Worldwide Beacon DGPS Status and Operational Issues

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May, 1999

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1. Biographies

Gunnar Mangs is Director of the worldwide Marine and Reference Station Business for Leica Geosystems Inc. in Torrance, California. He received his M.Sc. in Physics in 1970 from the Stockholm Technical University. From 1987 to 1997, Gunnar was President and CEO of C A Clase in Sweden, a company which distributes navigation products and systems to the commercial and military marine markets throughout Scandinavia and the United Kingdom. In partnership with Magnavox, C A Clase in 1991 installed the first Beacon DGPS Systems in the Baltic Sea. Gunnar also was the first chairman of the Scandinavian GNSS Industry Council.

Satish Mittal is the Product Manager for Differential GPS Systems, including DGPS Beacon Systems, at Leica Geosystems Inc. in Torrance, California. Satish received his BEE degree in 1974 and MEE in 1976 from Banaras Hindu University in India. Satish received an additional MEE in 1986 from the University of Toronto in Canada. He has more than 15 years experience in various disciplines of marine electronics, including the development of sophisticated, large scale, integrated navigation systems and DGPS systems.

Tom Stansell now heads Stansell Consulting. Previously he was a Vice President of Leica Geosystems in Torrance, California, where he was involved in technology development and strategic relationships. Tom received his BEE degree in 1957 and his MEE degree in 1964, both from the University of Virginia. At the Johns Hopkins Applied Physics Laboratory he participated in development of the Transit Satellite Navigation System. At Magnavox, he led the development of many Transit and GPS products and their underlying technologies, as well as initial development of the Magnavox Beacon DGPS systems and user receivers first installed in Sweden and Finland during 1991. He is the author of many technical papers, received the ION Weems Award in 1996 for continuing contributions to the art and science of navigation, and he was elected a Fellow of the ION in 1999.

2. Introduction

This paper was written at the request of Bill Adams, president of the RTCM. Bill asked Leica to look at Beacon Differential GPS (Beacon DGPS) from an overall and integrated perspective, rather than the more typical approach of dealing with a specific infrastructure design, a particular user equipment, or one nation's deployment status. We agreed because Leica has the perspective gained from being a significant supplier of both the infrastructure equipment, which provides and monitors the DGPS signals, and the user equipment for a wide range of marine applications. In addition, Leica has an important historical perspective, having been the first commercial company to develop and sell Beacon DGPS infrastructure equipment and among the first to develop and sell beacon DGPS receivers and navigation equipment.

The paper begins with three sections which provide important background material and overall perspective. The first of these shows how the Beacon DGPS service evolved, not as a single system but as a confederation of many systems. The reasons behind common signal standards are explained and praised, but the confusion resulting from different development paths, such as inconsistent definitions and terminology, are noted. The second of the background sections describes the extensive present and evolving coverage provided by Beacon DGPS transmitters. The third of these sections presents the key results from an international Leica survey of commercial users, knowledgeable sales agents, and experienced service representatives. Some of the results are quite surprising and already have influenced Leica's thinking about user equipment. Other insights should influence continued development of the worldwide Beacon DGPS service.

Following the three explanatory sections is a section which focuses on eight specific problems and suggests possible solutions for each. The titles of the eight subsections speak for themselves and are:

- Improve International Coordination and User Communication
- Provide Simple and Meaningful Status Indications
- Employ Higher Quality User Equipment
- Return to More Intelligent Beacon Signal Selection
- Improve Bridge Integration
- Reduce Inter-Station Interference
- Defend Against Natural and Manmade Interference
- Encourage and Prepare for an SA-Free Environment

The paper closes with a brief summary of the information presented and a review of the conclusions reached.

3. The Beacon DGPS Development Path

It is informative to compare development of the Beacon DGPS service with development of the Global Positioning System. In the case of GPS, a single organization, the Joint Program Office (JPO), was responsible for defining, developing, and testing every element of the initial GPS. This overall responsibility included the satellites, the ground control system, and many types of military user equipment. The development cost and the ongoing operational costs are paid by one nation. Since deployment, the U.S. Coast Guard Navigation Center (www.navcen.uscg.mil) has been designated as the point of contact and the official source of information for all non-military GPS users.

The Beacon DGPS development path was remarkably different. Rather than starting with a grand plan directed by one organization, it has evolved and grown with cooperation and input from many diverse organizations. It began as an experiment by the U.S. Coast Guard (USCG). At about the same time, several organizations realized that Selective Availability (SA) made differential GPS corrections necessary and that a standardized DGPS message would be desirable. As a result, the RTCM sponsored Special Committee 104 for this purpose. Participation from both government and industry was energetic and widespread. As a result, GPS receivers from almost every manufacturer are interoperable today due to the SC-104 standards. Because the USCG was a major participant in the work of SC-104, the Beacon DGPS data format both followed and helped drive the standard. The first operational deployment of Beacon DGPS transmitters in the U.S. was to reduce the cost of buoy tending and improve placement accuracy, not as an aid to navigation.

Other nations also began to realize the value of GPS and the need for DGPS, not only to improve accuracy but also to maintain control of their own coastal navigation signals. (It is troubling for a nation's local traffic to depend on another country's military navigation system, especially when accuracy is intentionally degraded and could be made worse at any time.) The Beacon DGPS concept was particularly attractive because Radio Direction Finder (RDF) beacon stations were well established, having been first deployed shortly after World War I (~1920). The land, the facilities, and, more important, the approved frequency band were all available. Furthermore, organizations were in place to maintain the beacons, decades of use had demonstrated the excellent coverage they provided, and their current utility was almost nonexistent because of newer navigation technology. Leica (then Magnavox) was the first company to develop and sell a complete suite of equipment which enabled existing RDF beacons to transmit RTCM DGPS messages. These first commercial systems were installed in Sweden and Finland in 1991.

