DGPS Broadcasting Stations

A New Generation of DGPS Broadcasting Stations

Leica Geosystems, Torrance

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Robin E. Franko, *Leica Geosystems Inc., Torrance*
Satish K. Mittal, *Leica Geosystems Inc., Torrance*
Thomas A. Stansell, *Leica Geosystems Inc., Torrance*
Richard Harris, *AMSA*
Eddy D’Amico, *AMSA*
Stewart Cannon, *Consultant*

BIOGRAPHIES

Robin Franko is a senior staff engineer responsible for the development of DGPS Beacon Systems and GPS receivers for the Marine environment. She received her BA in Mathematics and Computer Science in 1980 from California State University at Long Beach. Robin has been with Leica and Magnavox for over 17 years and was instrumental in the development of the Series 5000 Integrated Navigation system.

Satish Mittal is the Product Manager for all Differential GPS Systems including DGPS Beacon Systems at Leica. Satish received his BEE degree in 1974 and MEE in 1976 both 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 is a Vice President of Leica Geosystems in Torrance, California, where he is 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 technology. He is the author of many technical papers and received the ION Weems Award in 1996 for continuing contributions to the art and science of navigation.

Richard Harris completed his bachelors degree in Communications and Electrical Engineering in 1984 and his Ph.D. in Electrical Engineering in 1996 from the University of Queensland, Australia. After working for the Australian Government Departments of Aviation and Defense, Richard joined the Australian Maritime Safety Authority's (AMSA) parent organization, the Department of Transport and Communications in 1989. He is currently the manager of Project Engineering with the Engineering Maintenance Operations Business unit.

Edmondo D’Amico has been an engineer with the Australian Maritime Safety Authority for the past 3_ years. For six years prior to this he worked as an engineer in radio and television broadcasting. He is currently the systems engineer for the Australian Maritime Safety Authority’s DGPS Program and is the Authority’s technical expert in GPS and DGPS. He obtained his Communications Engineering degree from the University of Canberra (UCAN) in 1989 and is about to complete his MBA from the same institution.

Stewart Cannon graduated from the University of New Brunswick, in 1980, with a BSc degree in Survey Engineering. He has over 18 years experience designing and developing integrated navigation systems for commercial and military applications. Stewart has been involved in offshore operations worldwide throughout his career and was the lead software architect for Pelagos Corporation’s object-oriented integrated navigation and data management system. Currently, he is a Vice President of Racal Survey Ltd. and is in charge of their software development worldwide.

ABSTRACT

Based on practical experience with three trial Differential GPS (DGPS) Broadcast Stations and careful evaluation of future needs, the Australian Maritime Safety Authority (AMSA) prepared a specification for an advanced DGPS network. The specified network would meet all international standards, be simple to install, easy to operate, both remotely and locally, and would provide excellent accuracy and operational availability, even

under adverse conditions. A solicitation was issued for the initial requirement of three Broadcast Stations, one spare Broadcast Station (for training and maintenance purposes), hardware and software to upgrade the existing trial Broadcast Stations, and four Control Stations.

In May, 1996, AMSA awarded this contract to Leica, and all of the Broadcast and Control Stations were installed during 1997. The three Broadcast Stations were declared operational in March of 1998 along with one of the trial Broadcast Stations. The other two trial Broadcast Stations have been commissioned but have not yet been declared operational. Based on excellent performance of the installed sites, an option for four additional Broadcast Stations was exercised. These will be commissioned by the end of November, 1998.

AMSA uses the four Control Stations to remotely monitor and control the DGPS Broadcast Stations. Furthermore, a portable Windows 95 version of the Control Station software is used by maintenance staff to access the AMSA network via modem wherever they travel in Australia.

Windows NT is used for all other system software, which takes full advantage of its multi-tasking capabilities. A Windows user interface makes operation of this powerful system simple, intuitive, and easy to absorb.

The Broadcast Stations are available with either single or dual frequency GPS reference receivers and a single frequency GPS integrity monitor. The reference receivers and integrity monitors meet the latest RSIM and RTCM message standards, are extremely rugged, and are designed for continuous unattended operation.

Overall, the design provides a complete, turn-key solution, with continuous integrity monitoring, virtually no downtime, and which is easily installed, maintained, and operated. This new generation DGPS System and its capabilities are described, and the excellent field performance of the Australian DGPS Network is documented.

INTRODUCTION

The Australian Maritime Safety Authority (AMSA), Australia's primary maritime administration, is chartered by the Federal Government to enhance safety for seafarers and shipping and to protect the marine environment from pollution. Under this charter, AMSA identified the need for a DGPS service to provide more accurate positioning information for vessels near its coastline. In 1994, AMSA installed three trial DGPS Broadcast Stations to investigate performance capabilities in several locations under practical conditions.

In October, 1995, AMSA issued a Request For Tender (RFT) for the procurement of an operational DGPS System. Due to the critical nature of the project, AMSA commissioned the services of Connell Wagner Pty. Ltd. (recognized internationally as an independent expert group in this field) to assist in development of the Technical Specifications. It was deemed essential by AMSA that the DGPS System must follow prevailing relevant standards and recommendations of the RTCM (Radio Technical Commission for Maritime Services), IALA (International Association of Lighthouse Authorities), and ITU (International Telecommunications Union), thereby ensuring that shipboard equipment on international vessels would be capable of receiving and using AMSA's DGPS service.

AMSA convened an internal Tender Review Board to assess all tenders submitted, and engaged Connell Wagner to analyze the technical responses. In May, 1996, AMSA awarded a contract to Leica Geosystems Inc. to supply and deliver four DGPS Broadcast Stations (three operational and one spare), four Control Stations, and equipment to upgrade the three existing trial Broadcast Stations.

First installations were at Sydney (July 1997), Mackay (September 1997), and Cape Flattery (February 1998). Based on excellent performance, AMSA has exercised an option to purchase four additional stations, which will be commissioned by the end of 1998 at Ingham, Gladstone, Lockhart River, and Brisbane. This will provide full coverage of the Queensland coast and principle Great Barrier Reef entrances.

In February, 1998, AMSA declared its DGPS service operational.

Leica developed the AMSA DGPS Beacon System Network based on AMSA's specifications and 25 years of experience in the development, engineering, and application of GPS.

SYSTEM DESIGN - OVERVIEW

Each DGPS Broadcast Station, within a network of other Broadcast Stations and Control Stations, provides DGPS corrections to users in its region via marine radio beacon signals. Marine radio beacons, which operate in the 283.5 to 325.0 KHz frequency band, broadcast DGPS corrections by modulating the normal beacon direction finding signal with the DGPS correction information. The signals are received by the beacon receiver on board the user's vessel and are demodulated to recover the DGPS corrections.

The correction messages are transmitted from a Broadcast Station. Each Broadcast Station is equipped with three GPS receivers. There is one active and one spare Reference Receiver, which generate the DGPS messages. The third GPS receiver is an Integrity Monitor, which navigates at a known site, using the received DGPS corrections to provide an independent quality check on the broadcast DGPS corrections. The result of these tests is reported in the health status information contained in the header of the DGPS (RTCM) messages. If the Integrity Monitor detects a failure in the primary Reference Receiver, the Broadcast Station software will switch automatically to the backup Reference Receiver.

