The New THALES DG16 GPS Receiver

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BIOGRAPHY

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Dr. Sergei Lusin is a Research Scientist and a Group Manager at the Moscow Development Center of THALES Navigation. He holds a Ph.D. from the Moscow Aviation Institute. Dr. Lusin has over eight years of research and development experience in the areas of spread-spectrum design for communication and navigation systems.

Mr. Oleg Tubalin is Software Engineer at the Moscow Development Center of THALES Navigation. He holds a degree from the Moscow Aviation Institute and has over six years of experience in the development of GPS receivers.

ABSTRACT

With the growing demand for accurate and reliable worldwide differential GPS positioning, there has been a significant move towards the use of real-time Satellite Based Augmentation Systems (SBAS) with wide area differential positioning capabilities. The US Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay system (EGNOS) are good examples of such a move.

While these augmentation systems are developed to provide differential corrections and integrity data for satellite-based aviation, their signal will be available free of charge to all other non-aviation satellite positioning users in the respective coverage areas. Accordingly, non-aviation GPS users with WAAS/EGNOS-capable receivers will be able to do differential positioning across the United States and Europe with a free differential signal and achieve real-time 3 meter positioning.

The new THALES DG16™ receiver evolved from the Ashtech® G12™ receiver. The DG16 receiver is designed to track WAAS and EGNOS geostationary satellites and utilize their differential corrections in the navigation solution. The DG16 receiver can also track and utilize differential corrections through Beacon signals that are transmitted over the frequency range of 283.5 to 325 kHz. This paper presents the new THALES DG16 receiver and its DGPS performance results using WAAS/EGNOS and Beacon GPS correction signals.

INTRODUCTION

DG16 Receiver

The new DG16™ evolved from the Ashtech® G12™ receiver. The new DG16 receiver, shown in Figure 1, is designed to track SBAS satellites (WAAS/EGNOS/MSAS), as well as 300 KHz beacon signals, and to utilize the differential correction data from these systems to provide precise DGPS positioning for navigation and other applications. Wide Area Augmentation System (WAAS) is currently under development by the United States Federal Aviation Administration (FAA) for providing GPS-based en-route navigation, non-precision approach and Category-I precision approach capabilities for aviation. Beacon station network is being expanded in the US by the Nationwide Differential Global Positioning System (NDGPS).

The DG16 is a 16-channel GPS receiver with 12-channels dedicated to track L1 C/A code and carrier, 2-channels for tracking SBAS satellites and 2-channels for tracking 300 KHz Beacon signals.

DG16 can provide up to 20 Hz sub-meter three-dimensional position and raw data for real-time guidance and navigation. DG16 also incorporates the new Ashtech Integrated Differential Optimization™ techniques for using multiple sources of correction and can output SBAS ranging, ephemeris and differential corrections as well as beacon corrections through serial port.

The DG16 can track up to two geostationary SBAS satellites at the same time utilizing the two on-board channels for SBAS. The receiver is capable of automatically selecting the best SBAS satellites available in the region and can operate in single or dual mode. The user can also manually enter satellites to be tracked utilizing the single and dual manual modes.

Figure 1: The New THALES DG16 GPS Receiver

Similarly, the THALES DG16™ receiver can track and use correction data from up to two Beacon stations in the automatic or manual modes using the on-board beacon channel circuitry.

SATELLITE-BASED AUGMENTATION: OPERATIONAL STATUS

There are three Satellite Based Augmentation Systems (SBAS) under development. These are the WAAS program in the US sponsored by the FAA, EGNOS sponsored by the European Tripartite Group and MSAS sponsored by the Japanese Civil Aviation Bureau.

All three SBAS's are based on RTCA DO-229 and therefore designed to be interoperable with each other to achieve seamless transcontinental air navigation and to provide non-precision approach and landing information within their coverage areas without any modification needed to the user equipment.

A brief description of each system follows with emphasis in their particular characteristics and operational status.

WAAS

The US Wide Area Augmentation System (WAAS) is designed to provide GPS-based en-route navigation, non-precision approach and Category-I precision approach capabilities for aviation with an original cost estimate of well above one Billion US dollars.

WAAS will be broadcasted initially from INMARSAT satellites Atlantic Ocean Region-West (AOR-W PRN 122) and Pacific Ocean Region (POR PRN 134). Future phases will include additional satellites to provide coverage to central United States.

The FAA program also comprises the Local Area Augmentation System (LAAS), which provides enhanced accuracy using local GPS reference stations. The main aim of the WAAS and LAAS development is to provide a "sole means of navigation" for aircraft in the US. Thus, allowing for the decommissioning of land-based navigation aids such as VOR/DME or Loran-C in favor of the more accurate satellite-based system.

