set or clear the data valid flag is one that is made by the receiver internally. When processing the recorded data from the various receivers only data declared valid was used for display on the plots shown in this paper. What we observed was that the two marine grade receivers would typically provide erroneous positions as they entered and exited the jamming region, before GPS reception was denied entirely in the middle of the region of strongest jamming signal.

The magnitude of the position error varied between a few tens of metres and several tens of kilometres away from the true location. This means that positions that are output during periods of jamming, although erroneous, are still considered to be valid by these receivers.



Figure 5 : Google Earth™ plot of recorded positions identified as valid, with no GPS jamming unit active.

The colours are used to represent the reported vessel speed with blue <15knts, yellow< 50knts, orange <100knots and red >100knts.



Figure 6 : Google Earth™ plot of recorded positions identified as valid, with GPS jamming unit active.

The colours are used to represent the reported vessel speed with blue <15knts, yellow< 50knts, orange <100knots and red >100knts.

Figures 5 and 6 show the reported positions from one receiver, plotted in Google Earth<sup>TM</sup>. The lefthand plot is from a control run, where the jamming unit was disabled. The right-hand plot is from a run where the jamming unit was enabled and erroneous data was observed. The colour of each reported position is an indication of the reported vessel speed at that moment. Blue positions indicate a speed of less than 15 knots; yellow positions indicate a speed of between 16 and 50 knots; orange positions indicate a speed of between 51 and 100 knots and red positions indicate a reported speed of greater than 100 knots.

Figure 7 shows that the number of erroneous positions was significant, with the majority of positions incorrect and points coloured red indicating the reported speed was greater than 100 knots (the greatest reported speed was over 5000 knots). Clearly, if this data were being used as input to a navigation system, whether it was an autopilot or simply an electronic chart, the implications would be serious.

The results shown in Figure 7 were typical from the two marine grade receivers, although it was noted that the effect of jamming was more severe when sailing north, with the vessel superstructure positioned between the jamming unit and the GNSS receivers' antennas.



Figure 7: Google Earth <sup>™</sup> Plot of valid GPRMC data from one of the typical marine grade receivers with the comparison of an erroneous GPS position (red circle) against the eLoran position (green square) measured at the same time. The GPS position is reported as being inland 22Km west from the true eLoran position. (Red lines indicate main lobe of the jamming unit and position colours indicate reported speed: blue <15knts, yellow< 50knts, orange <100knots and red >100knts)

Therefore, it may be assumed that the jamming signal was attenuated due to the shadowing effect of the vessel's superstructure. This implies that the "moment of indecision", that period of time when the strength of the jamming signal was comparable with that of the GPS satellites, was greater and resulted in an increased number of erroneous positions. The more expensive survey grade receiver did not provide any erroneous data positions, rather opting to provide no position information when experiencing interference from the jamming unit. The latter is preferable in the sense that no data is better than erroneous data.

The GPS receivers used in the *Pole Star's* navigation system were also affected by the jamming signal and also reported inflated speeds, albeit to a smaller degree. The reported position on the vessel's Electronic Chart Display & Information System (ECDIS) wandered around and the reported speed also increased above the maximum speed of the vessel. However, the vessel's receiver did stop providing position information quite quickly once the vessel had passed into the jamming area. The implications of providing erroneous positions can be severe and can greatly affect the safety of the mariner and those around them.

As will be seen in the next section, the reported position from eLoran was not affected during GPS jamming and the receiver functioned as normal. Figure 7 also shows an erroneous position from one of the typical marine grade receivers compared to that from the eLoran receiver for the same moment in time. The magnitude of the position error is some 22km.

**4.2 eLoran.** The GLAs have long-recognised the dangers associated with an over-reliance on sole use GPS [2,3,4] as well as the many aspects of GPS vulnerability. e-Navigation, the future digital maritime architecture, emphasises the need for robust and resilient position navigation and time in order to reduce the impact of human error and to improve the safety, security and protection of the marine environment. The GLAs have identified the strategic benefits of having two satellite navigation systems (e.g. GPS and Galileo) as well as the importance of system diversity using eLoran.