Potentially there can be many unmanned Broadcast Stations. They are monitored and occasionally controlled by a few Control Stations which are staffed 24 hours a day. The Control Stations are connected to the Broadcast Stations by a Wide Area Network communication link with a backup telephone modem connection. Physically, the Control Station consists of a personal computer with 2 printers for alarm and report generation. The Control Station software, operating under Windows NT, permits one operator to monitor the entire network of Broadcast Stations and respond rapidly and effectively in case of trouble. In addition, a Windows 95 version of the Control Station software allows authorized personnel to dial in from other locations and both monitor and control the system, as appropriate.

SYSTEM DESIGN - HARDWARE

The AMSA DGPS Beacon System consists of a number of Control Stations linked with unmanned Broadcast Stations via a communication network. The Broadcast Stations are installed at strategic points along the Australian coastline, and the Control Stations are installed at regional operational sites. All of the equipment operates continuously. A wide area network is used as the communication link.

Broadcast Station

As shown by Figure 1, a Broadcast Station consists of two MX 9310 Beacon Reference Stations (each containing a GPS Reference Receiver and an MSK Beacon Modulator), an MX 9320 Beacon Integrity Monitor (GPS Integrity Receiver and DGPS receiver/demodulator), Data I/O which interconnects and switches between the system elements, the Broadcast Station Controller which is the on-site control computer, an Uninterruptible Power Supply (UPS) with battery backup, and dual Beacon Transmitters (not shown). The Broadcast Station Controller operates the Broadcast Station and reports to and receives instructions from the manned Control Stations.

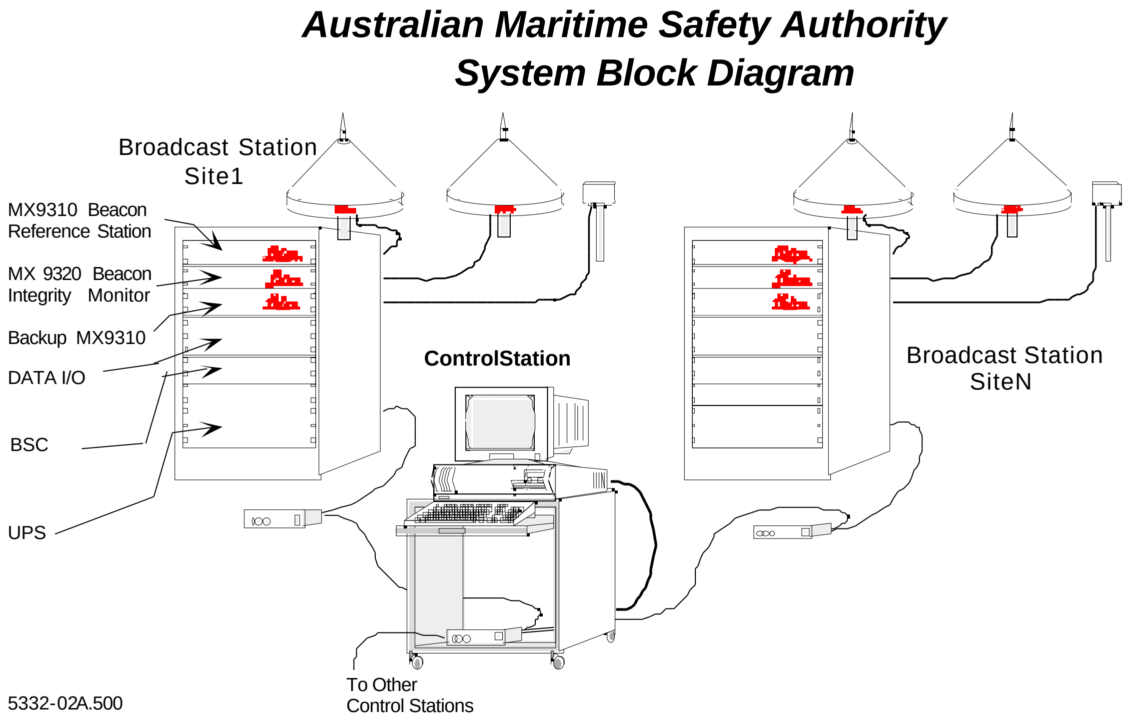


Figure 1: System Block Diagram

The Australian Broadcast Network consists of seven Broadcast Stations (including the spare station), each connected to a continuously manned regional Control Station by a wide area network with dial-up modem lines for backup. Each Broadcast Station transmits continuous DGPS corrections and related user information. Equipment redundancy is provided so that any single equipment failure does not preclude a healthy broadcast. In general, the Broadcast Stations operate autonomously, reporting to the Control Station periodically. However, they report immediately if a fault or out-of-tolerance condition occurs.

The Broadcast Station Controller is designed and programmed to operate the Broadcast Station autonomously and with full integrity, including resolution of the majority of potential problems by switching between redundant components. This is because communications with the Control Station cannot be guaranteed, and failure of the communications network, even for brief periods, must not jeopardize delivery of accurate and reliable DGPS corrections.

Each Broadcast Station continuously monitors its own transmission by means of a Beacon Integrity Monitor. Monitor-detected faults or out-of-tolerance conditions will cause the broadcast health status to be modified. Notification to the Control Station and navigation user occur automatically. If all on-air monitoring is lost, the station will continue to broadcast in an “unmonitored” mode, informing the user of this state. The Broadcast Station also can be controlled remotely via the Control Station or by an on-site operator.

The functions of the DGPS Broadcast Station are:

- computation and broadcast of DGPS corrections,
- broadcast of beacon almanac and reference station status information,
- failure detection of either the DGPS or the beacon transmitter equipment (or both), with automatic transfer to ‘hot’ spares and transmission of an alarm message to the Control Station,
- monitoring and logging of performance data (statistics). Periodically, these data are uploaded to the Control Station. If an out-of-tolerance situation occurs, the system issues a local user warning and notifies the Control Station.

Reliability

The AMSA DGPS Network has been designed to maximize system reliability so there is virtually no down time. Leica has enhanced system reliability in the following ways:

- redundant system functions,
- power conditioning unit (UPS) for support during a mains power failure,
- watchdog timer to monitor Broadcast Station Controller computer status,
- autonomous operation of Broadcast Stations,
- immediate notification to the end user of changes in DGPS correction quality,
- multiple communication methods to control and monitor Broadcast Stations from remote locations,
- maintainability with minimal downtime.

Redundancy of major functions is fundamental to ensuring that system operation will continue uninterrupted in case of a hardware failure. Each Broadcast Station contains two MX 9310 Beacon Reference Stations, one MX 9320 Beacon Integrity Monitor, one Broadcast Station Controller, and dual Beacon Transmitters. Each Reference Station includes an MSK modulator which can be switched to feed either beacon transmitter.

The MX 9320 Beacon Integrity Monitor continually monitors the quality of the DGPS broadcast by receiving the broadcast corrections, applying them, and comparing the resulting navigation solution to the known position. In this process, the Integrity Monitor monitors GPS satellite availability and geometry, DGPS data correctness and quality, DGPS signal presence, and transmitted power level. When any ‘alarm’ condition is detected, an alarm message is immediately sent to the Broadcast Station Controller for local response as well as the Control Station.