EGNOS

The European Geostationary Navigation Overlay System (EGNOS) is sponsored by the European Tripartite Group (ETG), which comprises the European Union, the European Space Agency (ESA) and Eurocontrol. EGNOS main contractor is Thomson CSF.

The EGNOS AOC (Advanced Operational Capability) System is very similar to WAAS. Unlike the WAAS program which uses GPS only, however, EGNOS uses both the GPS as well as the Russian Global Navigation Satellite System (GLONASS). It is complemented by the use of two INMARSAT GEO satellite navigation transponders, Atlantic Ocean Region – East (AOR-E PRN 120) and Indian Ocean Region (IOR), and the ARTEMIS satellite from ESA. The Initial Phase of this system development was completed in November 1998 and the Implementation Phase started in December 1998 and is planned for completion in 2003. In December 1999, a budget of two hundred Million Euros was approved to continue the implementation of EGNOS.

The EGNOS reference stations are called Ranging Integrity Monitoring Stations, or RIMS. The RIMS send data to the processing facilities called *Mission Control Center* (MCC). The system will eventually deploy a total of 34 RIMS located mainly in Europe and 4 MCCs.

MSAS

The Japanese Multi-Function Transport System (MSAS) is sponsored by the Japanese Civil Aviation Bureau (JCAB). The main contractors are Alcatel, Toshiba and Mitshubishi. MSAS relies completely on GPS (it does not use GLONASS). The Japanese and US Governments issued a joint statement in Setember 1998 by which they announced co-operation in the use of GPS.

MSAS has a very similar architecture to WAAS in the ground segment. The space segment, however, is comprised of a navigation transponder on board JCAB's own satellite whose launch failed on the first attempt.

NATIONWIDE DIFFERENTIAL GPS

Land based differential corrections can also be used to provide DGPS positioning with the aid of radios that can transmit these corrections. The useable range of such signals depend on several factors such as transmitting power, surface conductivity, interference from other sources and quality of the receiving device. A network of such radios with high transmitting power can be used to provide global land coverage. An example of such a network in the US is the Nationwide Differential Global Positioning System (NDGPS) [Cook, 2000].

The US NDGPS is being developed by the U.S. Department of Transportation (DOT) in cooperation with the U.S. Department of Defense (DOD) and the U.S. Department of Commerce (DOC). The program uses the existing DGPS radiobeacon network as a template and intends to populate this existing network with dual redundant terrestrial and waterway coverage. The existing DGPS radiobeacon network provides coverage to both coastlines, the Gulf of Mexico, the Great Lakes and major inland waterways.

The DGPS radiobeacon network installed by the USCG initially consisted of approximately 57 separate installations located in the continental United States, Alaska, Hawaii and Puerto Rico. DGPS radiobeacons broadcast signals within the 283.5 to 325 KHz frequency band, with modulation rates of either 100 or 200 bits per second. Differential correction data that is broadcast is formatted according to the Radio Technical Commission for Maritime Services, Special Committee no. 104 protocol (RTCM SC-104).

The Nationwide DGPS is well underway with 13 stations currently operating. The total number of operational sites including the USCG is currently 70. Many more sites are in the planning stage and have funding approved.

In this paper, we will briefly present the concept of DGPS and WADGPS positioning. We will follow that with the operation of DG16 receiver and its performance analysis.

DIFFERENTIAL GPS POSITIONING

GPS Measurement Errors

The GPS pseudorange observable contains the measurement errors listed in Table 1 [Wells et al., 1986].

Table 1: Typical/Max C/A Code Range Errors

Error Source	Typical (m)	Max (m)
Satellite Clock	Variable	300 000
Satellite Orbit	5 – 20	30
Ionosphere	2 – 30	150
Troposphere	2 – 20	30
Multipath	0 – 10	300
Receiver Clock Bias	10 – 10 000	Unlimited
Measurement Noise	0.1 – 3	5

Using the second-order polynomial coefficients contained in the satellite ephemeris message eliminates most of the satellite clock errors. Residual modeling errors, however, may result from using this model. These residuals are usually in the vicinity of three meters. Accordingly, and since the observed satellite clock error is the same for all receivers tracking the same satellite at the same time, differential positioning completely eliminates these residual errors.

Satellite orbital errors, on the other hand, are caused by the imperfect modeling of physical phenomena governing the dynamics of the satellite in the sky. Broadcast orbits are accurate typically within 20 meters. Orbital errors can be eliminated using differential positioning over short baselines. Over long baselines, however, satellite orbital errors tend to spatially-decorrelate causing baseline errors in the neighborhood of 1 ppm of the baseline length.

