The Role of Trust and Interaction in GPS Related Accidents: A Human Factors Safety Assessment of the Global Positioning System (GPS)

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Abstract

The Global Positioning System (GPS) uses a network of orbiting and geostationary satellites to calculate the position of a receiver over time. This technology has revolutionised a wide range of safety-critical industries and leisure applications ranging from commercial fisheries through to mountain running. These systems provide diverse benefits; supplementing the users existing navigation skills and reducing the uncertainty that often characterises many route planning tasks. GPS applications can also help to reduce workload by automating tasks that would otherwise require finite cognitive and perceptual resources. However, the operation of these systems has been identified as a contributory factor in a range of recent accidents. Users often come to rely on GPS applications and, therefore, fail to notice when they develop faults or when errors occur in the other systems that use the data from these systems. Further accidents can stem from the 'over confidence' that arises when users assume automated warnings will be issued when they stray from an intended route. Unless greater attention is paid to the human factors of GPS applications then there is a danger that we will see an increasing number of these failures as positioning technologies are integrated into increasing numbers of applications.

Introduction

Manual navigation techniques have changed very little over the centuries. For example, commercial and leisure activities continue to rely on dead reckoning where an initial position is established. The position is then estimated over time using an individual or vessel's speed and direction. The accuracy of dead reckoning calculations depend on the accuracy of the speed input and the effects of environmental factors including wind and current. After the Second World War, the development of radar and of differential radio signals helped to establish automated approaches to position location. These can be thought of as precursors to the satellite based GPS systems that have now become commonplace. GPS units are sold 'as standard' with many cars. They are widely used across the maritime industries. They can be carried in your pocket and attached to PDAs; providing continuous updates of location information during both work and leisure activities. This growth in the application of GPS technologies has fuelled and been fuelled by the use of these systems in safety-critical applications. For example, they have been integrated into the cockpits of both commercial and general aviation. However, the adoption of GPS systems in safety-related applications has led to a number of concerns. The FAA recognises that GPS alone cannot satisfy the high-levels of accuracy and redundancy that would be required across the National Airspace System. In consequence, a number of local and wide area augmentation schemes have been proposed. In Europe, more strategic concerns have been raised and plans continue to be revised for the creation of an alternate system.

It is important not to underestimate the complexity of human interaction with GPS applications. For example, the US National Oceanic & Atmospheric Administration (NOAA) released a warning in 2002 about some of the systemic effects of GPS on navigation behaviour. In particular, they observed that some mariners were more willing to follow higher risk routes closer to known hazards because they felt confident in the use of GPS technology to accurately identify the position of those hazards. NOAA went on to point out that the increasing accuracy of GPS fixes exposes underlying problems in the accuracy of charts and maps. Many of these guides were developed using less accurate fixes than those provided using GPS technology. It was argued that "prudent mariners should pass charted hazards such as shoals or isolated dangers with utmost caution and at a safe distance, no matter what navigational method is used" (NOAA, 2002).

Most of the concerns over the integration of GPS in safety related systems have focussed on technical and infrastructure issues. These include potential disruption to services from unintentional interference. Studies have been conducted to exclude or minimise the impact of very high frequency (VHF) radio, over the-horizon (OTH) military radar, and broadcast television. There is also growing concern over the vulnerability of navigation tools to external attack. One recent study described how a $300 jammer could cause the sudden loss of GPS signal (John Hopkins). In the most critical scenario, this might cause an aircrew to abort a Category III precision approach. However, many existing systems would use interpolation and dead reckoning so that performance degradation would be extremely limited immediately after a signal was lost. Arguably greater concern centers on longer term disruption to GPS signals in future scenarios in which these applications become more tightly integrated with Air Traffic Management services.

Such concerns are shaping the future application of GPS technology. In contrast, these systems have already been implicated in a number of accidents where the underlying technology worked as intended. In many of these mishaps, the primary cause was identified as human 'error'. Partly in consequence, investigatory agencies have issued general advice on the use of GPS technology. For instance, the New Zealand Maritime agency has argued that: "GPS derived positions are a useful tool in determining a vessels position but should be used in conjunction with all other means of position fixing at the navigators disposal. The temptation to push a button to obtain such data and not utilize more labour intensive, traditional methods of position fixing is, to put it bluntly, bad seamanship that puts vessels and their crew at risk. Maritime New Zealand is concerned at what appears to be a growing tendency for mariners to place excessive reliance on GPS generated data in place of traditional methods of navigation and issues a strong warning against such practise" (Maritime New Zealand, 2006).