Both Reference Stations remain fully functional and are connected to one of the two transmitters. The equipment set actually transmitting the corrections is referred to as the active or primary unit and the other as the backup or passive unit. The second set of hardware operates as a ‘hot’ backup which can be activated at any time. If, for any reason, the DGPS broadcast becomes unhealthy, the backup unit is activated automatically from the Broadcast Station Controller or manually from the Control Station using preset criteria.

Any failure resulting in a loss of signal to the beacon transmitter or a significant decrease in the output power of the beacon causes the system to switch automatically from transmitter #1 to #2. Since the Broadcast Station Controller monitors the Reference Stations, Integrity Monitors, Modulators, and Transmitters, a failure occurring in any of these is automatically detected.

In case of a mains power failure at the Broadcast Station, the Broadcast Station Controller has sufficient time to establish a link to the Control Station and report the problem, since the system is supported by a power conditioning unit with battery backup (Uninterruptable

Power Supply). Additionally, the Broadcast Station Controller contains a built-in watchdog timer which automatically reboots the Broadcast Station Controller computer in the event that activity is suspended, thus further providing for autonomous operation.

In case of a failure with the CPU or the communication link, the DGPS correction broadcast is maintained. Although the Reference Stations are controlled from the Broadcast Station Controller or the Control Station, they are designed to operate unattended. If a fault occurs which indicates that a change of Reference Station or Beacon Transmitter is required but, due to the fault, cannot occur, then the active Reference Station continues to operate, but in an 'unhealthy' state.

One important aspect of reliability is ensuring the quality of the DGPS corrections to the end user. A quality indication is provided in the health information broadcast in the RTCM message header. A feedback loop from the Integrity Monitor directly into both Reference Stations is part of the system design. Periodic feedback messages are transmitted from the Integrity Monitor to the Reference Station indicating one of the following conditions:

- DGPS Corrections OK
- DGPS Out of Tolerance (Reference Station Unhealthy)
- Reference Station Unmonitored

Results of the feedback input to the Reference Station are reflected in the subsequent RTCM messages broadcast. The *DGPS Corrections OK* status is transmitted when the Integrity Monitor has reported that the DGPS corrections have passed all quality checks. If the position error at the Integrity Monitor exceeds the user-specified tolerance, the RTCM health status would indicate *Reference Station Unhealthy*. The *Reference Station Unmonitored* status can occur for a variety of reasons:

- the Reference Station is not receiving feedback messages from the Integrity Monitor,
- the Integrity Monitor is receiving the DGPS information, but cannot validate it,
- the Reference Station does not receive a feedback message from the Integrity Monitor (at a minimum of once per hour) which identifies those satellites being tracked at the Integrity Monitor.

In the event that a high residual for a given satellite is detected at the Integrity Monitor, that satellite is re-acquired automatically at both the Reference Station and the Integrity Monitor as part of the automatic feedback function between the Integrity Monitor and the Reference Station. If an anomaly is detected in one of the satellite signals, the periodic feedback is bypassed and the Integrity Monitor generates an immediate message to inform the Reference Station of the condition.

Real-time operator messages are part of the system design. Messages indicating impending status changes, poor satellite signals, etc., are user-defined and can be generated at any time. These messages allow the operator to notify DGPS users of important conditions in a timely fashion.

Complete integrity of any system also must include the end user. The equipment employed by the end user must be capable of detecting changes in the Reference Station health and informing the user of this condition. Corrections which are not 'healthy' should never be applied by the user equipment, and corrections which are 'unmonitored' must be carefully reviewed. Unfortunately, some user equipment pays little or no attention to these integrity messages. Leica's shipboard user equipment does provide complete system integrity by system alarms, reporting changes to Reference Station health status, and continually testing for invalid measurements and corrections.

Multiple communication methods provide an additional safety net for monitoring and controlling the Broadcast Station sites. The Broadcast Station Controller and the Control Station have been developed to support two communication links:

- Ethernet connection to a Cisco router - using TCP/IP protocol;
- Dial up modem via an RS-232 data port.

If one of the communication links fails, the other provides backup.

The communication protocol within the Broadcast Station between the GPS equipment and the Broadcast Station Controller adheres to the Reference Station Integrity Monitor (RSIM) specification developed by the RTCM and endorsed by IALA.

Maintainability of the AMSA DGPS Network is an important design factor. When maintenance is required, it must be quick and easy and cause minimal station down time. Although the computer hardware for the Broadcast Station Controller and Control Station computer portions of the DGPS Network are field proven, industry standard platforms, they too can fail. As a result, each system contains a CD ROM drive (SCSI interface) to allow technicians to upload and configure the entire Windows NT operating system in less than 20 minutes. Since the DGPS Network runs under Windows NT, technicians need not concern themselves about loading the proper SCSI drivers for the CD ROM, as Windows NT automatically loads the drivers for the connected devices at boot time. The technicians simply attach the cable to the SCSI port and reboot the system. Windows NT takes care of the rest.

Maintainability from a real-time standpoint is also a feature of this system. The user can command a restart of any of the GPS receivers located at the Broadcast Station, either locally or from a remote site. Digital I/O lines connect each device to enable the user to command a power on, or to remotely reset various hardware functions (alarm systems, security doors, etc.).

SYSTEM DESIGN - SOFTWARE

The AMSA DGPS Beacon System is based upon a design that allows flexibility, ease of use, and provides for future expansion. The system supports high level program languages (such as C or Pascal) and has memory map support with memory protection. Database management, password protection, print spooling, multiple tasking, and linkages with external vendor software packages are incorporated into Leica's approach.

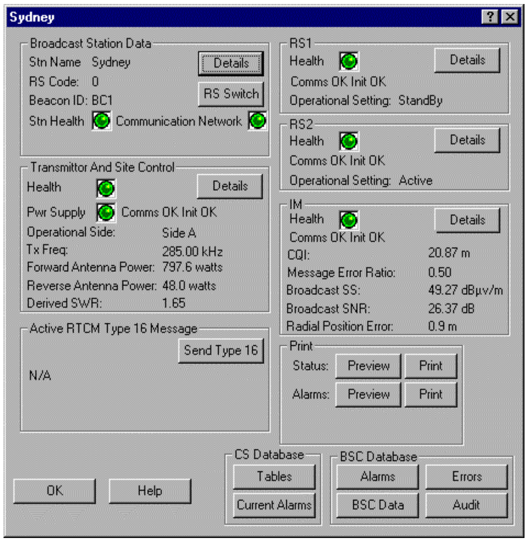
Operating System

The Windows NT Operating System provides an ideal platform for implementing the Control Station and Broadcast Station Controller features. Its built-in security, stability, multiple language support, preemptive multi-tasking capabilities, operator interface familiarity among a large base of users, and long-term support from Microsoft makes Windows NT the best choice of Operating Systems for the AMSA DGPS Beacon System.

Ease Of Use

The Windows NT documentation includes guidelines for operator interface design and operation which ensures that operators familiar with other Windows applications will be able to use the software in less time than with competing systems. Windows NT also provides the framework for implementing context-sensitive help in a standard manner. The AMSA system has been designed with these principles in mind.

