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GPS Jamming and the Impact on Maritime Navigation

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The US Global Positioning System (GPS) is currently 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, possibly together with other Global Navigation Satellite Systems (GNSS) e.g. Galileo, being the core PNT technology for e-Navigation – the future digital maritime architecture. GPS signals, measured at the surface on the Earth, are very weak. As such, the system is vulnerable to unintentional interference and jamming, resulting in possible denial of service over 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 (HMI) for navigation and situational awareness, depending on how the GPS receiver reacts to the jamming incident. Recognising this, the General Lighthouse Authorities of the United Kingdom and Ireland (GLA), in collaboration with the UK Ministry of Defence (MOD) 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.

This paper presents the key findings of these trials and provides important information on the effect of GPS denial. The GLA are playing a pivotal role in the establishment of eLoran as an independent source of PNT, taking advantage of eLoran's complementary nature, having dissimilar failure modes to GPS and the future GNSS. This paper provides information on the performance of an eLoran receiver in an area of GPS service denial. The paper presents the rationale for the work, details the system architecture employed, the data gathering efforts and finally the data analysis procedures, results and conclusions.

KEY WORDS

1. GNSS. 2. eLoran. 3. GNSS Vulnerability.

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, Ireland (as a single entity) 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. The vulnerabilities of GPS are well known [1], as the signals are so weak on reception, they are susceptible to interference and jamming, whether intentional or not. As such the GLA are keen to understand the effectiveness of their AtoNs, and the navigation systems being employed by mariners within their waters, under conditions of GPS service denial. The GLA 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, with dissimilar failure modes to GNSS [2].

This paper details the approach and results of the trial conducted in collaboration with the UK Government's Defence Science and Technology Laboratory (DSTL), which both 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 an indication as to the behaviour of navigation systems affected through interference or jamming, whether intentional or not.

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 GLA 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.

The trial was designed to test multiple facets of safe navigation from the perspective of the vessel's crew, a review of how the GLA AtoN services are affected and finally a review of vessel-based navigation systems.

2. TRIAL METHODOLOGY.

The trial was conducted over several days during April 2008 at Flamborough Head on the East coast of the United Kingdom. DSTL provided a professional low-to-medium power jammer, which was controlled remotely by two VHF transceivers and transmitted a known pseudo-random noise code over the civilian L1 frequency providing a jamming signal over the whole 2MHz bandwidth of L1. Although the unit was capable of broadcasting on the P code, this was not activated. The total power of the signal over the 2MHz bandwidth was approximately 2 dBW (~1·5W) of power. This unit was used with either

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

a "Qpar2003" directional antenna or an omni-directional antenna depending on the test being conducted (shown in Figure 1). The trial was conducted over three days, with two days devoted to dynamic trials and one day to static trials, each designed to test different elements of safe navigation.

2.1. *Dynamic Trials.* For the dynamic trials, the Northern Lighthouse Board vessel *NLV Pole Star* steered a course back and forth between two waypoints on a path that dissected both the main lobe of the GPS jammer and the two side lobes, but with sufficient length beyond the jamming region to enable the various GPS enabled units to reacquire satellites (coverage of the jamming unit is shown in Figure 2).

During the dynamic trial 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 creates a line on the screen that is parallel to the ship's course, but offset to the left or right by the distance the planned track passes off a radar conspicuous fixed radar target. The navigator maintains course by manoeuvring to keep this line over the fixed radar target. 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 target. For the duration of the dynamic trials the jamming unit was left at a constant power, although disabled when not required.