Since then, the number of Beacon DGPS stations has grown tremendously. According to data from the WEB site of Communication Systems International Inc. (CSI of Calgary, Canada, www.csi-dgps.com), at this time 34 countries have installed Beacon DGPS stations, with 189 stations listed as on-line, 37 on-line without integrity monitoring, and 10 on-line in a test mode, totaling 236 on the air. Another 76 are listed as planned or under construction, giving a potential total of 312.

Each participating country follows its own path in establishing a Beacon DGPS service. The USCG internally developed its own system and software, while using commercially available components such as transmitters and GPS receivers. Other nations have solicited proposals and purchased a complete system from one of several commercial suppliers. A variation of this is for a nation to prepare a detailed specification which must be met by one of the commercial suppliers. Australia is a recent example of this approach, as described in Reference [1]. At least two nations initially chose to encrypt the beacon signals in order to collect revenue for their use. Fortunately this decision has been reversed and the signals are now freely available, as with all other participating nations. Nowadays the manufacturers are required to comply with the RTCM RSIM standard (issued in 1996) for the communication between the various elements within the beacon reference station. This helps to give current systems equal operational characteristics. Some of the earlier systems may however not be compliant with the RSIM standard.

Integrity control has taken at least two paths. The U.S. system is based on command and control. Any problem sensed at a reference station is communicated to one of two control centers where decisions are made and control messages are sent back to the reference station. In contrast, the Australian reference station software is designed not only to report to the control center but also to react autonomously to a problem in order to maintain station integrity even if communication with the control center is not available.

The preceding paragraphs highlight the differences between a system such as GPS, the development of which was centrally managed from signal source to user equipment, with development, operation, and maintenance paid for by a single government, compared with the Beacon DGPS service which has spread around the world in a far less formal and structured way. The cost and the responsibility has been shared, and the fact that the same set of navigation equipment can be used anywhere in the world that signals are available is a testament to effective international cooperation. The term Confederated System comes to mind when describing the Beacon DGPS service

There are, of course, some difficulties with having a Confederated System rather than a centralized system. Some of these will be noted in the section on Problems and Potential Solutions, below.

4. Beacon Coverage

Beacon DGPS coverage has grown dramatically during this decade. Figure 1 shows the coverage of stations declared by their national authorities to be fully operational, interim operational, or simply on-line. The difference between full and interim operational is driven primarily by on-air availability statistics, not by accuracy or integrity issues. Some of the on-line stations are unmonitored. However, the stations are considered trustworthy and are in daily use. (Note that these three figures have been supplied courtesy of Communication Systems International Inc., which in turn obtained station locations and status information from the national authorities.)

We have not shown those few stations which transmit encrypted signals in order to receive revenue for their use. In fact, we regret that any nation permits encryption of signals in this frequency band for revenue purposes. The band has been allocated and used for open radionavigation, without tolls, for many decades.

In addition, a few stations in this band have been installed by private companies for their own use, and the signals are not encrypted. Scanning beacon receivers will find and use these signals. Our concern is whether they are sanctioned by a nation member of the confederation and whether the reference survey coordinates and the signal standards meet accuracy, safety, and integrity requirements. This international radionavigation band should not be used for private commercial interests, at least without being sanctioned and required to provide safe public access.

Figure 2 adds stations which are on the air but are in a test mode. These also are being used by mariners and should be declared operational in the near future. Adding the stations in test mode increases coverage primarily in Egypt and around India. Figure 3 adds the pending stations, which are being installed but are not transmitting. As you can see, the entire U.S. land mass, including Alaska, will be covered. Growth also occurs in Spain, including the Canary Islands, Russia, Bangladesh, China, and Australia. To distinguish between pending and operating stations, the pending stations are shown with a black center dot and the operating stations with a white center dot. This is not the end of growth. Other national systems are being planned and will be installed in the coming months.

In a relatively short time, the world has obtained an important new infrastructure which promotes safety, protects the environment, supports commerce, and even aids pleasure activities on every continent. The challenge ahead is to consolidate and expand this growth, to improve system performance, and to adapt to a major change on the horizon.