Much of this important advice is focussed on the recommendations that emerge from particular incidents. There have been few attempts to gather together the lessons that can derived from a number of different mishaps across a range of different industries. The following pages, therefore, provide a brief overview of recent accidents in the aviation and maritime industries in which it is argued that interaction with GPS technology either triggered or exacerbated various forms of operator failure.

The Operational Benefits of Interactive GPS

The benefits of GPS and associated technology can be illustrated by the extent to which they have become integrated into a number of safety-critical industries. For example, a recent accident report described the standard navigational aids on board a fishing vessel equipped for a crew of three, these included: a radar, an echo sounder, a watch keepers alarm and an autopilot. The fishing vessel also carried two different GPS plotters and a GPS receiver (Maritime New Zealand, 2004). The significance of this equipment can also be illustrated by the consequences that can arise when it is used incorrectly. The subsequent investigation found that the vessel had run aground because the skipper had not set waypoints on the GPS equipment but had instead been using the cursor on one of the GPS plotters to keep an informal note of course and position.

Before reviewing hazards that can arise during interaction with GPS technology in more detail, it is first important to summarise the wide range of benefits that these applications provide to their users. The problems that complicate interaction with these systems often stem from the operational features that provide the greatest utility under normal operations. As noted in the previous citation, the accuracy and availability of GPS data can lead to an over reliance that leaves users unprepared to cope when these systems fail. The following list summarises further benefits of positioning technology. Subsequent sections use this list, together with an analysis of previous accidents to identify many of the problems that arise during the use of these systems.

1. *Reduced workload.* An important benefit of GPS applications is that they can reduce workload across teams of operators in safety-critical systems. The precise nature of this support varies from domain to domain. For example, in many commercial maritime systems the data from GPS applications is seen as an adjunct to rather than a replacement for conventional manual and radar based navigation techniques. However, as we shall see, in other parts of the world crews have come to rely on GPS technology within routine operations so that alternate techniques for location identification are only used to supplement GPS readings. In other words, the bulk of routine navigation tasks has passed from manual and radar based techniques to the automated satellite based systems.

2. *Reduce uncertainty.* In many applications, navigation is a complex task in which operators have to account for subtle changes in meteorological and other environmental conditions. Under poor visibility, it can be

difficult to account for the influence of varying tides or wind speeds using dead reckoning. In other areas, for example in desert or jungle terrains and other remote areas there may be insufficient landmarks or radar beacons to easily employ alternate forms of navigation. In such circumstances, GPS tools provide a critical means of reducing uncertainty in complex navigation tasks.

3. *Multi-criteria optimisation.* GPS tools cannot be viewed in isolation. The position information that they provide is, typically, integrated into a wide range of location finding and route planning systems. This integration enables complex optimisation tasks to be performed where for example speed can be traded for fuel usage or routes can be tailored to avoid congestion. These optimisation tasks would otherwise occupy considerable perceptual and cognitive resources if they had to be performed manually. This creates significant vulnerabilities when operators must learn to cope with degraded modes of operation (Johnson and Shea, 2007).

4. *Dynamic problem solving.* An important aspect of multi-criteria optimisation is the manner in which GPS applications can quickly compute alternate routes or changes in performance characteristics in order to achieve particular objectives in the face of changes both in an application process or operating environment. For example, positioning equipment can automatically monitor the mean speed of its operator over given terrain and then adjust routing information to exclude similar areas should they fall behind the predicted schedule. As with many of the benefits identified in previous items, it is often infeasible for operators to manually conduct the continual forms of self-monitoring that routinely inform route revision algorithms in existing applications.

5. *Monitoring of primary systems.* GPS systems provide an important means of confirming information that can also be derived from primary sensors. For example, it is possible to use successive location fixes to compute speed in a range of aviation, ground and maritime applications. Similarly, the influence of tides and currents can be inferred by comparison of performance data with location information over time. Significant deviations between the GPS derive data and the output of other primary systems can also be used to trigger alarms for the crew that warn them of potential failures in either application.