The Control Station and Broadcast Station Controller appear as a standard Windows Application to the operator. The familiar menu bar, tool bar, client window, and status bar format is used. Since this is a standard Windows Application, it is possible to change the size or minimize the Main Window. Also, it is possible to run other applications simultaneously while the software continues to perform all real-time functions in the background or while minimized.



Stn Name Sydney
RS Code: 0
Beacon ID: BC1
Stn Health ● Communication Network ●

RS1
Health ●
Comms OK Init OK
Operational Setting: StandBy

RS2
Health ●
Comms OK Init OK
Operational Setting: Active

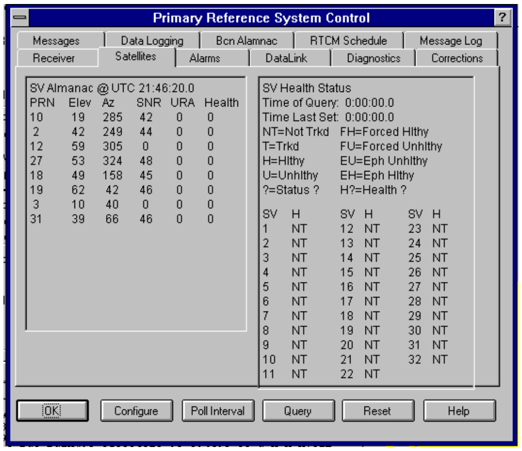
Transmittor And Site Control
Health ●
Pwr Supply ● Comms OK Init OK
Operational Side: Side A
Tx Freq: 285.00 kHz
Forward Antenna Power: 797.6 watts
Reverse Antenna Power: 48.0 watts
Derived SWR: 1.65

IM
Health ●
Comms OK Init OK
CQI: 20.87 m
Message Error Ratio: 0.50
Broadcast SS: 49.27 dBμv/m
Broadcast SNR: 26.37 dB
Radial Position Error: 0.9 m

Active RTCM Type 16 Message
N/A

Figure 2: Control Station Overview Window

Standard Windows controls are used for all operator interaction. General overview windows display important system data and traffic light status indicators (refer to Figure 2) are used wherever possible to help the operator determine system status at a glance. Secondary windows are accessed by a simple mouse click. This allows the operator to view the operational status of all Broadcast Station Controllers while also inspecting various detailed system parameters when required.



SV Almanac @ UTC 21:46:20.0

PRN	Elev	Az	SNR	URA	Health
10	19	285	42	0	0
2	42	249	44	0	0
12	59	305	0	0	0
27	53	324	48	0	0
18	49	158	45	0	0
19	62	42	46	0	0
3	10	40	0	0	0
31	39	66	46	0	0

SV Health Status
Time of Query: 0:00:00.0
Time Last Set: 0:00:00.0
NT=Not Trkd FH=Forced Hlthy
T=Trkd FU=Forced Unhlthy
H=Hlthy EU=Eph Unhlthy
U=Unhlthy EH=Eph Hlthy
?=Status ? H?=Health ?

SV	H	SV	H	SV	H
1	NT	12	NT	23	NT
2	NT	13	NT	24	NT
3	NT	14	NT	25	NT
4	NT	15	NT	26	NT
5	NT	16	NT	27	NT
6	NT	17	NT	28	NT
7	NT	18	NT	29	NT
8	NT	19	NT	30	NT
9	NT	20	NT	31	NT
10	NT	21	NT	32	NT
11	NT	22	NT		

Figure 3: Reference Station Control Window

Tab control windows are used to a large extent because of their ability to group data items from a common source in an organized manner. For example, the operator is able to view all data from a Reference Station on a single property sheet containing multiple tabs (refer to Figure 3). This provides an intuitive interface for operator control and inspection.

Alarm Display

The AMSA operator enables specific alarm conditions by using window drop down menus. This can be performed at the Broadcast Station Controller or from the Control Station. When the Control Station receives an alarm, a permanent dialog box is displayed until the operator responds, regardless of other current system functions. This dialog contains a list of all alarms, along with a button to acknowledge them. The Alarm window displays the particular alarm condition, origin, duration, and present status. This allows the operator to quickly identify the source of the alarm and take the necessary action. The alarm window remains the foremost window until the alarm condition is acknowledged and rectified.

Database

Local databases retained in the Control Station are updated by polling the Broadcast Station Controllers over the network to obtain status, alarm, and error data. All RSIM data messages from each Broadcast Station Controller are logged and archived to a database on the local hard disk. Alarm data are logged to the Alarm Printer as well as to the Alarm Database. The Control Station also generates a Weekly Report for each Broadcast Station Controller for which it is a master.

The Control Station operator interacts with the system via a keyboard and mouse, setting Control Station and Broadcast Station Controller configurations and initiating data requests using graphics, dialogs, and tables. Two printers are attached; a system printer to provide general status/report information and an alarm printer to generate an independent hard copy of all logged alarms.

A database manager module allows the operator to view selected data and generate hard copies on the system printer.

Figure 4 shows a graphical display of position error for a single Broadcast Station site. In addition to position error, the Control Station and Broadcast Station Controller can graphically display the following information:

- Forward Power
- Backward Power
- Signal Strength
- Signal to Noise Ratio
- Message Error Ratio
- Correction Quality Indicat

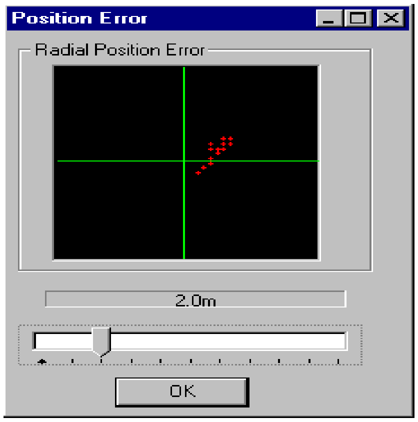


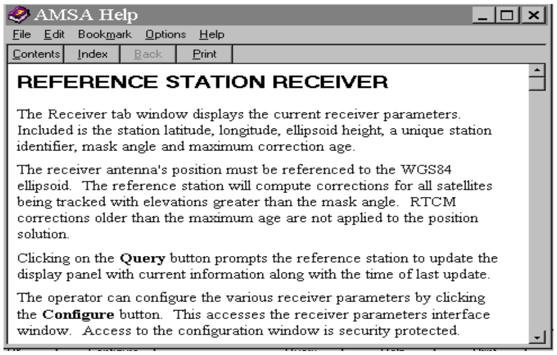
Figure 4: Position Error Display

Password Protection

Password protection and security for individual operator hierarchy and access to the Broadcast Station Information Database is maintained using Windows NT security features. This provides AMSA with the ability to pre-define which controls are available to each operator. Depending upon the level of security privilege assigned to the user, certain selections may not be accessible.

On-line Help

The On-line help features are implemented using Microsoft Windows Help. Each dialog and screen has a Help button allowing access to a typical Help screen describing the use and terms of the current display (context sensitive help). A Windows style Help option also is available from the Main Menu, allowing access to a typical help system using Hypertext links, a Contents Option, and an Index. Figure 5 shows a typical help window.