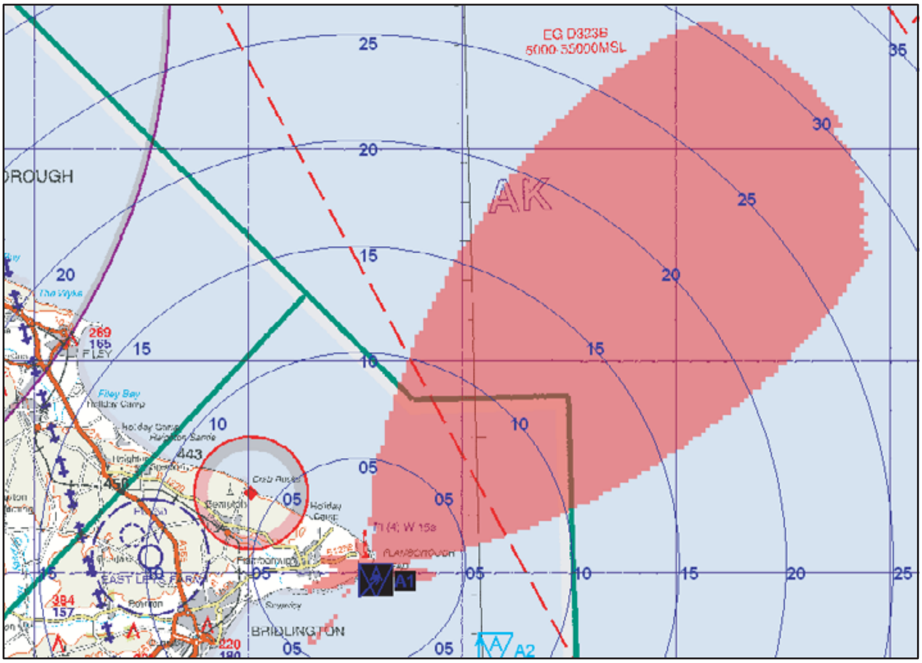


Figure 2. Coverage area of the GPS jamming unit at 25m above ground level on maximum power of 1·58W ERP. (Image courtesy of DSTL)

2.2. *Static Trials.* The static trials were conducted on land at Flamborough Head lighthouse. This part of the trial focused on assessing the effects of GPS jamming on Differential GPS reference stations and synchronised lights.

3. VESSEL CREW ABILITY.

An important area to be investigated as part of this trial is 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 navigate safely. This is particularly relevant for vessels when they are performing applications that require high accuracy. 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 were expecting GPS-enabled systems to fail. This allowed *Pole Star* to navigate safely to the first waypoint and prepare the radar so that it 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 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 had a significant effect. The effect could be made worse depending on the time of day (potentially a vessel's bridge can be single-manned at night, or with one officer and a look-out) 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 backup) and during the periods of jamming some crew members became frustrated when trying to look at the ECDIS. This resulted in the monitor being switched off!

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 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.

4. GLA AIDS-TO-NAVIGATION.

4.1. *eLoran*. The GLA have long recognised the dangers associated with an over-reliance on 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 PNT in order to reduce the impact of human error and to improve safety, security and protection of the marine environment. The GLA 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 GLA, supported by the UK Department for Transport (DfT) have invested in a 15-year contract for the provision of an eLoran service from a site 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 transmission with a centre frequency of 100kHz. The times of arrival of the signals are measured by the user's receiver and the 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 eLoran receiver used for the trial had an integral GPS receiver, which meant that the unit was able to calculate stand-alone GPS, Differential GPS using Eurofix corrections, calibrated Loran using GPS, Addition Secondary Factor (ASF) corrected Loran and stand-alone Loran. For the trial, the receiver operated in Eurofix corrected GPS, while GPS was available, and then reverted to calibrated Loran and finally ASF corrected Loran.

While GPS was available the eLoran output was periodically calibrated by the GPS solutions. This was effectively the same as continuously using the GPS position as a "ground truth" and computing the offset of the eLoran positions from it. eLoran pseudoranges were adjusted according to the position offset. When GPS was not available, the integrated output was derived from Loran using calibrated Loran pseudoranges. Calibration of the Loran ranges was done every time a new Loran measurement was available (e.g. every 5 seconds). The calibration value was determined based on a minimum set of 5 calibration points, hence there was some 30 seconds before a calibrated eLoran position was first output. Over the set of available calibration measurements a weighted average calibration value was computed. When GPS was unavailable the last calibration values were employed. Under GPS denial conditions it depends on how long the GPS receiver still reports positions before it affects the eLoran calibration. Typically, many GPS receivers do not indicate if the position is wrong due to interference and this was witnessed during the trial.