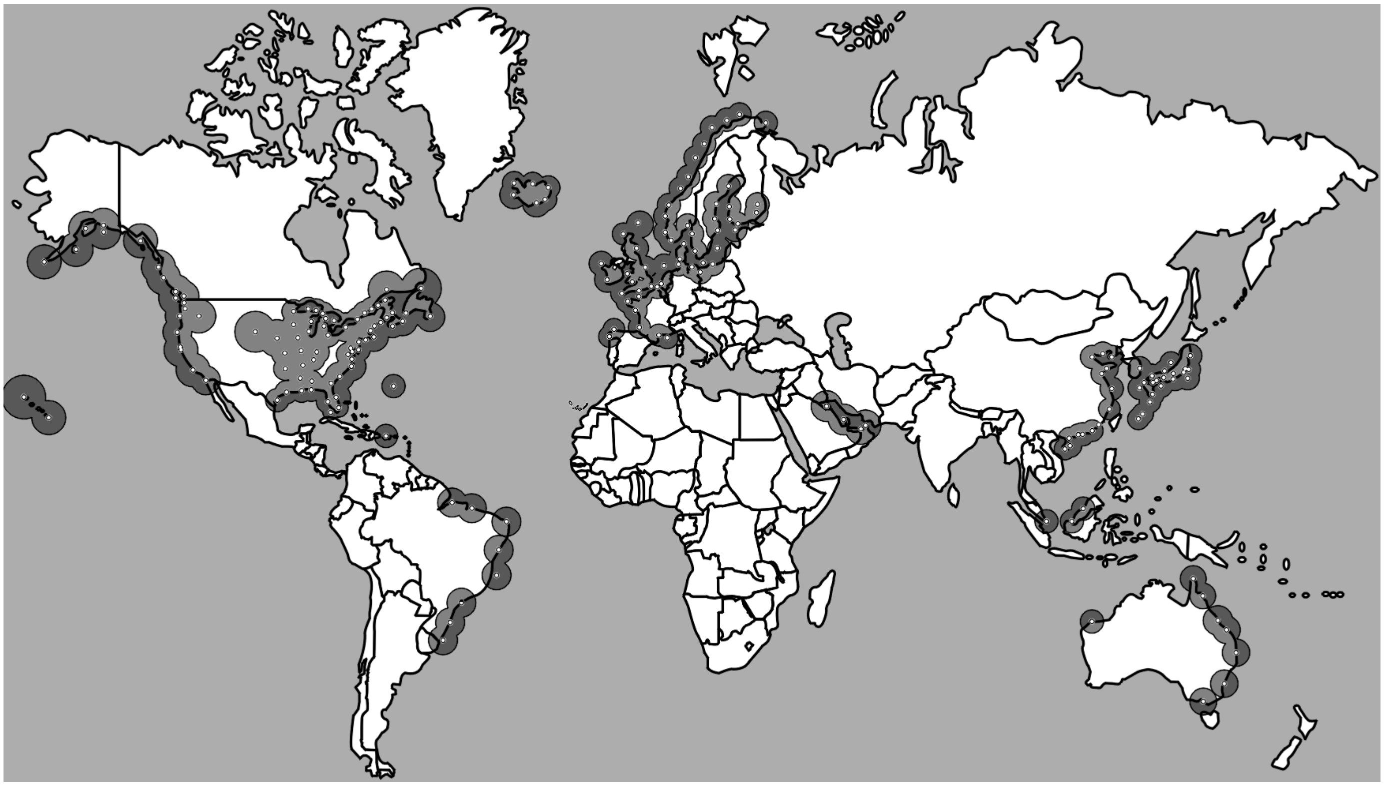

Figure 1 – May 1999 Coverage of Stations Declared Operational, Interim Operational, or On-Line
(Courtesy of Communication Systems International Inc.)

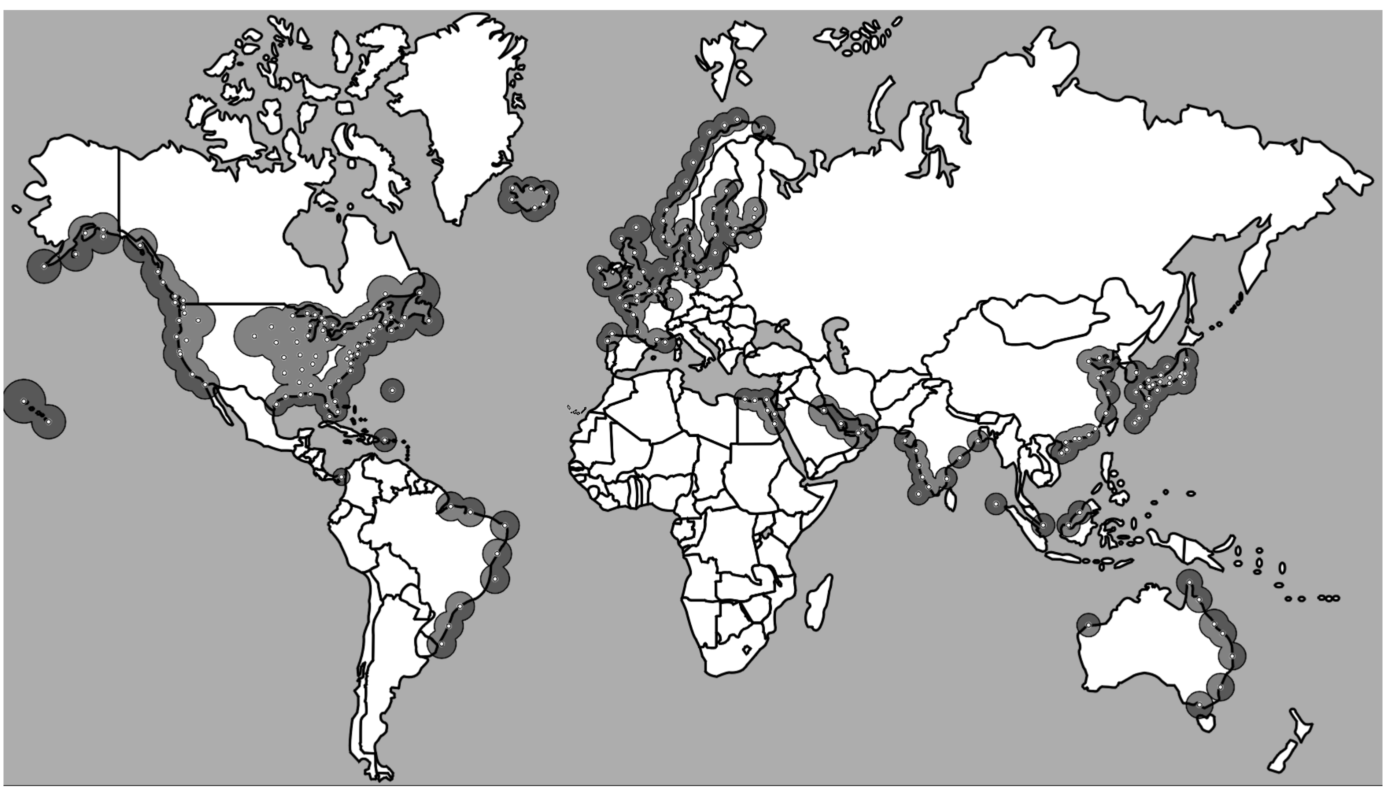

Figure 2 – May 1999 Coverage of On-Air Stations, Including Those in a Test Mode
(Courtesy of Communication Systems International Inc.)