REFERENCE STATION RECEIVER

The Receiver tab window displays the current receiver parameters. Included is the station latitude, longitude, ellipsoid height, a unique station identifier, mask angle and maximum correction age.

The receiver antenna's position must be referenced to the WGS84 ellipsoid. The reference station will compute corrections for all satellites being tracked with elevations greater than the mask angle. RTCM corrections older than the maximum age are not applied to the position solution.

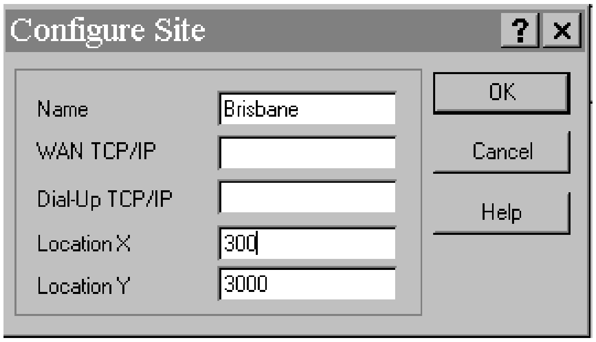
Clicking on the **Query** button prompts the reference station to update the display panel with current information along with the time of last update.

The operator can configure the various receiver parameters by clicking the **Configure** button. This accesses the receiver parameters interface window. Access to the configuration window is security protected.

Figure 5: On-line Help Window

Network Control

AMSA uses its wide area network (WAN) to control the Broadcast Stations from four Control Stations, located at the AusSAR (Australian Search and Rescue) facility in Canberra, and operational areas in Melbourne and Brisbane. The AusSAR Control Station is the primary monitoring center and is used to monitor the DGPS broadcast stations 24 hours a day. All AMSA DGPS stations communicate via a router and leased lines to AMSA's WAN. Figure 6 shows the window used to configure the network connection for a Broadcast Station.



Name: Brisbane
WAN TCP/IP:
Dial-Up TCP/IP:
Location X: 300
Location Y: 3000

Figure 6: Network Configuration Window

FIELD TEST RESULTS

Testing of the DGPS Beacon System was grouped into the following categories: broadcast availability, signal monitoring, and position accuracy.

Broadcast availability is an ongoing test which records the number of operational and down hours from each of the Broadcast Stations, both individually and combined.

The signal monitoring tests were conducted to verify the quality of the broadcast signal under varying conditions. The monitoring sites ranged from 65 to 152 NM from the Broadcast Stations and were affected by different levels of noise activity and unique path profiles.

The position accuracy tests were conducted by AMSA in conjunction with the signal monitoring tests and also by the University of New South Wales for an independent assessment of the performance accuracy.

It is very important to understand that position accuracy with Beacon DGPS is primarily affected by the time interval between receipt of correction messages. This is because Selective Availability (SA, which is the process of reducing GPS accuracy for users without military crypto access) causes the unaided solution to wander randomly within a 95% error boundary of 100 m. If every DGPS message is recovered, corrections are applied frequently and error is minimized. However, if some of the DGPS messages are not recovered, then corrections are applied less frequently and SA wander is able to introduce substantial navigation error.

Dependability of communication from the Broadcast Station to the user is primarily affected by natural as well as man-made noise sources. Lightning bursts and ignition noise are typical examples of such noise sources. The stronger the beacon signal, the less likely noise will interfere with reception. Fortunately for marine applications, beacon signals are attenuated far more over a land path than over water.

It also is important to note that the U.S. Government plans to discontinue use of Selective Availability by 2006 (although many observers expect this to happen much sooner). When SA is switched off, both the accuracy and the dependability of DGPS will be greatly enhanced. Without the SA wander, the GPS signals will be extremely stable, and a good correction every minute or so will provide excellent accuracy. Therefore, when SA is suspended, coverage will be extended, noise tolerance will be improved, and accuracy will increase.

Broadcast Availability

Table 1 shows the broadcast availability of AMSA's DGPS Service since it was declared operational in February, 1998 (current as of June 30, 1998). The figures in Table 1 are for a period of 90 days, in which there has been only one outage due to a maintenance visit to the Cape Flattery Broadcast Station site.

Station	Operational Hours	Hours Unavailable	% Availability
Sydney	2160	0	100
Mackay	2160	0	100
Cape Flattery	2160	6	99.72
Horn Island	2160	0	100
Total	**12960**	**6**	**99.95**

Table 1: Broadcast Availability

DGPS Signal Monitoring Program

AMSA established a signal monitoring program in order to assess the performance of its DGPS Service. The aim of this program was to monitor the quality of the broadcast signals from the Broadcast Stations.

AMSA used two DGPS signal monitors (non-Leica equipment) to record RTCM messages transmitted from the Broadcast Stations. Data logged for 24-hour periods were placed into text files and analyzed using Excel.

The logged data consisted of the signal strength, signal to noise ratio (SNR), radial error, and the number of RTCM Type 9 messages that failed parity checking. Data events were summed into discrete bins for efficient storage. The signal strength bins ranged from 14 dB to 71 dB at intervals of 3 dB. The SNR bins ranged from 0 dB to 19+ dB at intervals of 1 dB. The radial error bins ranged from 0 m to 45+ m at intervals of 5 m. Any logged data whose maximum value was greater than the highest bin value was recorded as an event in the highest bin value.

Results of the accuracy tests obtained for the Broadcast Stations installed at Sydney, Mackay, and Cape Flattery, as well as the upgraded station at Horn Island, are presented here.

The monitoring sites used for these tests are outlined in Table 2. Each site was chosen for different reasons. Some monitoring sites were located in noisy industrial areas, while other sites were located in quiet rural areas. Some sites had a sea/land path to the Broadcast Station, while others had a rugged terrain land path to the Broadcast Station. Some sites were located where the service was expected to work well (within 100 NM), while others were located at the boundaries of the estimated coverage area.

DGPS Station / Monitoring Site	Dist. (NM)	Path Profile	Noise	Wet/ Dry	SS **
Sydney					
Jervis Bay	65	sea/land	R*	dry	51
Newcastle	76	land rugged	I*	dry	54
Canberra	146	land rugged	S*	dry	30
Mackay					
Bowen	86	sea/land	R*	dry	63
Rosslyn Bay	152	land	S*	dry	42
Cape Flattery					
Cairns Depot	120	sea/land	I*	wet	54
Cairns Suburb	130	land	S*	wet	51
Horn Island Upgrade					
Weipa	126	land	S*	wet	39

*R = Rural, I = Industrial, S = Suburban

**SS = Signal Strength in dBµV/m

Table 2: DGPS Signal Monitoring Sites

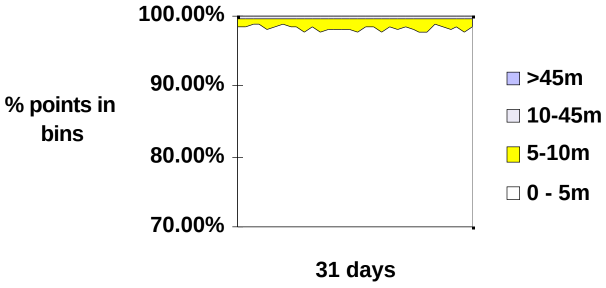
The DGPS service must provide corrections to enable better than 10 m accuracy 95% of the time to meet AMSA's accuracy requirements. For this reason radial error bins of 5 m were chosen.