6. *Multiple input mappings.* GPS tools can also be used to navigate using a range of different input data. This might seem like a trivial issue. However, there are strong benefits to be achieved if crew can choose whether or not to specify a route in terms of individual waypoints, physical landmarks, map coordinates or even ZIP codes. The difficulty of translating from these navigational reference systems into a single input scheme increases burdens on operators especially if they are under time pressure. GPS applications often provide considerable flexibility so that information can be entered in a form that is convenient and familiar to the end user.

7. *Multiple output mappings.* GPS systems also offer considerable flexibility to their users in terms of the presentation format of navigational information. They offer a host of two and three dimensional graphical displays where map or plan views can be extended to show fly-by simulations of potential routes from or to a known location. In other domains, GPS data is used to generate audio alarms so that crew members are only alerted when they have moved close to a known danger or away from a recommended course. Audio warnings can also be used to provide alerts when there are potential disagreements between primary sensors and GPS technology, indicating possible system failures.

8. *Log maintenance.* The Global Positioning System and future location technologies provide increasingly important resources for accident investigators. These tools can automatically log location changes over time to a level of granularity that is infeasible using manual documentation techniques. In consequence, GPS data is often the primary resource for identifying the location of a vessel or aircraft immediately before a mishap occurred. From the perspective of system operators, the availability of GPS log functions may be used to justify some reduction in the frequency of manual recording.

This is a partial list. The range of benefits derived from the Global Positioning System will increase in proportion to the variety of potential applications. However, these strengths also create potential vulnerabilities. Increasing reliance on navigational tools can erode traditional skills and leave operators particularly exposed when they are deprived of these components in their underlying infrastructure.

Incidents and Accidents Involving Interaction with GPS Tools in the Aviation and Maritime Industries

Marine Accident 1 - The Royal Majesty: Arguably one of the most notorious recent incidents involving interaction with GPS applications occurred in 1995 with the grounding of the cruise ship Royal Majesty (NTSB, 1997, Heidiecker et al, 2003). The GPS receiver on the Royal Majesty provided position data that was accurate to within 100 meters. The crew also had access to a Loran-C radio-based navigation system. This relies on time differences between land based radio signals to provide position data along the coasts of the United States. Both GPS and Loran-C data were fed to an integrated NACOS 25 autopilot that could be programmed with the vessels performance characteristics using waypoints specified in terms of latitude and longitude. The NACOS unit provided a number of operating modes. For example, the NAV function could be used to steer the vessel along a pre-programmed track using the GPS and other senor inputs to compensate for gyro error, wind, current and sea conditions. Alternatively, the unit could operate in HYBRID navigation mode using position data from Loran-C or two other positional systems not based on GPS. The unit was also programmed to default to a DEAD RECKONING mode when satellite data were unavailable. When the GPS unit switched to dead reckoning mode it was designed to issues a series of warning sounds lasting around a second. The unit would also display the letters 'DR' indicating the transition into this mode. On the night of the accident, all the officers of the watch testified that they did not see 'DR' displayed on the GPS unit. They did, however, confirm that they understood the meaning of these symbols and had seen them on previous occasions.

Following the accident it was determined that the vessel lost all contact with satellite based position data around thirty minutes after it left port. The failure was traced back to the antenna assembly; however, there was insufficient evidence to accurately identify the cause of the problem. Several hypotheses were generated. The GPS antenna had originally been installed on the radar mast. Several months before the accident, it had been moved to improve signal reception. Subsequent examinations indicated that the GPS antenna was incorrectly routed so that members of the crew could inadvertently kick it or trip over it. This, in turn, created stresses that might contribute to the separation of the antenna cable connection. The antenna had also been painted on two occasions. The consequence of the antenna failure was that the vessel continued to record alternate courses of 197° and 000° from shortly after leaving harbour until the vessel's arrived in Boston even though it had maintained a course close to 336° before the accident. The logs also recorded a speed of 12.7 knots. This was not consistent with the speeds recorded manually in the bridge log. In other words, the interruption of the satellite signal placed the GPS into dead reckoning mode. The autopilot did not detect this change in status and no longer began to correct for the effects of wind, current, or sea conditions. As might be expected the actual position began to drift with respect to the location indicated through dead reckoning. The effects of an east-north-easterly wind and sea resulted in a 17-mile error.