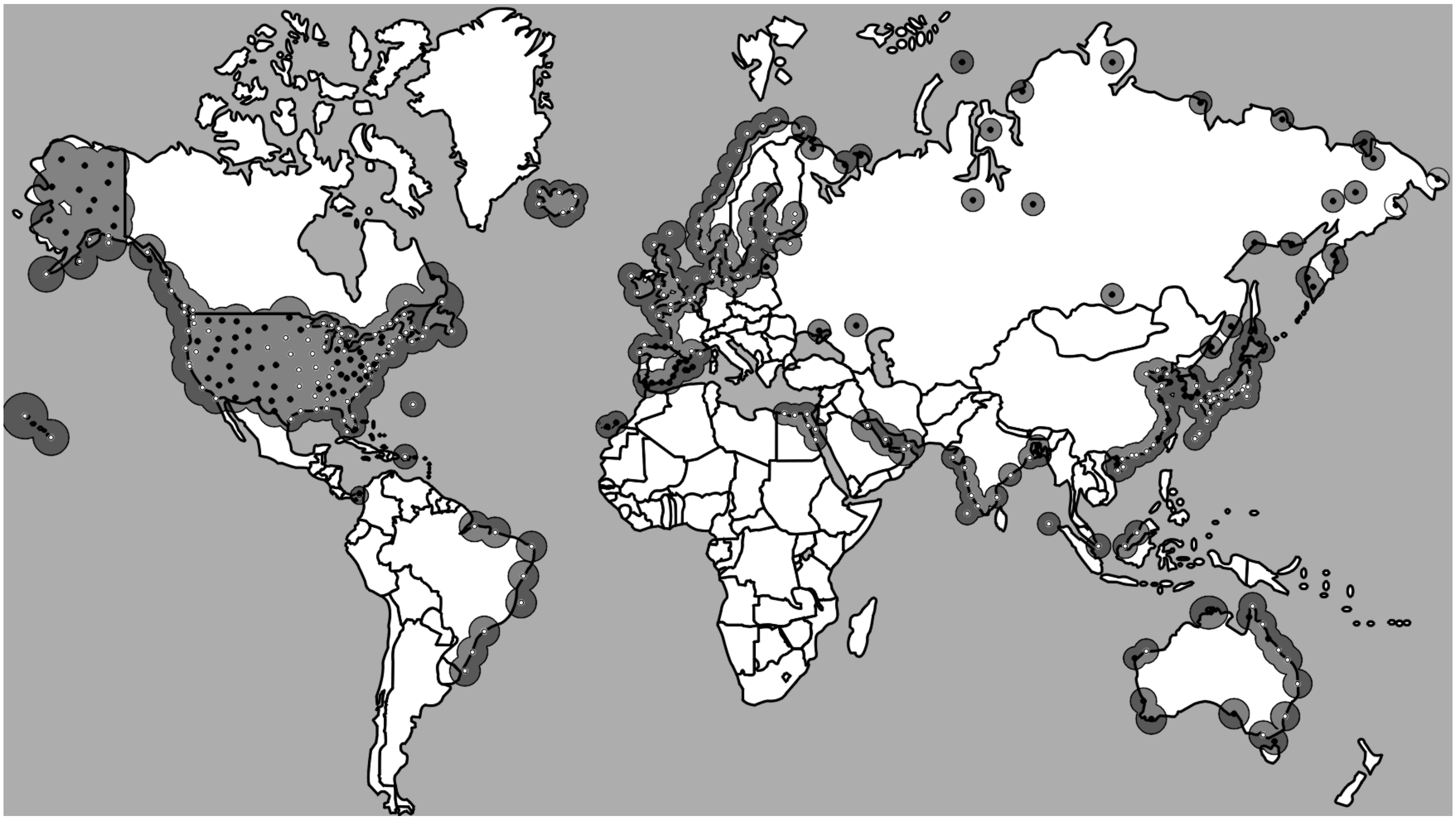

Figure 3 – Anticipated Coverage of Stations Whether Operating or Pending Operation
(Courtesy of Communication Systems International Inc.)

5. User Experience

Leica conducted a survey among commercial users of the Beacon DGPS service in various parts of the world. The most experienced agents and service representatives also were interviewed. The prime purpose was to see if users would identify any major aspects of the service that should be modified in order to extend and improve this use of GPS for navigation. Below is a summary of the survey results.

5.1 General View of the Service Provided

Most commercial users are satisfied with the reliability and accuracy of the Beacon DGPS service. Over 90% of the people interviewed expressed their satisfaction with the service and use it whenever they can receive the signal. It is our opinion that many users in the countries that first applied this technology regard it as a commodity. There is an expressed requirement for additional coverage in nations that more recently started to transmit Beacon DGPS signals.

The main advantages seem to be:

- Stabilization of the ECDIS display. This is essential, especially when navigating in restricted waters.
- Accurate speed input to the autopilot. In piloted waters this is in many cases the prime (or even the only) speed sensor used. Particularly for icebreakers, this is the only reliable speed sensor.
- Stable speed and heading, which racing yachts find the essential.
- Higher position accuracy, which is particularly valuable for fishing because it permits the fishing gear to be placed closer to the desired obstructions.

Those who were skeptical about the value of DGPS expressed concerns regarding:

- The value of an accurate position solution is undermined by the poor accuracy of Electronic Charts.
- There are inadequate accuracy or quality indications regarding the DGPS solution.

- Apparently there are problems in safely integrating DGPS into an automatic navigation system.
- It is a problem that control of the system is in foreign (i.e., American) hands and that accuracy is denied.

5.2 Transmission Quality

The move to RTCM Type 9 messages and in some countries to a 200 Baud data rate make the system quite robust. The range of the stations is considered sufficient in most cases.

5.3 Interference

The influence of "bad weather" as well as man-made noise, including own ship's noise, are the main causes for interruption of the signal. The real explanation for this "bad weather effect" is somewhat unclear. Precipitation static, which used to cause problems in high latitudes, is now considered to have been cured by the use of H-Field antennas.

5.4 System Integrity

There is limited understanding of the system operational status. Normally the user looks for the DGPS symbol on his GPS navigator and then judges the "stability" of his position display to evaluate accuracy.