Enhanced Loran (eLoran) is needed to mitigate the well-known vulnerabilities of GNSS, thereby securing critical infrastructure and allowing users to retain the safety, security, and economic benefits when GPS, and other GNSS services, are disrupted. The GLAs, supported by the UK Department for Transport (DfT) have invested in a 15-year contract for the provision of an eLoran service from Anthorn in Cumbria. In addition, the US government has recently selected eLoran as its national backup to GPS [5,6,7].

eLoran is an all-in-view navigation system employing pulsed groundwave radio transmissions with a centre frequency of 100kHz. The times-ofarrival (TOA) of the signals are measured by an eLoran receiver and these pseudoranges are used in a positioning algorithm in much the same manner as that employed by GPS. This trial presented an unrivalled opportunity to investigate the real-life performance of eLoran under conditions of GPS service denial.

The Loran receiver used for the trial also had a built in GPS receiver. It could produce standalone GPS, standalone Loran and integrated GPS-Loran position solutions – all at the same time. Its integrated output was based on integration in the position domain and effectively produced Loran positions that had been previously calibrated by GPS.

In operation the receiver outputs NMEA type sentences that can be read by electronic navigation software. The receiver switches automatically between five different positioning solutions depending on what services and data are available in the following precedence:

- Eurofix corrected GPS
- Stand-alone GPS
- · GPS calibrated eLoran
- Additional Secondary Factor corrected eLoran
- Stand-alone eLoran

If GPS and the Loran Data Channel Eurofix is available, the output is based on a regional area DGPS solution, and it continuously calibrates the eLoran output using this solution automatically. It then moves down this list should components disappear for some reason. So for example when jamming is activated, and GPS disappears, the receiver will operate in GPS calibrated eLoran mode having stored GPS calibration parameters earlier while GPS was operating correctly. Should those calibration parameters become invalid, or unavailable to start with, the receiver will use Additional Secondary Factor (ASF) corrected eLoran, provided ASFs have been stored in the receiver, otherwise it will default to using standalone Loran.

Since the effect of GPS jamming on the GPS calibrated mode of operation was not known, and could occur at random times depending on the automatic calibration process, ASF data were recorded during a control run when GPS jamming was not enabled. This data were stored in the receiver and as backup data files on the lap-top PC to which it was connected.

Once GPS became unavailable, or the latest GPS calibration became invalid, the receiver would then

automatically revert to using ASF corrected Loran for its positioning output. Figure 8 shows the grid of ASF data stored within the receiver.

The control run was also used determine the positioning accuracy performance of Loran off Flamborough Head. This was achieved by comparing calculated calibrated Loran positions against differential-GPS as provided by Eurofix.



-igure 8 - ASFs were measured along the trial route and stored in grid format in the receiver.

Figure 9 shows a scatter plot of the comparison of the Loran positions against the differentially corrected GPS positions. The red circle indicates a repeatable position accuracy of 8.1m(95%) with respect to DGPS with its accuracy of 1 to 2m. It was only possible to assess the accuracy of calibrated Loran in this manner as the eLoran receiver will only revert to the other positioning modes, when GPS is not available and, since the receiver was moving, DGPS was required to provide the true position. The position accuracy determined here may also be assumed to be the accuracy of 'ASF corrected eLoran' mode, since the ASF data is derived from the same GPS calibration technique and so the accuracy is the same.



Figure 9: Scatter plot showing the performance of calibrated Loran when compared to Differential GPS. Loran demonstrates an accuracy of 8.1m (95%) off Flamborough Head.



Figure 10: Two plots of eLoran data displayed in Google Earth ™. The left-hand plot is the reported positions during a control run when there was no GPS jamming. The right-hand plot shows the reported positions during a run with GPS jamming switched on. The red lines indicate the approximate boundaries of the main lobe of the GPS jamming signal. eLoran was not affected by GPS jamming.

The left-hand plot of Figure 10 shows eLoran derived position data as the vessel navigated through the jamming region with the jamming unit switched off. The right-hand plot of Figure 10 shows eLoran output with the GPS jamming unit switched on. In both cases one can clearly see the route taken between the waypoints, and eLoran is unaffected by GPS jamming. The only discrepancy between the two plots is a slight 'wave' to right-hand trace. This is due to the vessel being navigated using parallel indexing, which is significantly less accurate (being around 30m or so [9]) than GPS and eLoran.