The previous paragraphs have briefly outlined the technical causes of the GPS failure. In contrast, the focus of this paper is on the human factors issues that arose during interaction with the navigation equipment. According to the master, he arrived on the bridge around 22:00. After talking with the second officer for several minutes, he checked the vessel's position using the plots on the chart and at a map overlay on the ARPA radar display. This system enabled the officers to move the radar display to know locations that could be identified from the navigation system. The corresponding plots could then be compared for accuracy with the direct radar feeds to the bridge. The master asked the second officer whether he had seen the BB buoy and the second officer stated that he had. Satisfied that the positions plotted on the chart and that the map displayed on the radar continued to show the vessel to be following its intended track, the master left the bridge around 22:10.

There were several further opportunities for the crew to identify the potential problem before the grounding took place. Others officers on the bridge received reports that the lookouts had sighting several high red lights as well as a flashing red light on the port bow. These were inconsistent with the current positional information and should have caused the officers to look again at the radar systems. They might have noticed that the radar maps did not coincide with the ARPA display. They might also have increased the range of radar systems and then identify their proximity to Nantucket Island. Had the officers queried the flashing red light, they might have determined that the nearest source was the Rose and Crown Shoal buoy. This could have warned them that they were no longer in the traffic lanes. The subsequent investigation concluded, however, that the officers of the watch had only a limited understanding of the functioning of their GPS systems. This was compounded by the way in which procedures failed to ensure the use of diverse positional information. For example, the master required that officers continue to make manual plots of their location. However, his colleagues used GPS as the most convenient source for this information. In consequences, the fixes that were plotted on the chart corresponded with the map and positions displayed on the central console. The manual plotting was, therefore, derived from the GPS data.

The grounding of the Royal Majesty provides an important case study for the analysis in the paper because it illustrates many of the problems that complicate interaction with GPS applications. Firstly, like many similar systems the vessel was provided with multiple redundant sources of location information. However, this redundancy was little more than 'skin deep'. In practice, the convenience of GPS systems meant that the crew relied on this source of data to guide all of their monitoring and validation procedures for navigational information. This created further vulnerabilities because different members of the crew each assumed that their co-workers were accessing diverse information sources and so felt justified in them continuing only to rely on GPS input. Secondly, the Royal Majesty illustrates the dangers that arise when GPS applications are integrated into more complex systems that are, typically, not well understood by the people who must operate them. In this case, the master and the officers could recognise the dead reckoning mode but they were poorly prepared for the causes and consequences of failures that could lead to this style of operation.

Marine Accident 2 – Sanga Na Langa: The consequences and notoriety of the Royal Majesty accident justify its inclusion in this analysis. However, it is important not to overlook the growing number of less well known incidents involving interaction with GPS technology that have been reported across a range of industries. For instance, the New Zealand maritime agency report on the grounding of the Sanga Na Langa, a 13.5 meter commercial passenger and fishing vessel operating off Waiheke Island in the Hauraki Gulf, in 2006 (Maritime New Zealand, 2006). As with many similar incidents, the skipper was familiar with the area of coast in which the incident occurred. In particular, he knew the location of a range of offshore rocks that posed a danger to mariners. These rocks were well indicated on the display unit of his GPS applications and were indicated at some off the starboard side of the vessel. The skipper's sense of wellbeing was increased by his confidence in the GPS, which had been installed and calibrated by a friend some six years before. It had also always given him accurate readings before, although the unit had previously been repaired by the manufacturer's agent to correct a display fault. He was also using an electronic chart that is widely used in the area where he was operating.

The skipper reported that he was just about to refer to a paper chart when a lookout identified broken water ahead. Approximately ten seconds later, the vessel's hull and propeller ground over the top of a rock. The bilge pumps were able to cope with the subsequent ingress of water and the vessel was successfully beached. The official report into the incident concluded that the skipper had broken 'one of the cardinal rules of navigation namely over reliance on GPS data' (Maritime New Zealand, 2006). Similarly, the electronic chart came with the warning that it should only be used as a backup to official government paper charts and traditional methods of navigation. The day after the accident, the skipper observed that the GPS placed the vessel on top of a small island even though they were some distance away from it on their homeward journey. This significantly undermined the skipper's confidence in GPS technology. This sudden erosion of trust that may take many years to establish also illustrates the central role of human factors issues in the operation of new generations of navigation equipment.