Since the effect of GPS jamming on the GPS calibrated mode of operation was not known, ASFs were recorded during one of the control runs, when GPS jamming was not enabled, and the ASF data was stored in the receiver. Once GPS becomes unavailable, or the latest GPS calibration becomes invalid, the receiver will automatically revert to using ASF corrected Loran for its positioning output.

By using data collected during the control runs of the trial, it was possible to determine the positioning accuracy performance of Loran in the area of the trials. This was achieved by comparing calculated calibrated Loran positions against differential-GPS as provided by Eurofix. Figure 3 shows a scatter plot of the comparison of the Loran positions against the differentially corrected GPS positions. The red circle indicates a 95% position accuracy of 8·1m. 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.

Figure 4 shows eLoran derived position data as the vessel navigated through the jamming region under control conditions, when the jamming unit was not operating (left-hand plot), and when the GPS jamming unit was operating (right-hand plot). In both cases one can clearly see the route taken between the waypoints. From the right-hand plot of Figure 4 it is possible to see that the eLoran receiver was able to provide a useable position output throughout the jamming trial. The only discrepancy between the two plots is a slight wave to the trace. This is due to the vessel being navigated using parallel indexing which is significantly less accurate than GPS and eLoran. Clearly the performance of eLoran is not affected by GPS jamming, as one would expect.

This trial justifies and confirms the GLAs' eLoran strategy.

4.2. *Differential GPS.* The GLA operate 14 Differential GPS reference stations, arranged throughout the United Kingdom and Ireland. These stations provide mariners with GPS corrections by which they can increase their positioning accuracy

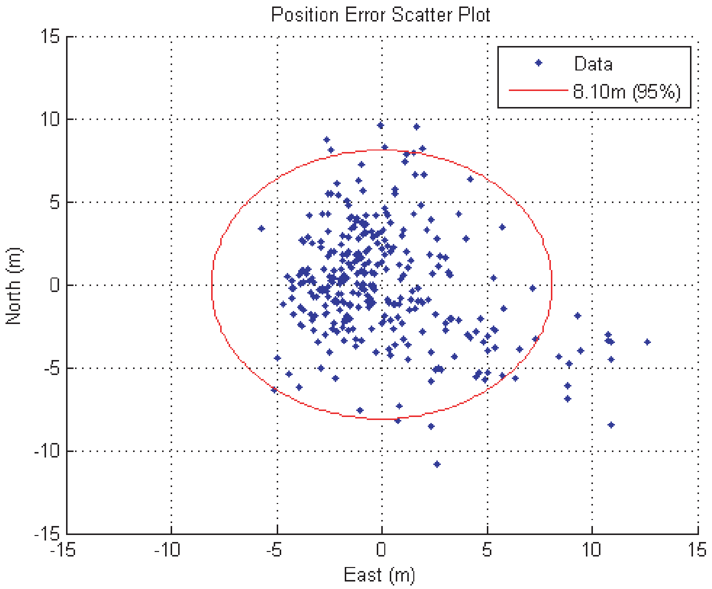


Figure 3. Scatter plot showing the performance of calibrated Loran when compared to Differential GPS. Loran was accurate to 8·1m (95%).