Ionospheric errors are the atmospheric delay effects on the pseudorange while passing through the ionosphere, which is the layer extending from about 50 to 1000 kilometers above earth. Ionospheric delays are caused by the total electron content along the path of the GPS signal between the satellite and the receiver. Many factors affect the magnitude of these effects including sunspot number, time of day, location on the surface of the earth, satellite elevation angle and measurement signal frequency. Average correlation time and distance of ionospheric effects are about 3 hours and 1000 kilometers, respectively. Ionopsheric effects can be eliminated, or at least minimized, by differential positioning or modeling. Dual-frequency GPS receivers can utilize the information on both GPS frequencies to determine the amount of delay caused by the ionophere. Single frequency GPS users, however, can either use differential GPS to eliminate ionospheric effects or apply the broadacst ionospheric model which is only 50-60% effective.

Tropospheric errors are the delay effects caused by the non-ionized layer of the atmosphere extending from the surface of the earth to about 50 km above. Applying standard models such as Hopfield's or DGPS can eliminate tropospheric effects.

Finally, multipath and noise are site and equipment specific and are not eliminated by differential positioning. Receiver clock bias, on the other hand, is estimated along with the receiver unknown coordinates.

Differential GPS Positioning Techniques

Single-Reference DGPS

Between-receivers single difference GPS positioning is the most common differential GPS positioning technique. It involves the use of two receivers, one stationary at a reference (or base) station, and the other (usually called "remote") roving or simply located at a new station in the vicinity of the reference station.

As shown in Figure 2, the two receivers simultaneously track GPS signals from the same satellites. By knowing the base coordinates, errors in the GPS measurements taken at the base receivers can be estimated. Moreover, since both base and remote receivers track the same satellites, the errors estimated at the base can then be used as real-time corrections for the measurements at the remote. Accordingly, position fixes computed at the remote receiver are more accurate than in the case of single-point stand-alone positioning, simply because of the availability of the corrections from the base station.

A key benefit of differential modeling is the ability to reduce or eliminate many GPS measurement errors. The satellite clock error, for example, is totally eliminated from the observation as a result of the inter-receiver differencing process. Also, ionospheric, troposheric and orbital errors are greatly reduced through differential modeling, especially over short baselines, where the errors experienced at the two receiver sites are highly correlated.

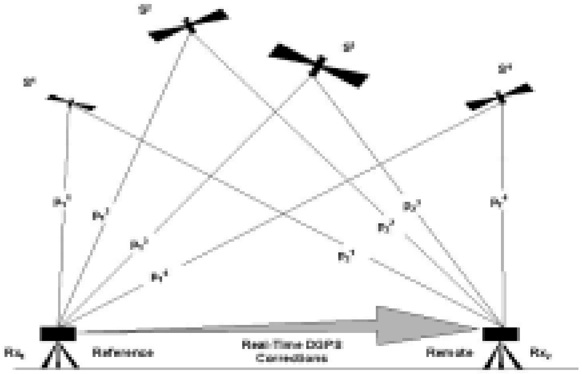


Figure 2: Differential GPS Positioning

Receiver noise and multipath, on the other hand, are neither eliminated nor reduced. Receiver noise is not site-dependent and multipath is not receiver or satellite dependent. In fact, both receiver noise and multipath are amplified by differential modeling according to the law of propagation of errors [Vanicek and Krakiwsky, 1982].

Shown in Table 2 is the reduced error budget with DGPS positioning. As a result of the reduced error budget, one-to-five-meter DGPS positioning is feasible.

Real-time differential applications utilize over-the-air communication links to transmit measurement corrections estimated at the base receiver to the remote receiver. For error correlation purposes, however, and for practicality purposes as well, real-time DGPS surveys have to be conducted over reasonably short baselines.

Table 2: Reduced GPS Errors w/ DGPS

Error Source	**Typical DGPS**
Satellite Clock	0
Satellite Orbit	0.5 – 0.1 ppm
Ionosphere	0.2 – 0.4 ppm
Troposphere	0.3 – 3 ppm
Multipath	0 – 14 m
Measurement Noise	0.1 – 4.2 m

Over longer baselines, DGPS corrections become less accurate, causing degradation in the resulting positioning accuracy. This is why the concept of wide area differential GPS (WADGPS) is being given increasing attention.

Multi-Reference DGPS

The need for multiple base stations in DGPS has initially evolved from the continuous and growing demand for highly accurate and reliable GPS positioning. Conventional single-reference DGPS has a limited accuracy performance, and the fact that the corrections are supplied from one source is not appropriate for several applications (e.g. aviation) for availability and reliability reasons.