Knowledge about and use of the Type 16 message is limited. In fact, most user equipment does not display this information. Even worse, many receivers do not display the Station Health Status (healthy and monitored, unmonitored, or unhealthy) provided in each message. Some authorities send out frequent warning messages if the system has not been declared operational, and most users do not know how to relate to this information (if their equipment is capable of displaying it). Most use the correction signal anyway and disregard the warning messages.

An alternative DGPS system is used in some areas for backup. This can be either an RDS FM sideband service (e.g. the Swedish EPOS) which is operated by a government authority, a satellite differential service, or a private reference station owned by the shipping company itself. Switching to these systems is done manually and is executed if the beacon system fails to deliver usable corrections. These users do recognize that these back-up systems are unmonitored and in some cases have an uncontrolled latency. The additional cost for such back-up systems is perceived as a major problem.

5.5 Switching between beacon stations

The common method used for station selection is either manual tuning or automatic scanning of the frequency band and selecting the strongest signal. It is a well known problem among experienced users that the beacon receivers with automatic scanning and switching can lock to a sky wave from a distant station and ignore a more suitable station that produces a weaker but fully usable signal. This may force the user to manually select the station and thereby make the operation more cumbersome.

5.6 Shipboard Equipment

The operators today view DGPS equipment as a commodity. Few understand the operational details and quality of the various components. There is an expressed need for some "position quality indication" and for relevant alarms.

Some users have raised aspects of the integration of the DGPS sensor to the ship's navigation system. Many use the DGPS speed as the only speed input to the ECDIS and navigation systems and set the GPS receiver to DGPS mode (forced differential). The loss of GPS corrections has in some cases caused the ship to completely lose automatic steering, since no automatic backup was provided.

6. Problems and Potential Solutions

6.1 Improve International Coordination and User Communication

As described in the Development Path section above, the worldwide Beacon DGPS service is a confederation of independent national systems rather than one centrally controlled system. Each country separately acquires, installs, and operates its own system. A key indication of this is just how difficult it is to determine the status of all existing or planned Beacon DGPS stations in all 34 countries. Some nations provide a WEB site for their own stations, e.g., www.navcen.uscg.mil for the U.S., www.amsa.gov.au for Australia, www.trinityhouse.co.uk/dgps.htm for Great Britain, www.fma.fi/radionavigation for Finland, or www.ccg-gcc.gc.ca/tosd-dsto/awtj/dgps/table.htm for Canada. (A brief WEB search on Yahoo for Beacon DGPS found companies which supply user equipment, but none of these government resources.) It is significant that the best overall source is the WEB site of a commercial organization (CSI of Calgary, Canada, www.csi-dgps.com).

An additional problem with this confederated system is that there are many different ways to describe the status of a beacon station, which makes it very difficult for a mariner to know what the status really means. For example, the CSI status descriptions include: On-line, On-line no Auto Integrity Monitoring; On-line Test Mode; No Service, and No Integrity Monitoring. The following information was recently obtained from the national WEB sites. "On March 15, 1999, the USCG announced that the U.S. system had achieved Full Operational Capability (FOC)". Prior to that date, the status was Interim Operational Capability (IOC). The status of most stations is simply listed as Operational. There is no indication as to how that does or should affect the mariner. The status of the Canadian stations for the most part is Initial Operational Service (IOS). The Australian status is Partially Operational, with individual stations listed as on-air or on-air-testing. The Finnish WEB site simply lists stations which are maintained by the Finnish Maritime Administration, with no other status indication.

There is a clear need for: (a) standardization of status terminology, (b) a clear definition of how the mariner should treat the status information (what operational difference should it make?), and (c) for a combined, coordinated, standardized, and frequently updated list of all Beacon DGPS stations and their status.

It would seem that the logical organization to fulfill this role is the International Association of Lighthouse Authorities (IALA, which also is known as Association Internationale de Signalisation Maritime, or AISM.). Quoting from their new WEB site (www.iala-aism.org), "Today IALA comprises 200 members, 80 of which are national authorities and 60 are commercial firms." IALA publishes Beacon DGPS standards, and IALA meetings (the next one of which is during 9 – 19 July, 1999, in Hamburg, Germany) are used to discuss and coordinate Beacon DGPS issues. We urge IALA to volunteer for this new task, which would involve: (a) reaching international agreement on a standardized status reporting format, (b) collecting status information very frequently from national authorities, and (c) making the status information available in a timely way on its WEB site. All participating national authorities would be urged to mirror or link to this information and to make it readily available to mariners by standard communication methods. All participating commercial firms would be urged to inform their customers about how to obtain this information.

Equally important, we urge IALA to create a document which informs mariners about the meaning of status messages, including the Type 16 messages broadcast by the beacons. The main purpose would be to suggest (not mandate) changes in navigational procedure based on the status information. This document should be disseminated by as many methods as possible. We believe an important secondary objective of this task will be to cause national authorities to collaborate in re-thinking the operational implications of status and warning messages from the mariner's perspective, which could result in an improved message strategy.

Finally, we believe it would be useful to increase the rate and the amount of communication between the confederation of signal providers and their worldwide users. Establishing a point of contact, such as the USCG Navigation Center is for GPS and for the U.S. Loran-C and Beacon DGPS services, should be considered. Part of the objective would be to document user inputs, suggestions, and complaints and to make them available to all users and signal providers. Service status changes would be shared with all. National organizations presumably would link their users to this central service and forward user inputs. The Confederation also could use a private part of this medium to exchange insights and even carry on debates about standards. Continuous and rapid communication should strengthen the Confederation, help raise standards, improve service, and thus benefit all users.

6.2 Provide Simple and Meaningful Status Indications

The current "health status" of each station is provided in its transmitted RTCM messages. There are three relevant states: (a) monitored, (b) unmonitored, and (c) not working or out of specification. States (a) and (c) are unambiguous. The signals are known to be reliable and accurate or they are known to be bad. Unfortunately, ambiguity is inherent in state (b); the signals probably are good but there is no independent information from an integrity monitor to verify the condition. In spite of the ambiguity, even worse is the fact that many DGPS receivers do not display the health status conditions at all.