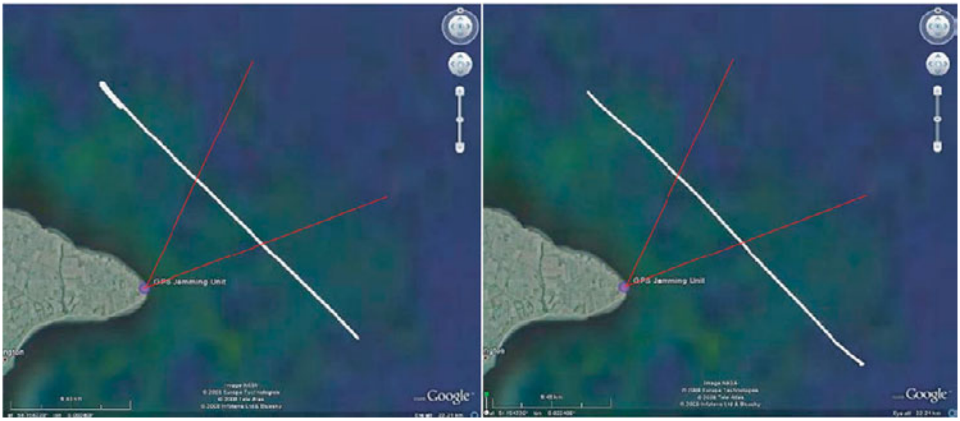
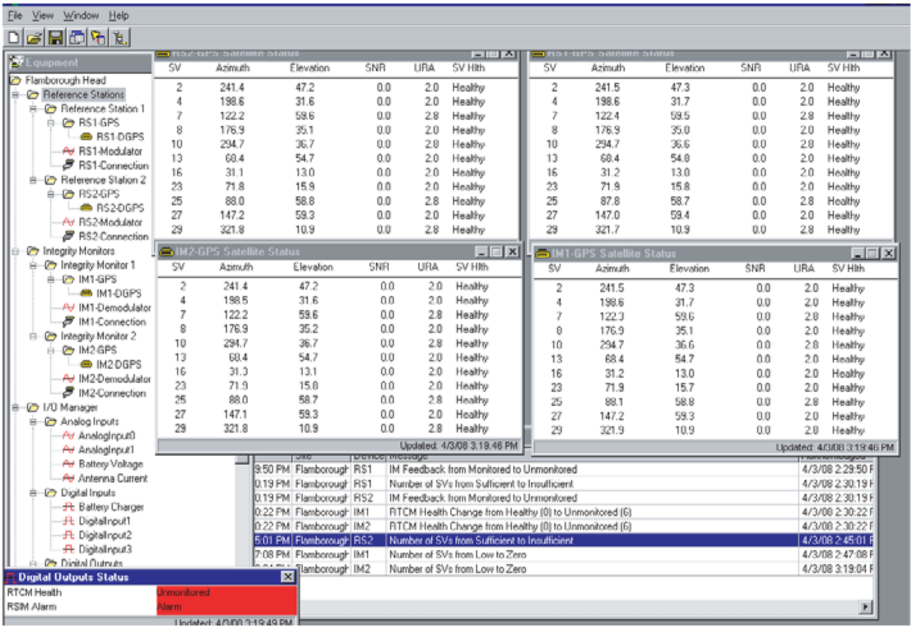


Figure 4. Two plots of eLoran data displayed in Google Earth™. The left-hand plot is the reported positions during a control run when there was no GPS jamming. The right-hand plot shows the reported positions during a run with GPS jamming switched on. The red lines indicate the approximate boundaries of the main lobe of the GPS jamming signal. eLoran was not affected by GPS jamming.

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



RS2-GPS Satellite Status

SV	Azimuth	Elevation	SNR	URA	SV Hlth
2	241.4	47.2	0.0	2.0	Healthy
4	198.6	31.6	0.0	2.0	Healthy
7	122.2	59.6	0.0	2.8	Healthy
8	176.9	35.1	0.0	2.0	Healthy
10	294.7	36.7	0.0	2.8	Healthy
13	68.4	54.7	0.0	2.0	Healthy
16	31.1	13.0	0.0	2.0	Healthy
23	71.8	15.9	0.0	2.0	Healthy
25	88.0	58.8	0.0	2.8	Healthy
27	147.2	59.3	0.0	2.0	Healthy
29	321.8	10.9	0.0	2.8	Healthy

RS1-GPS Satellite Status

SV	Azimuth	Elevation	SNR	URA	SV Hlth
2	241.5	47.3	0.0	2.0	Healthy
4	198.6	31.7	0.0	2.0	Healthy
7	122.4	59.5	0.0	2.8	Healthy
8	176.9	35.0	0.0	2.0	Healthy
10	294.7	36.6	0.0	2.8	Healthy
13	68.4	54.8	0.0	2.0	Healthy
16	31.2	13.0	0.0	2.0	Healthy
23	71.9	15.8	0.0	2.0	Healthy
25	87.8	58.7	0.0	2.8	Healthy
27	147.0	59.4	0.0	2.0	Healthy
29	321.7	10.9	0.0	2.8	Healthy