Figure 11 shows the performance of a typical marine grade GPS unit in the left-hand plot, compared to the eLoran receiver during the same jamming run. Finally, Figure 12 shows a screenshot taken from the eLoran chart display software live during one of the trial runs. The vessel is in the centre of the main beam (the point of strongest signal along the passage) of the jamming signal and eLoran continues to provide positions. Clearly the performance of eLoran is not affected by GPS jamming. This trial justifies and confirms the GLAs eLoran strategy.



Figure 11 – GPS performance (left-hand plot) and eLoran performance (right-hand plot) during the same jamming run.



Figure 12- Live screenshot of navigation chart showing vessel in the middle of the main beam of the jammer with a position provided by eLoran.

4.3 Automatic Identification System (AIS). The Automatic Identification System provides information on the vessel's identification, position, course and speed, as well as its destination, estimated time of arrival and other information. It can provide this information from ship-to-ship or ship-to-shore. AIS transponders exchange information over two marine VHF band frequencies using Self Organised Time Division Multiple Access (SOTDMA), which requires a common timing source, for which AIS uses GPS. Therefore, GPS denial will not only affect the vessel's reported position and heading, but also the synchronisation of data between AIS transponders. Although AIS transponders would primarily use GPS for slot timing, they can still function bv using а base station for synchronisation, however, as long as they rely on GPS for position. GPS service denial could render AIS useless. When entering the jamming region, Pole Star's AIS unit provided an audible alarm when it lost GPS. From that point on it was not able to calculate its own position and although it was receiving information from surrounding vessels it was not able to calculate a range or bearing. The result of this was that the data presented on the Minimum Keyboard Display (MKD) had limited use. In addition, incorrect AIS data was overlaid on the vessel's radar display.

By observing the radar display, one could see one of the more significant effects of GPS jamming, one with hazardous consequences. Figure 13 shows a photograph of *Pole Star's* radar display. There is a yellow crosshair (marked in the red square), which highlights the radar return for a nearby vessel. That vessel's reported position via AIS is considerably further to the north (vessel number 33458, highlighted in the red circle), clearly showing the effect of jamming on the GPS receiver onboard that vessel.



Figure 13 : Photo of *NLV Pole Star's* radar with AIS overlay: Note the yellow crosshair (red square) indicates the radar return of vessel "33458" whose AIS position is reported to be some distance to the North (red circle).

The effect of GPS jamming can also be observed in Figure 14, which was provided by the Maritime and Coastguard Agency (MCA). This was recorded from their AIS base station in Flamborough. The figure shows a series of snapshots of the maritime traffic off the east coast of Flamborough, with the left-hand image preceding the right-hand image by a few seconds.

Close to the centre of both images is the reported position of the trial vessel *NLV Pole Star*, which was being tracked and one can see the green trace over the peninsular as a result of several runs between the two defined waypoints. The image was taken while the GPS receiver that provides *Pole Star's* AIS position is in a "period of indecision" and its output is wandering around.

These images also give an indication of the effect of GPS jamming on other vessels in the vicinity of the jammer. On these AIS plots vessels are identified by green triangles the orientation of which provides an indication of the vessels' respective headings (the direction in which the vessels are pointing). The course-over-ground of each vessel is indicated by the blue dashed line (the direction in which the vessel is moving), with the length of the line indicating the vessel's speed. Many vessels are seemingly not affected and their reported position data looks normal - the vessel's heading and course-over-ground agree with each other.

However, if one compares the vessel highlighted in the two images, the "Dutch Progress", she is clearly being affected by GPS jamming. In the lefthand image, the vessel is south of *Pole Star* and reporting that she is travelling in a southeasterly direction, although the reported course over ground is northeast.



Figure 14: AIS traces as observed from the MCA station at Flamborough. Note the recorded trace of *NLV Pole Star* as she passed through the GPS service denial region. The trace not only extends further north and south than the true passage, it also shows the vessel crossing the land. The location of "Dutch Progress" is also marked as her position changes due to erroneous GPS input to her AIS.