One of the most significant findings from our survey of ship captains and other well informed mariners is that no one knows what to do about most, if not all, warning messages. What should he do knowing that a station is unmonitored? What should he do if the GPS receiver begins to warn that the station is no longer monitored? Some Type 16 messages continually repeat a warning, such as being in test status, with no problem being evident to the mariner. Therefore, the common response is simply to ignore all warnings! As a result, the entire purpose of warning the mariner, other than to limit the liability of the provider, has been lost. Today's warning procedures are less than ideal, and they could be dangerous by promoting complacency.

Leica has realized that equipment suppliers can do more to aid the mariner. The new techniques may be controversial at first, and they must be subjected to extensive review, field testing, and verification, but some of the directions are clear. Our user survey revealed that most mariners now consider Beacon DGPS equipment to be a commodity that either works properly or else it must be broken. The subtleties of propagation issues, natural interference, warning messages, and the like, are not appreciated and therefore are ignored. We believe the mariners are right and that equipment suppliers should be able to reduce these variables to a simple Green, Amber, or Red status indication.

We believe it is possible to provide shipboard integrity checking. Even if the received DGPS messages are not being monitored for integrity, the shipboard navigation solution with a high quality GPS receiver can determine if the DGPS corrections are precise relative to the defined reference station antenna location. In effect, the shipboard equipment can be its own integrity monitor. Even with warnings of an unmonitored station, the navigation equipment itself could give the mariner a green light. (The liability problem inherent in such a clear and meaningful display must be resolved.)

Following this approach, the only problem which could lead to a navigation error is for the DGPS message to report the wrong position of the reference station antenna. There are at least three ways for the shipboard equipment to detect such an error. First, with over 200 stations on the air, growing soon to over 300, the opportunity to receive multiple Beacon DGPS signals is substantial, especially because of skywave propagation. Even if the second signal is subject to many dropouts, a few good messages from another location can be used to verify that the primary message source does not have a substantial antenna position error. The second technique is the same idea, but using other sources of DGPS corrections, such as a Vessel Traffic System (VTS) or DGPS from an FM sideband system. The third method is to compare the DGPS position with other means of navigation, such as a radar map display. (The DGPS navigation equipment could ask for this confirmation before giving a green light.)

In addition to the above, shipboard DGPS equipment should be designed to use more than one source of DGPS corrections. For example, if two or more beacon signals are continuously processed, the loss of one signal will not cause even a momentary navigation outage. Also, by using two or more marginal DGPS signals, excellent navigation results still could be obtained. Other sources of DGPS corrections also can be used, as mentioned above. Today this is done by manual intervention, switching from one source to another. The mariner has a right to expect this switching and/or combining of DGPS sources to be performed automatically. He should become involved only if there is a problem.

We believe DGPS navigation equipment can be designed to provide a universal and unambiguous status display. This will simplify operation, but more importantly it will avoid the general tendency of mariners to discount and thus ignore the warnings they receive today.

A key problem, however, is the tendency of ship owners to purchase the least expensive equipment which satisfies minimum requirements. This is for the sake of economy and because most ship owners are not mariners. The only solution is to raise the regulatory standards, which is a far more difficult task than designing better equipment.

6.3 Employ Higher Quality User Equipment

Tests have demonstrated that there is a wide range of user equipment performance. Reference [1] notes an Australian Beacon DGPS test in which one equipment gave satisfactory results while the performance of another, at the same location, was unacceptable. Unfortunately, both of these probably met minimum carriage requirements.

In addition, although we noted above that mariners are ignoring the warning messages, that does not excuse the fact that some DGPS navigation equipment will not even display the broadcast Type 16 messages. The use of unsophisticated navigation equipment aboard large vessels is the result of inadequate regulation and the poor level of understanding, or caring, by ship owners.

6.4 Return to More Intelligent Beacon Signal Selection

Leica (then Magnavox) originally set the standard for Beacon DGPS receivers. It gave the responsibility for tuning the beacon receiver to the GPS receiver. The idea was to take full advantage of the computer in the GPS receiver, as well as its knowledge of position, to determine and then select the best beacon signal for that area. This concept is why the RTCM SC-104 format includes message Type 7, which is an almanac giving the location and frequency of other nearby beacon signals. By storing almanac messages from many stations, the GPS receiver can build an internal almanac of all stations it has been near. During a voyage, the GPS receiver, knowing its position, commands the beacon receiver to tune to the nearest and/or the best signal in that area.

Unfortunately, the original idea was nearly swept aside by the availability of less expensive one and two channel beacon receivers which, on their own, simply find the strongest beacon signal. This relieved the GPS receiver of having to monitor and control these decisions. The result was cheaper, and it seemed to work well.

However, as the number of Beacon DGPS transmitters has increased and as operational experience has grown, a problem has emerged. The strongest signal may be a skywave from a more distant transmitter. Or, something might be wrong with the strongest signal when a weaker but entirely satisfactory signal is available.

Although the less sophisticated approach may be adequate for low cost consumer products, we believe large ships should be equipped with a more sophisticated signal selection process. Too often today's mariner feels that he must manually select the best beacon signal because automatic selection by signal strength alone is not reliable. This task is better done by the GPS computer for several reasons: (a) it will not forget to make the next selection, (b) it can be programmed to recognize signal problems and make a better selection or selections, and (c) not all mariners are adept at or willing to make appropriate manual selections.

A related issue is that some beacons do not transmit the Type 7 almanac message. With a return to more intelligent signal selection, we strongly recommend that every beacon should provide Type 7 messages.