IM2-GPS Satellite Status

SV	Azimuth	Elevation	SNR	URA	SV Hlth
2	241.4	47.2	0.0	2.0	Healthy
4	198.5	31.6	0.0	2.0	Healthy
7	122.2	59.6	0.0	2.8	Healthy
8	176.9	35.2	0.0	2.0	Healthy
10	294.7	36.7	0.0	2.8	Healthy
13	68.4	54.7	0.0	2.0	Healthy
16	31.3	13.1	0.0	2.0	Healthy
23	71.9	15.8	0.0	2.0	Healthy
25	88.0	58.7	0.0	2.8	Healthy
27	147.1	59.3	0.0	2.0	Healthy
29	321.8	10.9	0.0	2.8	Healthy

Updated: 4/3/08 3:19:46 PM

IM1-GPS Satellite Status

SV	Azimuth	Elevation	SNR	URA	SV Hlth
2	241.5	47.3	0.0	2.0	Healthy
4	198.6	31.7	0.0	2.0	Healthy
7	122.3	59.6	0.0	2.8	Healthy
8	176.9	35.1	0.0	2.0	Healthy
10	294.7	36.6	0.0	2.8	Healthy
13	68.4	54.7	0.0	2.0	Healthy
16	31.2	13.0	0.0	2.0	Healthy
23	71.9	15.7	0.0	2.0	Healthy
25	88.1	58.8	0.0	2.8	Healthy
27	147.2	59.3	0.0	2.0	Healthy
29	321.9	10.9	0.0	2.8	Healthy

Updated: 4/3/08 3:19:46 PM

	Site	Device	Message	
9:50 PM	Flamborough	RS1	IM Feedback from Monitored to Unmonitored	4/3/08 2:29:50 F
0:19 PM	Flamborough	RS1	Number of SVs from Sufficient to Insufficient	4/3/08 2:30:19 F
0:19 PM	Flamborough	RS2	IM Feedback from Monitored to Unmonitored	4/3/08 2:30:19 F
0:22 PM	Flamborough	IM1	RTCM Health Change from Healthy (0) to Unmonitored (6)	4/3/08 2:30:22 F
0:22 PM	Flamborough	IM2	RTCM Health Change from Healthy (0) to Unmonitored (6)	4/3/08 2:30:22 F
5:01 PM	Flamborough	RS2	Number of SVs from Sufficient to Insufficient	4/3/08 2:45:01 F
7:08 PM	Flamborough	IM1	Number of SVs from Low to Zero	4/3/08 2:47:08 F
	lamborough	IM2	Number of SVs from Low to Zero	4/3/08 3:19:04 F

Digital Outputs Status

RTCM Health	Unmonitored
RSIM Alarm	Alarm

Updated: 4/3/08 3:19:49 PM

Figure 5. 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 (four windows to the top 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).

The DGPS reference station at Flamborough Head was intentionally disrupted using the jamming unit on a reduced power. The power of the jamming unit was gradually increased until it affected the performance of the reference station. This was observed on the Trimble Beacon Control Software™ (BCS), which is used to control the reference station. Figure 5 shows a screenshot of the BCS software with a number of windows visible. The four windows on the top right of the image give details of the satellites being observed by the two reference stations in the top row (RS1 and RS2) and the two integrity monitors in the bottom row (IM1 and IM2). Within each of these windows the location 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. 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.

4.3. *Synchronised Lights.* With the increase of background lighting in ports and port approaches, it is becoming more difficult for mariners to recognise AtoN lights and thereby ensure that they are in the correct position. The GLA are actively looking at methods for making AtoN lights more conspicuous so that they can be easily recognised. One important method is to deploy synchronised lights.

Synchronised lights are conventional AtoNs, 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. 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 wait 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 oscillator to GPS and then resynchronise with GPS every 20 minutes. 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 hand-held 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 started.