The following charts show the percentage of observations in the 0-5 m, 5-10 m, 10-45 m and >45 m radial distance error bins. These charts also indicate in which radial distance error bin 95% of the observations occurred. If 95% of the readings are in the 0-5 m bin then we can be confident that the accuracy is better than 5 m, 95% of the time.

Monitoring of the Sydney DGPS Station

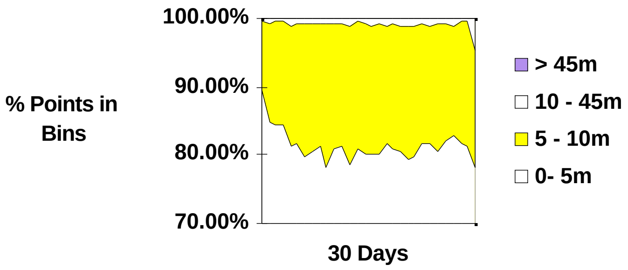
The Newcastle and Jervis Bay monitoring sites were chosen as they are located near important shipping areas requiring coverage by the DGPS Service. The Newcastle site was located in an industrial area which has high levels of electrical noise. The Jervis Bay site, on the other hand, was located at a quiet site. Both sites had path profiles traversing mountainous terrain. A further site was established at Canberra to monitor the service near the boundary of the estimated coverage area, again over a rugged terrain land path. All three sites were monitored during winter when thunderstorm activity was low.

CHART 1
Monitoring Results Jervis Bay



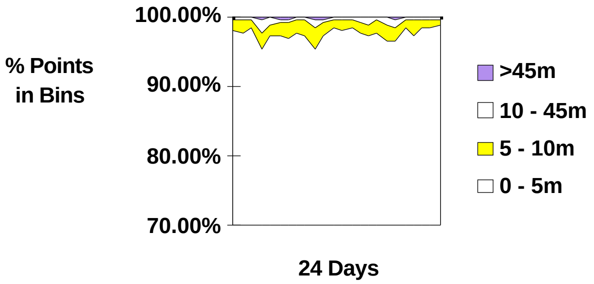
The daytime signal strengths at Jervis Bay and Newcastle were 51 and 54 dBµV/m, respectively. From earlier studies AMSA assumes that DGPS coverage for 95% availability extends to where the daytime signal strength is 42 dBµV/m. Hence, both monitoring sites are well within the coverage area. At Jervis Bay (Chart 1) the accuracy is better than 5 m 95% of the time, while at Newcastle (Chart 2) the accuracy is better than 10 m 95% of the time. The difference in accuracy is caused by an increased number of messages with a high correction age received at Newcastle because of interference from man-made noise.

CHART 2
Monitoring Results: Newcastle



Although the daytime signal strength at Canberra (Chart 3) was only 30 dBμV/m, the accuracy was found to be better than 5 m 95% of the time with a recorded SNR of 10 dB. This is significant as the results show that in areas where there is low man-made noise or atmospheric noise, the DGPS signal can be received with good accuracy much farther than that specified by AMSA. (AMSA's specification of 95% availability is defined as distance where daytime signal strength is 42 dBμV/m.)

CHART 3
Monitoring Results: Canberra

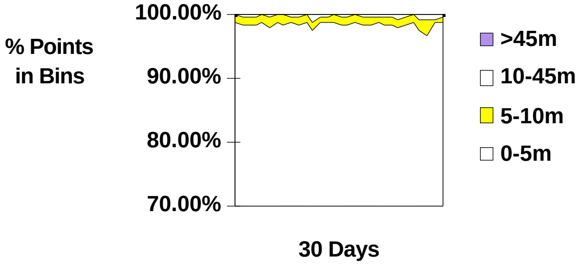


Monitoring of the Mackay DGPS Station

The Mackay DGPS station was monitored at Bowen and Rosslyn Bay, approximately 90 and 150 NM north and south of Mackay, respectively. The path from Mackay to Bowen is partly over sea and partly over land while the path to Rosslyn Bay was mostly over land. Noise at both sites was considered to be rural and suburban respectively. Both sites were monitored during spring when thunderstorm activity in the area was low.

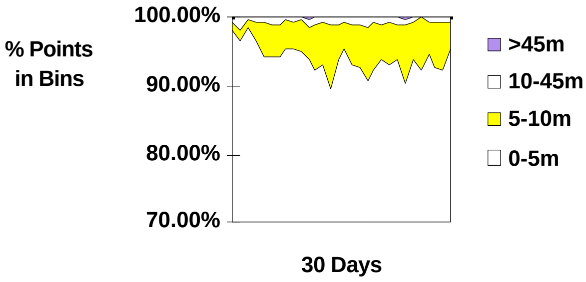
Bowen was chosen as a monitoring site because the Inner Great Barrier Reef route is directly beyond. The day time signal strength received at Bowen was 63 dBμV/m which indicates that the coverage from Mackay extends well beyond Bowen. Chart 4 shows that more than 95% of the radial error observations were less than 5 m.

CHART 4
Monitoring Results: Bowen



At Rosslyn Bay the received daytime signal strength was 42 dBμV/m, and was, therefore, on the boundary of AMSA's assumed coverage. From Chart 5 it can be seen that for 95% of the time, 9 of the 30 days had position errors in the 0-5 m bin while the remainder were in the 5-10 m bin. Hence, it can be assumed that the Mackay service extends beyond 150 NM for an over land path.

CHART 5
Monitoring Results: Rosslyn Bay

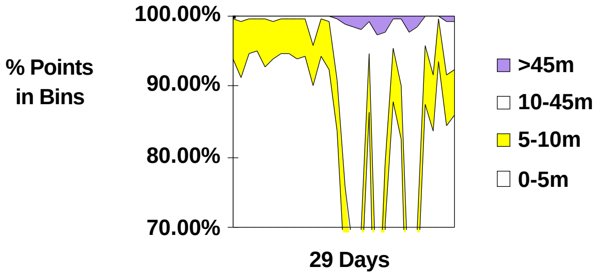


Monitoring of the Cape Flattery DGPS Station

The Cairns Depot is approximately 120 NM south of Cape Flattery and was ideally situated to monitor the Cape Flattery Broadcast Station. The path from Cape Flattery to the Cairns Depot is over a partly sea/land path. Noise at the Cairns Depot was considered to be industrial. The monitoring period was during summer when thunderstorm activity in the area was high.

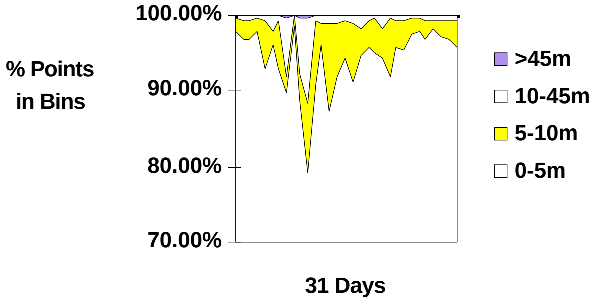
The daytime signal strength received at the Cairns Depot was 54 dBμV/m indicating that the Cairns Depot was within the Cape Flattery coverage area. However, a close examination of Chart 6 suggests otherwise. For the first half of the monitoring period the results appeared reasonable, but towards the end of the monitoring period the results were unexpected. On the worst day only 58% of the observations were better than 10 m.