6.5 Improve Bridge Integration

A key issue from the user survey derives from the extent to which DGPS has become the primary source of speed (velocity) input to the autopilot, the radar plotter, and the ECDIS or ECS. This is a natural evolution because DGPS is the most accurate source of velocity as well as of position. However, many integrated bridge systems apparently do not automatically switch to a backup speed sensor when the DGPS output is interrupted. Perhaps worse, in many cases the GPS receiver is set to a Differential Only mode, meaning that it will provide a navigation solution only if the GPS measurements are being corrected. If local or manmade noise or other problems interrupt the beacon signal, the DGPS speed measurement to vital systems such as the autopilot suddenly drops to zero. We understand that at least one accident was caused or abetted by such an event.

A subtler version of this issue is the question of how GPS receivers derive velocity. Particular issues are how much filtering is applied and how long the receiver will continue to extrapolate position and velocity if the GPS signals are interrupted. One GPS receiver model was infamous for continuing to show a straight path well after the ship had begun its turn.

On one hand, the GPS receiver should be tuned properly for the application. Equally important, those responsible for integrating navigation sensors with vital control systems must understand the individual sensor characteristics and interactions and make provision for automatic backup if something fails, even briefly. Regarding the speed or velocity input, an integrated bridge system should make the best use of DGPS navigation when it is available but switch immediately to autonomous GPS or to a speed log when it isn't. Tuning the system to make use of a less accurate or biased input and warning the mariner of the change should occur without hesitation.

For the sake of safety, companies supplying sensors and companies combining them into systems should communicate more effectively and more thoroughly with each other. Regulatory organizations should understand these subtle interactions and put pressure on companies to supply and on ship owners to buy better and safer integrated bridge systems.

6.6 Reduce Inter-Station Interference

We think that in the early days of Beacon DGPS there was little concern about inter-station interference. Because of the limited number of frequency slots and because of the long distance a skywave signal can travel, this problem is becoming much more common.

There are at least three things which can be done. IALA and perhaps other organizations are engaged in predicting these interactions and beginning to allocate and even change frequency assignments to minimize the problem. We strongly endorse and encourage these activities.

The second step was mentioned above. By building smarter DGPS navigation equipment, especially with more beacon receiver channels, the GPS receiver can select only the best corrections or combine corrections from multiple sources to provide reliable navigation results. Use of beacon receivers which automatically select the strongest signal is not effective.

We are not experts in this area, but we suspect that a better job can be done of employing the available bandwidth. For example, many stations continue to provide separate signals for DGPS corrections and for direction finding, separated by 500 Hz. The practical need for marine radio direction finder (RDF) beacons in this age of GPS, Loran-C, and other navigation aids does not exist. The RDF signals should be discontinued and the transmitter power for these signals should be used to increase the DGPS signal power. By opening the RDF frequencies for DGPS signals, the inter-station interference problem would be reduced.

Other nations, such as the U.S., space the beacon signals a full kilohertz apart. By spacing the signals at 500 Hz intervals, the number of available channels would be doubled. It may be true that 500 Hz spacing is not desirable when using the preferred 200 Hz data modulation, although it does work. However, we must anticipate the removal of Selective Availability (SA), in which case a much lower data rate will support today's accuracy. Some dream of then providing two (or three) frequency phase corrections to support decimeter or centimeter navigation with the 200 Hz data rate capacity, which is a valid objective. Another approach would be to move to 100 Hz, or even 50 Hz, data rates in order to make space for many more non-interfering channels. It is past time to begin evaluating and debating the options possible when SA is removed.

6.7 Defend Against Natural and Manmade Interference

Because the beacon band is at such a low frequency, it is quite subject to natural as well as to manmade interference. Much progress against precipitation static has been made in the transition from E-Field to H-Field antennas. Even so, lightning storms and shipboard machinery can disrupt the service. It is at least ironic that accurate navigation may be most vital during stormy conditions.

There are only two defenses against lightning storm interference. One is to increase transmitter output power. For stations which transmit both an RDF and a DGPS signal, this could be done by discontinuing the RDF signal and diverting its power to the DGPS signal. The U.S. Government intends to cover all of the U.S. land mass with overlapping Beacon DGPS coverage. This is termed NDGPS, for Nationwide DGPS. The Air Force GWEN (Ground Wave Emergency Network) transmitters and antennas are being converted for this purpose. Because the antenna height and the ground plane radius is about twice that of the antenna installations used for coastal coverage, the efficiency is much better and therefore the radiated power from these sites is substantially higher. A bigger antenna is one way to transmit more power.

The second defense against storm interference is extremely effective, costs nothing, and provides other important benefits. This important safety enhancement is to discontinue Selective Availability, as discussed more fully below.

Manmade interference comes largely from arcing or sparks caused by electrical machinery or combustion engines. One difficult aspect of this type of interference aboard ship is that it can change through aging of existing equipment or by installation of new equipment. Fortunately, much of this equipment may not be in use when the ship is underway. However, this type of source can be located with simple or improvised test equipment (such as a portable AM radio), and there are ways to eliminate or to shield these sources. Mariners would benefit from a better understanding of noise sources, how to find them, and how to minimize or eliminate them.

6.8 Encourage and Prepare for an SA-Free Environment

As you know, Selective Availability (SA) is the process whereby the U.S. Department of Defense (DoD) reduces the accuracy of autonomous (i.e., non-differential) GPS navigation for all but friendly military forces to about 50 meters RMS (100 meters 2dRMS). This is the dominant error source for civilian navigation, and it has been the primary motivator for differential GPS services.

The U.S. Government has announced that SA will be discontinued by at least 2006 and possibly as early as 2000. You may be surprised to learn that although the DoD will not have its replacement for SA (which is denial of GPS access to the enemy in a local area of conflict) in full operation for many years, there is little DoD support for continuing SA. Therefore, many are optimistic that SA will be discontinued as early as 2000.

Now that DGPS services are so prevalent, the navigation community realizes that DGPS will continue to have a significant role to play even after SA is discontinued. Without SA, DGPS accuracy will improve and always be better than autonomous GPS accuracy. Equally important, however, is the extra integrity provided by DGPS, which assures that a GPS satellite failure cannot cause a subtle but dangerous navigation error.