The grounding of the Sanga Na Langa is also instructive because it illustrates some of the problems that arise for investigatory agencies when they attempt to diagnose the causes of problems with GPS applications. These systems can provide incorrect data for a variety of reasons. GPS assisted groundings are often caused by inaccuracies in electronic charts. In this case, the manufacturer's representatives noted that the position of the rocks as displayed on the screen correlated with their position in the government maps. The investigators concluded that 'it is not uncommon for display screens that have been monitoring a vessel's position whilst stationary, for example whilst berthed overnight, to show positions a considerable distance from the vessel's position' (Maritime New Zealand, 2006).

This incident again illustrates a number of key issues that complicate interaction with GPS system in safety-related domains. The skipper of the Sanga Na Langa was familiar with the area in which they were operating. This seems to be a common feature of many similar accidents. Further work is required to provide more sustained evidence that familiarity with a location increases the likelihood of being involved in a GPS related incident. It is possible to identify a number of potential explanations for this hypothesised correlation. For instance, if an operator understands local hazards then they may be more willing to dismiss them as soon as they can be seen on a GPS application without necessarily checking to ensure that the GPS has accurately located those hazards.

The grounding of the Sanga Na Langa raises further issues. For example, the skipper placed a high degree of trust in the reliability and calibration of their GPS application. In part, this was justified by his experience of the operational performance of the unit. However, it may also have been influenced by the growth of consumer applications for this technology. GPS is increasingly being integrated into mass market 'of the shelf' products. Familiarity may create an unjustified degree of confidence in the reliability of what is a complex, distributed system of systems.

Aviation 1- Cessna Floatplane: The introduction to this paper has stressed the need to exchange insights and lessons learned from GPS induced mishaps across several different safety-critical industries. It is for this reason that the following examples focus on interaction with new navigation technologies within both commercial and general aviation. Again, it is important to stress that the use of GPS related systems has figured as a contributory cause in both major accidents and in less well publicised incidents. For example, the US NTSB describes how the pilot of a Cessna 208 seaplane forgot to retract the gear on takeoff from a runway. This version of the aircraft has wheel installed on the floats. On approaching his destination the pilot realised that the navigation system was using the position of a nearby resort island called Filitheyo rather than the GPS position of the landing site about 2.5 miles (4 km) to the north. The captain, therefore, began attempting to correct the GPS co-ordinates for the landing site.

As he touched the water, the aircraft seemed to 'spring back' and the captain recognized that he had left the landing gear down. The aircraft flipped onto its back pivoting on its nose and left wing. The subsequent investigation identified pilot error as the probable cause of the accident. Contributory factors included a failure to use the approved checklist when ensuring that the landing gear was properly raised, a failure to monitor appropriate instruments and a failure to pay due attention to aural warnings. The manufacturer responses to the incident by changing the aural 'gear down' warning to occur at a higher speed, 'thereby allowing the pilot time to react accordingly without distraction during the final approach segment of the flight' (NTSB, 2000). The pilot was recommended to undergo additional type training.

One of the most salient features of this incident is that the recommendations focussed on the retraining of the pilot and on minor technical changes in the on-board warning systems for the landing gear. The findings of the investigation did not focus on the problems that the pilot experienced in interacting with the navigation systems. Previous research has identified a broad range of issues that complicate the reprogramming of GPS applications in safety related domains (Johnson, 2004). These range from the confusion that often arises over the difference between insertion and appending of a waypoint into a list of fixes through to the difficulty of distinguishing between the different modes of operation that are provided by these navigation systems. In this case, a relatively minor correction to the location of the destination could not be completed by the pilot without considerable concentration. However, the subsequent investigation did not explicitly raise this as an area for further concern.

In other areas of human computer interaction and human factors, there has been a move away from blaming operators who experience similar problems during interaction with complex systems. It has been argued that retraining the users will only alleviate the symptoms of an underlying problem but will not address the causes (Johnson book). In contrast, greater emphasis has been placed on the need to redesign interactive systems rather than rely on retraining to address previous weaknesses in the operation of complex systems.