CHART 6
Monitoring Results: Cairns Depot



From closer examination it was discovered that during peak times for power usage in Cairns, the number of messages which failed parity increased. It was confirmed by the Far North Queensland Electricity Board that the high voltage lines near the Cairns Depot were overloaded around 7 AM and 5 PM. A similar problem was encountered with AM radio at the Cairns Depot. To determine if this man-made interference, coupled with the high atmospheric noise, was a significant problem in the Cairns area, the signal monitor was moved to an electrically quiet location in a Cairns suburb.

CHART 7
Monitoring Results: Cairns Suburb



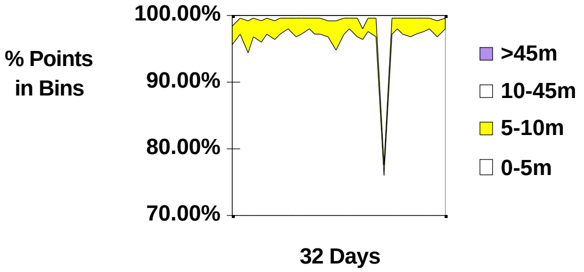
From the results of Chart 7 it is obvious that the accuracy was significantly better in the quieter location. Only three observation days had an accuracy worse than 10 m 95% of the time due to a high level of thunderstorm activity. On the worst day about 89% of the position errors were less than 10 m. Close examination showed that for these three days the actual radial error bin for 95% of time was the 10-15 m bin. The daytime signal strength received at the Cairns suburb was 51 dBμV/m.

Monitoring of the Upgraded Horn Island DGPS Station

The signal monitor at Weipa was located at a busy port approximately 126 NM south of the Horn Island DGPS station. The path from Horn Island to Weipa is a wet land path. This site was chosen as it was located close to the estimated edge of the Horn Island station coverage, as seen by the received daytime signal strength at 39 dBμV/m.

On most of the 32 days of the monitoring period there were more than 95% of the positions falling within the 0-5 m radial error bin. It was noticed on day 23 that this value dropped to about 76%. From further examination, it appeared that no valid corrections were received for a seven-hour period (even though messages were being transmitted from the Broadcast Station). The reason for this has not been determined but may have resulted from a problem with the signal monitor logging.

CHART 8
Monitoring Results: Weipa



Conclusions from DGPS Monitoring Program

From the DGPS monitoring program it can be concluded that the accuracies obtained from the Broadcast Stations are better than 5 m 95% of the time in locations where man-made noise is defined as rural/suburban. This assumes a daytime signal strength greater than 42 dBμV/m.

In locations where man-made noise is defined as industrial, this value increases to be between 5-10 m. Where man-made noise is very high and atmospheric noise is also high (as experienced at the Cairns Depot) the accuracies may even become greater than 10 m 95% of the time. DGPS Broadcast operators may need to use a daytime signal strength higher than 42 dBμV/m in areas of high atmospheric noise conditions. However, as stated earlier, this should not be a problem once SA is removed.

UNSW DGPS Monitoring Assessment

The University of New South Wales (UNSW) conducted an independent assessment of the accuracy and performance of the Sydney Broadcast Station during September, 1997. The University is situated a few kilometers from the coast and 20 NM from the Sydney station.

A Leica MX 52R DGPS Beacon Receiver was used to demodulate the broadcast RTCM message and to provide information to differential-ready DGPS receivers via a serial port. Monitoring was conducted over two periods; the first period of 25 days using a ‘low-end’ GPS receiver and the second period of seven days using a ‘high-end’ GPS receiver (both non-Leica receivers). The GPS antenna was mounted on a pillar that had been previously surveyed.

The UNSW provided daily plots of horizontal position error, as well as statistics such as the mean, maximum, and 2-sigma daily values of the DGPS horizontal position error.

Summary of Results

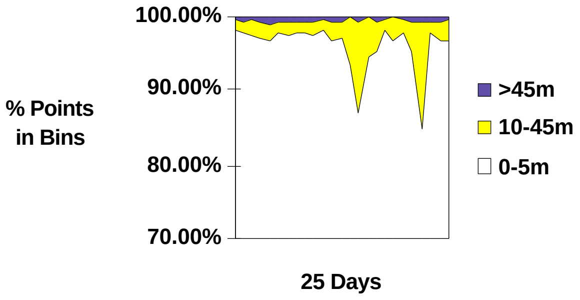
Summaries of the results for the two monitoring periods are shown in Charts 9 and 10. For statistical analysis purposes, the UNSW made the assumption that the distribution of accuracy observations was Normal. Any outliers (radial distance error greater than 45 m) were excluded from the statistical analysis.

The UNSW used three bins of range 0-5 m, 5-45 m and >45 m for the purpose of this report. Most observations fell in the 0-5 m bin. Observations in the 5-45 m bin reflected an aging correction message while those in the >45 m bin indicated a bias in the computed position. Circular probability confidence levels were also used as another measure of accuracy.

Results of First Monitoring Period

For this monitoring period, data were logged every 30 seconds over a 24 hour period for 25 days. On most of the 25 days of the first monitoring period more than 95% of the positions fell within the 0-5 m radial distance bin. It was noticed that on days 15 and 22 this value dropped well below the 95% level. On both these occasions there was an increase in the 5-45 m error bin, indicating that the age of corrections were older, producing reasonable but less accurate positions.

Chart 9
Low-End DGPS Receiver Test

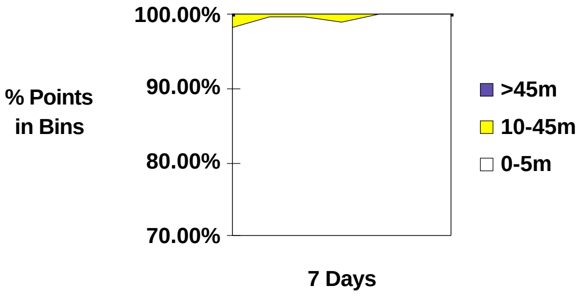


The 2-sigma value and the 95% CEP (Circular Error Percentage) values were close (ranging from 3.67 m to 11.00 m) and the overall mean was 2.03 m. This test also showed that a maximum distance error ranging between 150 m and 200 m was observed on most days, suggesting a gross error in position. To determine if the receiver produced the errors, UNSW decided to conduct a second test using a ‘high-end’ GPS receiver.

Results of Second Monitoring Period

For this monitoring period, data were logged every 20 seconds over a 24 hour period for one week. The logged data also included information on the age of the correction message. In this test only seven values of radial distance greater than 45 m were observed over the week period. One of these errors resulted from a significantly old correction message; the other six values were considered to be gross errors.