Now is the time to plan for changes in DGPS systems when SA is discontinued. This is especially true for the confederated Beacon DGPS service, which preferably will continue to employ common signal standards. Much time will be needed to agree on and to coordinate the changes.

The implications of no SA are profound. The fundamental change will be to have a very stable satellite clock rather than one which intentionally wanders randomly. The rate of SA wander has forced DGPS signals to provide fresh corrections every few seconds, otherwise the wander quickly generates meters of navigation error. With very stable satellite signals, accuracy can be maintained with infrequent DGPS updates. For example, the drift of a stable satellite signal will be measured in centimeters per minute, which means that corrections every few minutes will be more than adequate to maintain today's DGPS accuracy.

Many opportunities will be created when SA is discontinued. Without a message change (although changes could improve these results), it is clear that the range of beacon coverage will increase substantially and there will be much greater resistance to interference. These improvements occur naturally because complete corrections are needed only every few minutes. Excellent performance will continue even if most messages are lost due to weak signals or to interference. (Low rate or intermittent corrections might seem to violate integrity requirements. However, with improved accuracy, Receiver Autonomous Integrity Monitoring (RAIM) will be extremely robust and should more than compensate for low rate messages.)

With no SA, it will be possible to modify Beacon DGPS signals to achieve decimeter (if not centimeter) accuracy, and in three dimensions. Accurate knowledge of keel depth relative to underwater topography has enormous economic value. On the other hand, reducing the data rate would allow many more non-interfering channels within the same band.

The purpose of this discussion is not to offer solutions. It is to say that eliminating SA will have a major impact on all DGPS services, and this new era could begin in a few months. An SA-free environment will, of itself, improve performance, but it will invite change in order to take better advantage of the new environment. We should begin work now to understand and to accelerate the change process. We have three recommendations:

1. This community should actively call for SA to be discontinued as soon as possible, preferably in 2000.
2. Studies, experiments, and discussions of how best to use the SA-free environment should begin now.
3. The level of communication among Beacon DGPS confederation members, suppliers, and users should increase quickly in order to prepare for a coordinated transition when the inevitable changes occur.

7. Summary and Conclusions

We are pleased that Bill Adams, president of the RTCM, asked Leica to prepare this paper. It prompted us to conduct a survey of commercial users, knowledgeable sales agents, and experienced service representatives to determine how they viewed the Beacon DGPS service. It also caused us to think more deeply about overall system issues. Some of the results already have influenced Leica's thinking about user equipment, and other results probably should influence further development of the worldwide Beacon DGPS service.

Three sections of background material and overall perspective were presented. The first showed how the Beacon DGPS service evolved, not as a single system but as a confederation of many systems. The reasons behind common signal standards were explained and praised, but the confusion of inconsistent definitions and terminology were noted. The second of the background sections described the present and evolving signal coverage. The third of these sections presented the key results from the Leica survey.

After the three explanatory sections, we focused on eight specific problems and suggested possible solutions for each. We called for a more centralized way to handle and to speed the communication between confederation members and the worldwide users. In particular we suggested that terminology be coordinated and that worldwide status information be made available from a common source. Our recommendation is for IALA to lead these efforts.

It was clear that mariners are confused by the ambiguity of the "unmonitored" status and by what to do differently when various Type 16 messages appear. The result is the potentially dangerous behavior of ignoring most if not all warning messages. We recommended that IALA work with the confederation to standardize meanings and publish these results. We also raised the possibility of providing the mariner with a simple but effective green, amber, or red indication, which would include on-board integrity monitoring.

We pointed out that some navigation equipment works much better than others, and we noted that such poor equipment is allowed on-board by inadequate regulations coupled with the desire of ship owners to buy the cheapest equipment that meets minimum requirements. Unfortunately we did not offer a simple solution to this problem.

The trend in beacon receivers has been toward autonomous tuning based on signal strength. Because of inter-station interference and other factors, we recommended a return to the earlier idea of having the GPS receiver tune the beacon receiver. This will lead to more dependable performance and reduce the amount of manual intervention now required. We also recommend that all beacon stations should transmit the Type 7 almanac message.

It was troubling to learn from our survey that some bridge integrated systems can allow the autopilot speed input to drop to zero if DGPS corrections stop for any reason. We recommended that companies which do the integration and companies which supply the DGPS equipment must increase communication in order to design interfaces and backups which avoid such dangerous conditions. This also calls for better understanding by regulatory agencies.

Inter-Station interference has become worse because of the increased number of DGPS beacon signals. Ways to reduce the effect of interference by smart signal tuning and use were suggested. Also, ways to add more channels were offered.

One of the biggest problems for Beacon DGPS is both natural and manmade interference. Suggestions for increasing signal strength and for smarter use of the existing signals were made. It was recommended that mariners be taught how to find and reduce or eliminate sources of own-ship interference using simple test equipment. To discontinue SA also was shown to be one of the most effective ways to defend against interference.

Finally, realizing that SA will disappear, perhaps just months from now, gave rise to a range of possibilities. A natural consequence is that DGPS performance will immediately become more accurate and more robust. The bandwidth released could be used to increase the number of non-interfering channels, or it could be used to provide multiple frequency phase corrections, leading to decimeter or centimeter accuracy. The desire to maintain common signal standards across the Beacon DGPS confederation was expressed, coupled with a call to begin analysis and discussions immediately about how best to serve navigators in an SA-free environment. We also urged this community to actively call for the elimination of SA as soon as possible, preferably in the year 2000. This would be a great Millennium gift to all navigators.

8. References

[1] R. Franko, S. Mittal, T. Stansell, R. Harris, E. D'Amico, and S. Cannon, "A New Generation of DGPS Broadcasting Stations", Proceedings of ION GPS-98, Nashville, Tennessee, September 1998.

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1023-Letter-5/99