However if one then compares the reported position in the right-hand image, taken a few seconds later, her location has moved north by some way and one sees that she is reported to be inland while showing a heading of southeast. Her course-over-ground is in the opposite direction and with a significant speed. This is a result of the vessel's GPS reporting erroneous positions and as such the vessel's reported position jumps around randomly.

AlS enables vessels and land based infrastructure to build up an image of the marine traffic around them. In times of GPS jamming, whether intentional or unintentional, the effect is to distort this image and to introduce hazardously misleading information. While larger vessels and port infrastructures combine reported AlS data with radar returns, the result is that two positions are given with a resulting ambiguity concerning which position report to believe.

**4.4 Communication systems – VHF Digital Selective Calling.** Vessels may employ several radio-communication systems including analogue (short-range maritime VHF and long-range maritime HF) and digital (cellular telephone and satellite systems). GPS service denial may affect digital communications systems if it is used as a source of accurate timing for data slots, or if it is used to provide a position input.

Digital Selective Calling (DSC) allows mariners to transmit their position, using GPS as a source, via digital data modulation of channels in the marine VHF band, to other DSC units in case of an emergency. This is also done automatically once the emergency button is pressed. Because of the implications of testing an emergency system, the emergency capability of the DSC unit onboard Pole Star was not activated, however the unit did issue an audible alarm when it lost GPS. Having not been able to actively test the DSC unit, it is not clear whether the integral GPS receiver would report an erroneous position or not. Clearly the implications could be significant if it did provide an erroneous position.

**4.5 Effects on Vessel's Crew.** An important area to be investigated as part of this trial was the effect of GPS service denial on the safe navigation of vessels at sea and in particular the ability of a vessel's crew to react and navigate safely. This is particularly relevant for vessels when they are performing applications that require high accuracy, and high bridge/crew workload. When ships' crews fail to recognise that the GPS service is being interfered with and/or there is a loss of familiarity with alternative methods of navigation or situational awareness, GPS service denial may make a significant impact on their safety and security.

The crew of *Pole Star* was fully briefed prior to the trial and so was expecting GPS-enabled systems to fail. This allowed *Pole Star* to navigate safely to the first waypoint and prepare the radar so the helmsman could use parallel indexing when GPS was denied. With this prior information, the vessel was able to adjust to a loss of GPS and navigate safely although it was not able to perform manoeuvres or applications that required either a high level of accuracy or integrity (i.e. position the vessel using dynamic positioning for deploying AtoNs). Without this prior information, it is not clear whether parallel indexing would have been performed in as timely and efficient a manner.

When Pole Star entered the jamming zone numerous alarms sounded on the bridge over a period of approximately 10 minutes. These alarms were all linked to the failure of different functions to acquire and calculate their GPS position, which included: the vessel's DGPS receivers, the AIS transponder, the dynamic positioning system, the ship's gyro calibration system and the digital selective calling system. The crew of the Pole Star was able to recognise each alarm and silence them efficiently but they were *expecting* the alarms to sound. In the situation where a crew was not expecting this level of system failure then the distraction caused by so many alarms sounding at once could have a significant effect. The effect could be made worse depending on the time of day (potentially a vessel's bridge can be singlemanned at night, or with one officer and a lookout) or if the vessel is performing a manoeuvre or operation demanding high accuracy and a high degree of human concentration at the time of GPS failure, such as docking in poor visibility.

Some vessels have integrated bridge systems, which enable automatic execution of a passage plan on autopilot. If this system is operating at a time that jamming occurs, then the vessel's course and heading may change without informing the crew, potentially leading to extremely hazardous consequences.

Although the *Pole Star's* crew was expecting GPS failure, problems were experienced. The vessel's Electronic Chart Display & Information System (ECDIS) was not updated due to the failure of the GPS input, resulting in a static screen. ECDIS is the normal mode of positioning on board *Pole Star* (with paper chart serving as a backup). During the periods of jamming some members of the bridge crew automatically looked at the ECDIS and forgot that it was not working. Eventually the monitor was switched off in frustration!