Chart 10
High End GPS Receiver Test



The 2-sigma value and the 95% CEP values were again close and more accurate than for the first test (ranging from 0.79 m to 3.15 m). The overall mean was 0.71 m.

Conclusion from UNSW Report

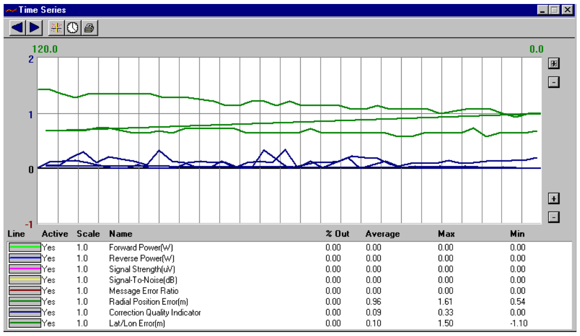
The very large daily maximums which occurred in both monitoring periods may cause concern to the end user. However, as the signal monitoring of the Sydney station at Newcastle overlapped with the UNSW tests, it was confirmed that these ‘spikes’ were **not** transmitted from the Broadcast Station. The daily plots of the horizontal position error suggest that these gross errors were isolated events and tended to return to a more reasonable value at the next epoch. It appears that the large error values were caused by multi-path disturbances and the inability of these GPS receivers to mitigate them. The UNSW mentioned in the report that previous GPS observations made at the same site have shown similar evidence of a severe multi-path environment.

Both the ‘low-end’ and ‘high-end’ GPS receivers used for the UNSW DGPS Monitoring Assessment tests validated the accuracy of the DGPS corrections transmitted from the Sydney Broadcast Station (better than 10 m accuracy 95% of the time). It can be seen that even in an area of high multi-path disturbance the GPS receivers can produce accurate results using the DGPS information broadcast from AMSA’s DGPS Beacon sites.

SYSTEM ENHANCEMENTS

Recently, Leica has enhanced the Broadcast Station Controller software for customers such as China MSA and India DGLL so that all Control Station functions are available at the Broadcast Station Controller. Additional features which have been implemented include:

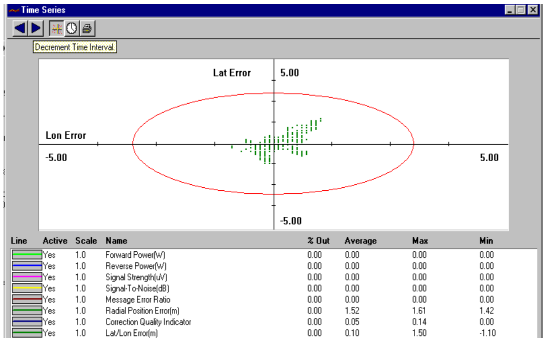
- Real-time display of time series graphs with complete operator control for forward power, backward power, signal strength, signal-to-noise ratio, message error ratio, radial position error, and correction quality indicator (see Figure 7).



Line	Active	Scale	Name	% Out	Average	Max	Min
🟩	Yes	1.0	Forward Power(W)	0.00	0.00	0.00	0.00
🟦	Yes	1.0	Reverse Power(W)	0.00	0.00	0.00	0.00
🟪	Yes	1.0	Signal Strength(uV)	0.00	0.00	0.00	0.00
🟨	Yes	1.0	Signal-To-Noise(dB)	0.00	0.00	0.00	0.00
🟥	Yes	1.0	Message Error Ratio	0.00	0.00	0.00	0.00
🟩	Yes	1.0	Radial Position Error(m)	0.00	0.96	1.61	0.54
🟦	Yes	1.0	Correction Quality Indicator	0.00	0.09	0.33	0.00
🟩	Yes	1.0	Lat/Lon Error(m)	0.00	0.10	1.50	-1.10

Figure 7: Time Series Plot

- Real-time display of bullseye plot for radial position error (see Figure 8).



Line	Active	Scale	Name	% Out	Average	Max	Min
🟩	Yes	1.0	Forward Power(W)	0.00	0.00	0.00	0.00
🟦	Yes	1.0	Reverse Power(W)	0.00	0.00	0.00	0.00
🟪	Yes	1.0	Signal Strength(uV)	0.00	0.00	0.00	0.00
🟨	Yes	1.0	Signal-To-Noise(dB)	0.00	0.00	0.00	0.00
🟥	Yes	1.0	Message Error Ratio	0.00	0.00	0.00	0.00
🟩	Yes	1.0	Radial Position Error(m)	0.00	1.52	1.61	1.42
🟦	Yes	1.0	Correction Quality Indicator	0.00	0.05	0.14	0.00
🟩	Yes	1.0	Lat/Lon Error(m)	0.00	0.10	1.50	-1.10

Figure 8: Real-time Radial Position Error Plot

- Recording of operator defined data at a user selectable interval.

- Statistics computation on recorded data. This feature takes advantage of the Windows NT multi-tasking capability and does not affect the real-time operation of the system. The results are displayed graphically and numerically.

- Local language support. For example, the use of a Chinese character display for the China MSA system.

CONCLUSION

This paper illustrates how the latest generation of Leica Beacon DGPS Systems was designed to meet the stringent requirements of AMSA. AMSA's System has proven to be highly reliable, with virtually no downtime. All independent testing of signals from each Broadcast Station yielded similar results, and the accuracies are within AMSA specifications.

AMSA operators have found the system simple and easy to use. Because of the intuitive nature of the Windows NT software for the Broadcast Station Controller and the Control Station, it took AusSAR operators only one hour to learn how to monitor the alarms at the Control Station and less than one day for the AMSA operators to learn the complete functionality at the Control Station. Hardware technicians have had a similar positive experience with on-site installations. Following the installation of the first three Broadcast Stations, AMSA has determined that only 1.5 days are required to install the hardware and another 1.5 days to commission the site, for a total of three days for a site to become fully operational.

There are several key observations which result from this rigorous process:

1. The new generation of Leica DGPS Beacon Systems now being used by AMSA meets rigorous standards of reliability, maintainability, ease of installation, ease of use, accuracy, and integrity.

2. Navigation users should not assume that all DGPS user equipment is equivalent. There are large variations regarding: GPS multi-path mitigation, beacon signal sensitivity, mitigation of impulsive noise in the beacon frequency band, alarms to the operator when age of DGPS corrections is excessive or when warning messages are received, and direct access to Beacon System warning messages. To preserve integrity, a DGPS navigator should make it clear whether the navigation solution is fully trustworthy or not. These issues are vital and can make the difference between tragedy and safety of life at sea.

3. When Selective Availability is switched off, DGPS Beacon systems will become much more robust and accurate. Without SA a high percentage of messages can be lost without affecting navigation accuracy. As a result, the navigator can get precision accuracy at the boundaries of beacon coverage and in areas of natural and man-made noise. Beacon DGPS systems will automatically realize an increase in coverage, accuracy, and reliability of service.

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[2] Robertson, D, *The Accuracy and Performance of DGPS using the Australian Maritime Safety Authority DGPS Broadcast Station at Glenfield, Sydney*, School of Geomatic Engineering, University of New South Wales, January 1998.

Leica Geosystems Inc., 23868 Hawthorne Blvd, Torrance CA 90505, USA
www.leica.com/gps

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