A final area of concern focuses on the dual nature of GPS navigation systems. One of the primary reasons for the introduction of these applications into safety critical systems has been that they can effectively reduce workload for crew members who might otherwise be preoccupied with relatively routine navigation tasks. The floatplane incident illustrates that these applications can also increase workload during key stages of flight. In particular, complex user interfaces create particular problems for the individuals and crews that must reprogram or reconfigure them in response to particular operational problems. In this incident, even a relatively minor correction occupied the pilot's finite perceptual and cognitive resources to such an extent that safety was undermined.

Aviation 2 – Bamiyan Controlled Flight into Terrain (CFIT): The second aviation accident forms a contrast to the relatively minor incident described in the previous paragraphs. Just as the grounding of the fishing vessel Sanga Na Langa contrasts with the more serious damage to the cruise liner Royal Majesty. This incident occurred in

November 2004when a Construcciones Aeronauticas Sociedad Anonima C-212-CC (CASA 212) twin-engine, turboprop airplane collided with mountainous terrain close to the Bamiyan Valley, near Bamiyan, Afghanistan. Several factors increased the significance of this accident. The aircraft was operating under a US Department of Defence (DoD) contract. The captain, first officer, and mechanic-certificated passenger, who were U.S. civilians employed by the operator, and the three military passengers, who were active-duty U.S. Army soldiers, received fatal injuries. The airplane was destroyed (NTSB, 2006).

The subsequent enquiry interviewed the program site manager who stated that he was not aware if route planning was explicitly performed for the mission. The accepted visual flight rules (VFR) flight plan contained destination information but did not indicate a specific route. Instead he argued that the pilots tended to follow well known routes between specific locations using a combination of GPS fixes and direct visual observations to ensure adequate clearance above mountainous terrain. However, analysis of the cockpit voice recorder revealed that the crew had never flown the selected route before. The mechanic was also heard to observe that the valley they had chosen to follow was not the most direct route. The captain later replied saying that they would 'just have to see where this leads'. The captain, first officer and the mechanic then discussed a topological map, the outside visual references and the coordinates derived from their GPS applications. The captain was then heard to remark 'well normally we'd have time to on a short day like this we'd have time to play a little bit do some explorin' but with those winds comin' up I want to [expletive] get there as fast as we can...with this good visibility … it's as easy as pie. you run into somethin' big you just parallel it until you find a way thru [sic]. … this is the first good visibility day I've had in the Casa. It's not just good it's outstanding' (NTSB, 2006). Sometime later the mechanic stated 'I don't know what we're gunna see, we don't normally go this route'. The captain replied '...all we want is to avoid seeing rock at twelve o'clock and the first officer stated 'Yeah you're an x-wing fighter star wars man'. The captain then replied 'You're [expletive] right. This is fun'. These informal exchanges continued when a passenger asked the flight crew about the route of the flight and the captain discussed some of their previous mountain flying experiences with the first officer. Shortly afterwards, the first officer stated that the ridgeline off to their left had a minimum elevation of approximately 14,000 feet meters above sea level. The captain stated that he was trying to find a 'notch to fly through', shortly afterwards the mechanic asked 'okay you guys are gunna make this right?' and the captain replied, "yeah h I'm hopin'. Ten seconds later, voice recorder seems to capture a stall warning tone single beep. The captain stated they could execute a 180º turnaround and instructed the first officer to lower the flaps. A further stall warning occurred and the mechanic stated, 'call off his airspeed for him'. The first officer responded 'you got ninety five' shortly before the recording ended.

The subsequent investigation argued that the exchanges captured on the cockpit voice recorder provided important insights into the attitude and behaviour of the crew in the immediate run up to the crash. It was suggested that the captain and first officer acted 'unprofessionally' in deliberately flying a nonstandard route low through the valley for fun even though the visibility was 'outstanding'. The captain's comment that he 'wouldn't have done this if we were at gross' was interpreted to mean that the captain made a conscious decision to fly the airplane in a way that he would not have done if the airplane had been at maximum gross weight.