More generally, there are several questions raised by this trial, such as the ability of a vessel's crew to quickly revert to traditional means of navigation and also the extent to which they are able to navigate with these means. Given the greater reliance on satellite navigation, in particular GPS, these traditional skills are not being used daily and are no longer second nature. This trial also raised awareness of the number of alarms that can sound on the bridge and how the sheer quantity can be distracting and is particularly hazardous during high workload situations.

**5. STATIC TRIAL RESULTS.** This section presents the details and results of the static trial, discussing the static trial facets outlined in Section 2.2.

**5.1 Differential GPS Service Provision.** The GLAs operate 14 Differential GPS reference stations, transmitting corrections via medium frequency (MF) radiobeacons, arranged throughout the United Kingdom and Ireland. These stations provide mariners with GPS corrections by which they can increase their positioning accuracy by about ten times the standalone accuracy, and gain integrity.

Each station consists of a reference station (RS) unit and an integrity monitor (IM) unit, which respectively calculates pseudorange corrections and then checks the integrity of those corrections before broadcast. The GLAs provide two of each unit within their stations ensuring system availability through redundancy should one unit fail. To ensure the integrity of the pseudorange corrections, each unit (RS or IM) calculates its own GPS position. One would therefore expect GPS service denial to affect the corrections provided.

The DGPS reference station at Flamborough Head was intentionally disrupted using the jamming unit set to a reduced power. The power of the jamming unit was gradually increased until it affected the performance of the reference station. The effects of jamming were observed within the Trimble Beacon Control Software™ (BCS), which is used to control the reference station. Figure 15 shows a screenshot of the BCS software with a number of windows visible. The four windows dominating the upper right area of the image give details of the satellites being observed by the two reference stations (RS1 and RS2) in the top row and the two integrity monitors (IM1 and IM2) in the bottom row. Within each of these windows the locations and health details for each satellite being tracked are shown along with the signal-to-noise (SNR) ratios. Before the GPS jamming signal was enabled, typical SNR values of between 15 and 20 were observed for all satellites.



Figure 15: Screen shot of the Beacon Control Software™ at Flamborough Head showing that the Signal-to-Noise ratios (SNR) for all satellites on both reference stations and on both integrity monitors (4 windows dominating the upper right of the image) are zero and that this has lead to the station issuing an alarm (red area at the bottom left of the screen).

When the power of the jamming signal was increased these SNR values fell and the number of satellites used by the reference station and integrity monitor units reduced until there were no usable satellites. The reference station raised an alarm when the number of satellites fell below the required minimum, showing that GPS jamming does affect the performance of Differential GPS reference stations as expected.

There is great potential for GPS service denial to have serious consequences for maritime radiobeacon differential-GPS service providers and their users. The trial shows that a relatively low power jammer placed near a reference station, or a passing vessel with faulty equipment onboard (e.g. a defective UHF active television amplifier [8]) could result in the disruption of DGPS service provision out to several hundred kilometres from the reference station.

**5.2 Synchronised Lights.** With ever increasing amounts of background lighting in ports and port approaches, it is becoming more difficult for mariners to recognise AtoN lights and thereby ensure that their vessel is positioned correctly. The GLAs are actively looking at methods for making AtoN lights more conspicuous so that they can be more easily recognised. One important method is to deploy synchronised lights.

Synchronised lights are conventional AtoN lights, however when multiple lights are situated in close proximity they can be synchronised to a common time source and configured to either flash together or flash in sequence, drawing the attention of the eye along a channel for example. Once they have attracted the eye the aid can be identified by its flash character and referenced to a navigation chart to confirm the vessel's position.

Typically, GPS is used as the common timing source in these units as it provides universal time (UTC) at low cost in a conveniently small package. Clearly, lights using GPS for timing will be affected by GPS service denial. The trial was set up with the GPS jamming unit set on reduced power to limit the jamming area. The lights used in the trial were configured to illuminate on power-up rather than waiting until dusk, and two tests were performed.