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

Clearly the results here are 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 several hours before any noticeable effects are seen. This latter statement remains to be confirmed although eLoran would also be a suitable timing source that is unaffected by GPS interference.

5. SHIPBORNE RADIONAVIGATION AIDS.

5.1. *GPS and Differential GPS Receivers.* Three additional receivers were installed on the trial vessel, two of which were typical marine grade differential GPS receivers, the third being a more expensive dual-frequency surveying receiver (configured to operate on GPS L1 only). Data in the form of NMEA sentences were recorded from each receiver throughout the jamming trial. It should be noted that due to a lack of space on the vessel's mast, antennas for the three receivers were

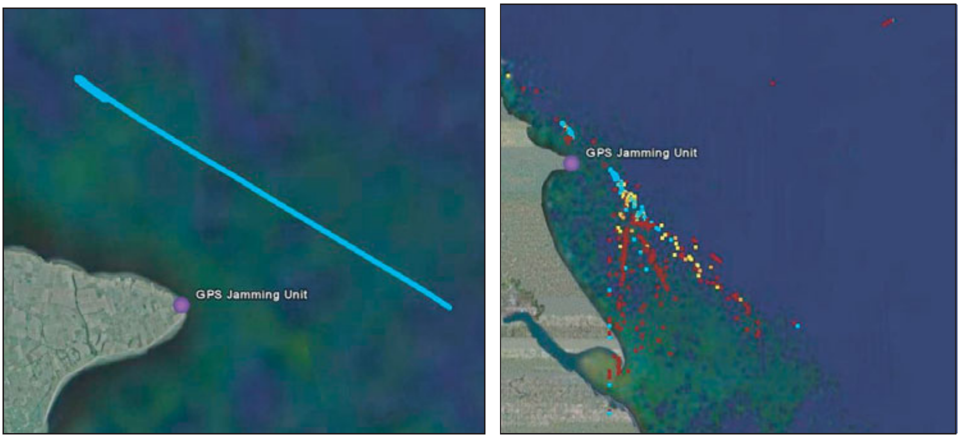


Figure 6. Google Earth™ plots of recorded positions identified as valid. Left: No GPS jamming unit active. Right: GPS jamming unit active. The colours are used to represent the reported vessel speed with blue <15knts, yellow <50knts, orange <100knots and red >100knts.

installed on the handrail of the main deck, which meant there was a certain amount of sky obscuration due to the vessel's superstructure.

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 as the reference station was also affected by the jamming signal, there were no 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 single bit flag. The decision to set or clear the data valid flag is one that is made by the receiver. When processing the recorded data from the various receivers only data declared valid was used, which resulted in the two typical marine grade receivers providing erroneous positions as they entered and exited the jamming region. The magnitude of the position error varied, with some small errors, but with others several tens of kilometres away from the true location. Figure 6 provides the reported positions from one receiver, plotted on Google Earth™. The left-hand plot is from the 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, with blue positions indicating a speed of less than 15 knots; yellow positions indicating a speed of between 16 and 50 knots; orange positions indicating a speed of between 51 and 100 knots and red positions indicating a reported speed of greater than 100 knots.

Figure 6 (Right), shows that the number of erroneous positions was significant, with the majority of positions coloured red, indicating the reported speed was greater than 100 knots (the greatest reported speed was over 5000 knots). Clearly, if this data was 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 were typical from the two marine grade receivers, although it was noted that the effect of jamming