This incident illustrates further aspects of the complex interactions that take place in the events leading to accidents that involve GPS applications. In this case, the use of navigation equipment was not a direct cause of the mishap. Instead it can be argued that it played a more circumstantial role in increasing the confidence of the crew that they could navigate their way out of the box canyon using little more planning that visual observations and periodic updates to their known location using satellite technology. In other words, the provision of GPS services formed a key component in the infrastructure that supported the sense of complacency that was criticised in the NTSB report. This complacency, in turn, was constructed on the high degree of trust that many operators place on modern navigation systems. As we have seen in previous accidents, this element of trust often goes far beyond what is advised by manufacturers and designers. It may also lead the operators of safety critical systems into situations from which navigation fixes may be insufficient to ensure the success of complex operations.

Overview of Human Factors Dangers of GPS

Previous sections have used two maritime and two aviation accidents to provide a limited overview of a wider range of recent mishaps that have arisen from operator interaction with GPS technology. These incidents have been deliberately selected to include both high profile failures, such as the grounding of the Royal Majesty, as well as lesser known but equally significant accidents in which users have been forced to cope without the expected support that they normally rely upon from satellite navigation systems, such as the CFIT involving the Cessna floatplane. Based on these incidents it is possible to develop an initial list of interaction problems that have occurred in the events leading to adverse events involving GPS related systems:

1. *Increased Workload.* The opening sections made the point that many of the benefits of GPS technology also create potential weaknesses under degraded modes of operation. For example, an important strength of many systems is that they remove the burdens associated with routine navigation tasks. However, many they also create additional workload in setting the systems up. Additional time must be devoted to planning a potential route and then programming appropriate waypoints into the system. Similarly, the complexity of interaction with these programmable systems can create significant dangers when operators are forced to fix even relatively trivial problems during more critical phases of operation. The additional burdens associated with specifying a revised destination for the floatplane is assumed to have prevented the pilot from realising that they were landing on water with the wheels extended.

2. *Interruption of Primary Tasks.* The failure of navigational systems can create a sudden increase in workload for particular crew members during critical phases of a safety related task. In other circumstances, problems may stem less from additional workload than from the way in which GPS tools can interrupt other non-navigational primary tasks. These interruptions occur during both normal and degraded modes of operation. It can be argued that there is a danger the pilot of the float plane might have forgotten to raise the landing gear even if he had been able to resolve the apparent problem with the destination fix. Human factors research indicates that even temporary distractions can be sufficient to cause slips and lapses in otherwise accurate plans (Reason, 1990). Several recent accident reports have described how crew deliberately chose to turn off the distractions created by the alarms generated by GPS applications (New Zealand Civil Aviation Authority, 2003).

3. *Hazards of Fail-silent Modes.* The floatplane accident was not caused because the GPS failed. In contrast, the system was programmed with the incorrect destination. The pilot observed the potential problem and intervened to resolve it. In contrast, the Royal Majesty ran aground because the autopilot and associated GPS continued to operate in a limited form of 'fail silent' mode based on dead reckoning. The crew were, therefore, faced with the opposite problems to those described in the previous item. Rather than being faced with the additional workload involved in solving a GPS failure, the crew continued to operate the system as though it were functioning normally when in fact they were receiving increasingly erroneous navigation data.

4. *Over-Reliance on Navigational Data*. A common theme across all of the incidents in this paper is the high degree of trust that operators place in GPS technology and their associated navigation systems. One element in this may be the increasing integration GPS applications into mass market consumer products. This may suggest that there is no additional requirement to consider the reliability and accuracy of GPS readings within the context of safety-critical systems; familiarity may breed complacency. The skipper of the Sanga Na Langa had operated his navigation systems for several years without any perceived failures and hence was extremely surprised when over-reliance on GPS data led to the grounding of his vessel.

5. *Lack of Hazard Monitoring and Over-Reliance on GPS Alarms*. Previous items in this list have considered the human factors problems that can arise when operators come to rely too much on the navigational information provided by GPS applications. One variation of this potential hazard stems less from any failure to monitor location information than from the high level of trust that can be placed on the alarms provided by these systems. For example, many autopilots enable operators to specify when visual and audio alarms are raised as they approach known hazards. This enables crew members to devote their attention to other primary tasks than to monitor the location of potential hazards in their environment. However, the grounding of the Sanga Na Langa illustrates what can happen when these alarms are not raised.