The first test followed the scenario that the lights are already on and synchronised when GPS is jammed. The second scenario was for GPS to be already jammed before the lights are powered-up. The particular lights used in the trial synchronise their internal clock to GPS upon power-up, and then resynchronise with GPS at 20-minute epochs, powering-down the GPS unit between epochs. If the units fail to re-synchronise then they rely on their internal oscillator to keep time. For the first scenario, the lights were powered and allowed to fully synchronise, at which point the GPS jamming signal was enabled. The power of the GPS jamming unit was increased until a handheld GPS unit situated alongside the lights failed to acquire any GPS satellites. The lights were left to operate for over an hour, during which time they could not re-synchronise, and over which time it was not possible to observe any loss of synchronisation. The lights were then switched off for 30 minutes before the second scenario was performed.

For the second scenario, the GPS jamming unit was enabled at the same power as before and then the lights were powered-up. After 30 minutes the lights had not synchronised and it was clear that GPS jamming was preventing synchronisation, at this point the lights were flashing out of phase.

Clearly the results here mean that the effect of jamming depends on whether the lights have been able to synchronise or not. If the lights have been able to synchronise then they are reasonably resilient to jamming signals, with manufacturers stating that lights can remain synchronised for between 20 minutes and several hoursbefore any noticeable effects depending on the quality of the crvstal oscillator used bv а particular manufacturer. This latter statement remains to be confirmed, although eLoran would also be a suitable timing source that is unaffected by GPS interference.

6. CONCLUSIONS. GPS is vulnerable and this trial has investigated GPS service denial by intentional interference using low-power jammers. It should be clear that the results can be extended to GPS service denial by unintentional interference. Unintentional sources of interference include spurious harmonics from active TV receiver antennas, damaged GPS antenna cables and ionospheric effects. The latter are correlated with the eleven-year sun-spot cycle and are prevalent at high particularly geomagnetic latitudes. This will bring additional challenges when arctic shipping routes become available. The main conclusion from this trial is that GPS service denial has a significant impact on maritime safety:

• On ships – navigation, situational awareness, chart stabilisation and DSC emergency communications will be lost if they are based on GPS. Some vessels have integrated bridge systems, which enable automatic execution of a passage plan on autopilot. If this system is operating at a time when jamming occurs then, depending on the system design, the vessel's course and heading may change without informing the watch-keeper, potentially leading to extremely hazardous consequences. At this point, continuation of navigational safety is dependent on mariners' abilities to recognise that GPS service is being denied and to operate effectively using alternative techniques (e.g. radar parallelindexing).

• **On AtoNs**– DGPS reference stations can be jammed and the impact may result in the absence of DGPS corrections and integrity information broadcast to users over a very large geographical area; AIS used as an AtoN may broadcast incorrect information; and synchronised lights may not be synchronised, thus having an adverse impact on visual conspicuity, and with AtoNs flashing with a characteristic that in contrary to that published.

• **On shore** – the marine picture presented to Vessel Traffic Services/Management (VTS) will be confused as AIS information with erroneous positions and high-velocities conflicts with the radar information. Further study is needed to determine how VTS operators will respond.

**On people** – People are conditioned to expect excellent GPS performance. As a result, when ships' crews or shore-based staff fail to recognise that the GPS service is being interfered with and/or there is a loss of familiarity with alternative methods of navigation or situational awareness, GPS service denial may make a significant impact on safety and security. In this trial, despite the fact that the Pole Star's crew was forewarned, problems were experienced with over reliance on the ECDIS. Moreover, the number of alarms that can sound on the bridge can be distracting. Moving to traditional navigation techniques can cause an increase in bridge workload.

On eLoran – eLoran was unaffected by GPS jamming and demonstrated an accuracy of 8.1m (95%) off the Flamborough coast, which is comparable to stand-alone, single-frequency GPS. Consequently, eLoran can be used to detect erroneous positions and high velocities that may be experienced during GPS service denial. Moreover, when GPS is unavailable, eLoran can provide a PNT input to all maritime Finally, in the future e-Navigation systems. environment, the combination of GPS, Galileo and eLoran will provide robust and resilient PNT in order to reduce the impact of human error and to improve the safety, security and protection of the marine environment.

**7. ACKNOWLEDGEMENTS.** The authors would like to acknowledge the assistance provided by

DSTL, the professionalism and undoubted patience of the crew of NLV Pole Star throughout the trials and the Maritime and Coastguard Agency for their assistance in collecting data.

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