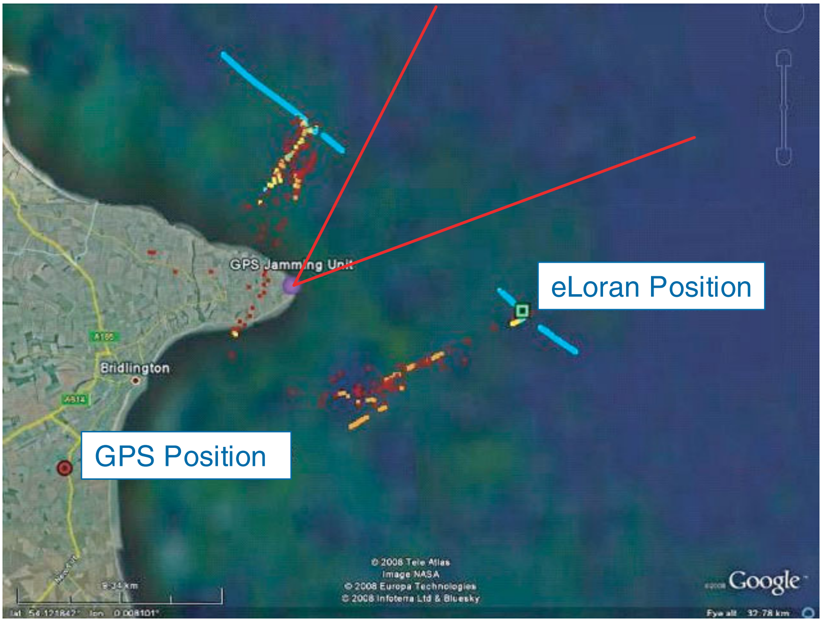


Figure 7. Google Earth™ plot of valid GPRMC data from one of the typical marine grade receivers with the comparison of an erroneous GPS position (red circle) against the eLoran position (green square) for the same time. The GPS position is reported as being inland 22Km West from the true eLoran position.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

was more severe when sailing North with the vessel superstructure between the jamming unit and the GNSS receivers' antennas. Therefore, it may be presumed that the jamming signal was attenuated due to the shadowing effect of the vessel's superstructure and 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; clearly this is the preferred situation.

The GPS receivers onboard *Pole Star* were also affected by the jamming signal and also reported inflated speeds, albeit to a smaller degree. The reported position on the vessel's 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 noted in Section 4.1, the reported position from eLoran was not affected during GPS jamming and the receiver was able to function as normal, as one would expect. In order to calculate the magnitude of error, an erroneous position from one of the typical marine grade receivers is compared to that from the eLoran receiver for the same moment in time, in Figure 7.

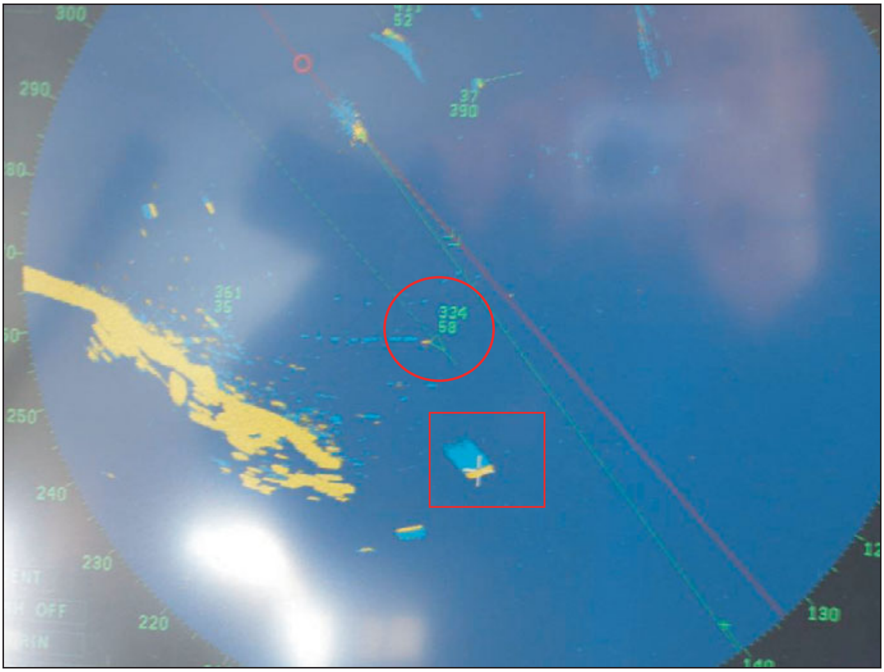


Figure 8. Photo of NLV Pole Star's radar with AIS overlay. Note the yellow crosshair (red square) indicates the radar return of vessel "33458" whose AIS position is reported to be some distance to the North (red circle).