6. *Inaccuracies in Charts and Maps.* The Sanga Na Langa incident also revealed further hazards from interactive navigation systems. The subsequent investigation conducted several studies to ensure not that the GPS was functioning correctly but to ensure the accuracy of the associated electronic charts. Even when operators may be concerned to verify the location data provided by GPS applications, they may rely

too much on the location of hazards identified in electronic charts and maps. Many of these data sources were drawn up at a time when these technologies were not available and, therefore, may not be as accurate as the fixes that are routinely available across many industries. In other words, the widespread availability of accurate navigational aids is exposing the inaccuracies in many of the charts and maps that guide the operators of safety-critical applications.

7. *Erosion of Traditional Navigational Skills and Practices.* A continuing concern through several of the reports that were studied in this paper is the suggestion that the increasing use of GPS will lead to an erosion of traditional navigation skills and practices. This does not simply refer to the users' ability to make an accurate fix on their position. It also stems from a concern that operators are not taking the same degree of care in planning their intended route in the belief that they can always rely on GPS support to get them out of any eventual problem. The lack of route planning before the loss of the CASA 212 may provide an eloquent example of this concern. It can be argued that greater care might have been taken by the crew had they not been able to rely on the support provided by satellite navigation systems. As we have seen, however, the benefits provided by their technology are not always sufficient to address the wide range of operation problems that can arise during safety-related operations in unknown terrain.

This list is not exhaustive; it summarises only those concerns that arose in the incidents examined in this paper. . It seems clear that further problems will arise in the interaction between operators and the increasingly complex technologies that are being integrated with GPS and its successors. It is ironic; however, that the rising number of these adverse events may still not outweigh the larger number of adverse events which have occurred because individuals and teams of co-workers chose NOT to use navigational systems (New Zealand Maritime, 2004).

Conclusions and Further Work

The Global Positioning System (GPS) uses a network of orbiting and geostationary satellites to calculate the position of a receiver over time. This technology has revolutionised a wide range of safety-critical industries and leisure applications ranging from commercial fisheries through to mountain running. These systems provide diverse benefits; supplementing the users existing navigation skills and reducing the uncertainty that characterises route planning tasks. GPS applications also reduce workload by automating tasks that would otherwise consume finite cognitive and perceptual resources. However, the operation of these systems has contributed to a number of recent accidents. Users often come to rely on GPS applications and, therefore, fail to notice when they develop faults or when errors occur in the other systems that use the data from these systems. Further accidents can stem from the 'over confidence' that arises when users assume automated warnings will be issued when they stray from an intended route. This paper has argued that greater attention must be paid to the human factors of GPS applications as these technologies are integrated into increasing numbers of applications.

The timeliness of this work is increased by the realisation that GPS applications are increasingly being used as primary navigation systems. Standard operating procedures across many industries maintain that staff must not rely on these applications; they must use them to supplement more traditional manual forms of route planning. The accidents reported in this paper together with a host of similar mishaps reveal that operational practices may instead be built on the use of GPS with other techniques only being used intermittently for additional assurance. It is also important to emphasise the wider impact of GPS on system safety. The availability of accurate real-time navigation systems is no longer viewed as an additional enhancement to existing operational practices. Instead, these applications can be seen as capacity enablers. Users will erode safety margins providing that they can call upon the information provided by GPS technology. They will travel faster at closer distances from known hazards. This exposes operators and members of the public to even greater hazards when problems do occur with positioning systems.

A limitation of the work presented in this paper is that we have not explored the underlying perceptual and cognitive factors that contribute to GPS related incidents and accidents. It seems clear that trust in the services provided by navigational systems contributes to a form of over-confidence. Many accident reports describe the sense of surprise that operators express when they realise that there may have been a problem with navigation systems; 'He will never again depend on GPS data to the same extent again and is happy to relate his experience so that other mariners will learn from his mistake' (New Zealand Maritime, 2006). Further work is required to understand the precise mechanisms that account for such over-confidence so that we can better prepare individuals and teams of co-workers for the many problems that can arise when interaction breaks down with GPS applications.

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