5.2. *Automatic Identification System.* The Automatic Identification System (AIS) provides information on the vessel's identification, position, course and speed, as well as 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 VHF 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 by using a 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 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, although corrupted AIS data could still be 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 8 shows a photograph of *Pole Star's* radar display. On the radar there is a 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

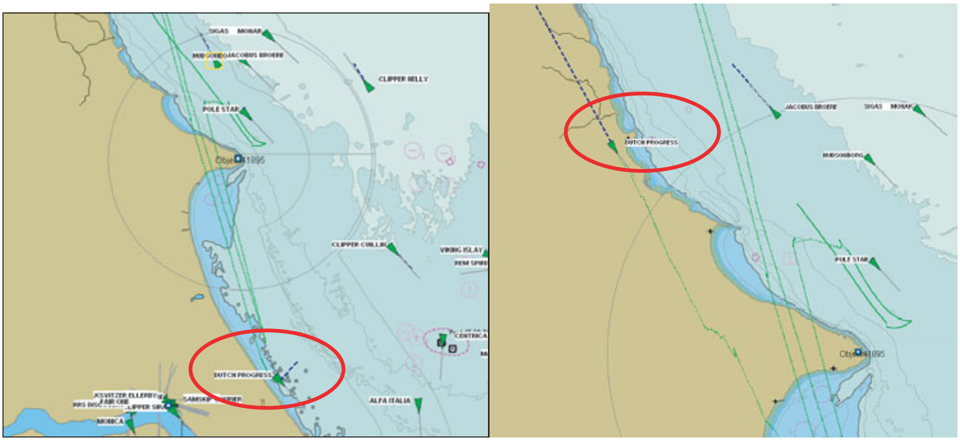


Figure 9. AIS traces as observed from the MCA station at Flamborough. Note the recorded trace of NLV *Pole Star* as she passed through the GPS service denial region. The trace not only extends further north and south than the true passage, it also shows the vessel crossing the land. The location of *Dutch Progress* is also marked as her position changes due to erroneous GPS input to her AIS.

showing the effect of jamming on the GPS receiver onboard this vessel, which is resulting in an erroneous AIS reported position.

The effect of GPS jamming can also be observed in Figure 9, which was provided by the Maritime and Coastguard Agency (MCA) and was recorded from the 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.

Both images show 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 provided *Pole Star's* AIS position was in the "period of indecision" and is wandering around. These images give an indication of the effect of GPS jamming on other vessels in the vicinity. 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 vessels are moving), with the length of the line indicating the vessel's speed. Most 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 left-hand image, the vessel is South of *Pole Star* and reporting that she is travelling in a South Easterly direction, although the reported course over ground is North East. 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 South East. 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.

AIS enables vessels and land based infrastructure to build up an image of the marine traffic around them and as observed, 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 AIS data with radar returns, the result is that two positions are given with uncertainty over which position to believe.

5.3. *Communication systems*. 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 is used to provide a position. Digital Selective Calling (DSC) systems use GPS to provide a positional input should an alarm be activated. DSC allows mariners to transmit their position, via digital data modulation of maritime band VHF, to other DSC units in case of an emergency, in order to request assistance.

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.

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 antennas, damaged GPS antenna cables and ionospheric effects. The latter are correlated with an eleven-year sun-spot cycle and are particularly prevalent at high latitudes. This will bring 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 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.
- *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.
- *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 parallel-indexing). Increased use of ECDIS will increase the attendant risks.

- *On People*. People are conditioned to expect excellent GPS performance. As a result, when ships' crews or shore 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 the ECDIS. Moreover, the number of alarms that can sound on the bridge can be distracting. Moving to other navigation techniques can cause an increase in bridge workload.

eLoran was unaffected by GPS jamming and demonstrated an accuracy of 8·1m (95%) 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 systems. Finally, in the future e-Navigation 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.

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