Despite the intriguing features of DGPS, availability and robustness of the DGPS reference station, its tracking capability and the nature of surrounding environment contribute significantly to the availability, accuracy and reliability of the differential corrections broadcast to the users. Also, for real-time applications, the validity of the corrections estimated and broadcast by the DGPS base station is restricted to local users; typically within a maximum radius of 200 kilometers around the reference site. Over larger separation distances between the reference site and the roving user, errors estimated at the reference site become decorrelated with those errors experienced at the user's location because of the spatial decorrelation between the error sources. These and other reasons, economic and logistical, have primarily contributed to the evolution of multi-reference (or multi-base) DGPS techniques.

To provide nationwide multi-reference DGPS coverage, however, a multitude of differential base stations are required with all sorts of GPS and communication equipment. This would obviously be overly expensive and uneconomical, especially for wide spread countries or regions like the United States or the European Union. Therefore, wide area differential GPS (WADGPS) techniques have been adopted for such a purpose.

Wide Area Differential GPS Positioning

A WADGPS system architecture involves a few widely separated GPS reference stations providing coverage over a large service area. A typical WADGPS mathematical algorithm combines the various WADGPS corrections received from all the different reference stations to produce locally-valid single set of DGPS corrections. The algorithm accounts for spatial decorrelation of GPS error sources at the different reference stations due to the large separation distances involved [Ashkenazi et al., 1993; Barker and Lapucha, 1994].

There are several WADGPS network approaches and algorithms varying in area coverage and complexity. These approaches range from extended DGPS networks to worldwide DGPS with corrections based on separate DGPS error estimates obtained from continuous coverage of all satellites. In essence, all the algorithms used can be classified into three groups: measurement domain, position domain and state-space domain algorithms [Abousalem, 1996].

Measurement domain WADGPS algorithms provide DGPS network corrections computed as the weighted mean of the various DGPS base station corrections. These algorithms may vary, yet they are all relatively simple and require just a few DGPS reference stations. A possible disadvantage of such algorithms, however, is the degradation of the correction accuracy with the distance from the network centroid.

Position domain WADGPS algorithms, on the other hand, provide DGPS position solutions computed as the weighted mean of the different DGPS position solutions resulting from using each of the available DGPS corrections independently. In other words, each of the incoming set of DGPS corrections is used separately to produce an independent position fix for the remote receiver. The resulting position fixes are then weighted and averaged to produce the final solution.

Finally, state-space domain WADGPS algorithms, as used by WAAS and EGNOS, provide highly accurate baseline-independent corrections using a number of DGPS reference stations equipped with GPS receivers (usually of the dual frequency type) and complex software. The complexity of the state-space domain algorithms comes from estimating (modeling) the individual error sources. The algorithm models the involved GPS error sources including satellite clocks and orbits, the ionosphere, the troposphere and the reference station clocks. The principle behind the various state-space models developed so far is to use the available multiple sets of WADGPS corrections to estimate the different error components involved, and thus be able to estimate local measurement errors. Therefore, the majority of state-space WADGPS reference networks employ dual-frequency GPS receivers for real-time dual-frequency ionospheric modeling. Users typically receive their differential corrections in multiple components to be integrated within their equipment with the locally measured GPS data. In the case of WAAS and EGNOS, the users receive their corrections in the RTCA DO-229 format which provides satellite clock corrections, satellite orbital corrections and ionospheric corrections all in separate components [FAA, 1997].

DG16 DESCRIPTION AND OPERATION

The DG16 is in many ways similar to the Ashtech® G12. DG16 dimensions are identical to G12. It has the same I/O connector and location as G12. DG16 serial interface is backward compatible with G12.

DG16 has many salient features such as improved signal tracking sensitivity, improved under-tree tracking, fast reacquisition, low power consumption, programmable sleep mode, user-defined messages, up to three RS-232 ports, reduced maximum latency (50 msec), user selectable dynamic modes and navigation algorithms (Least Squares or Kalman Filter), and Integrated Differential Optimization. In addition DG16 is also available with 3.3 VDC as input operating voltage (Std.: 5 VDC).

The DG16™ receiver is available in two configurations: GPS+SBAS and GPS+SBAS+Beacon. The DG16 (GPS+SBAS+Beacon) is a 16-channel GPS receiver with 12-channels dedicated to track L1 C/A code and carrier, 2-channels for tracking SBAS satellites and 2-channels for tracking 300 KHz Beacon signals. The DG14 (GPS+SBAS) is a 14-channel receiver with 12-channels dedicated to track L1 C/A code and carrier, 2-channels for tracking SBAS satellites.

SBAS

Both DG16 as well as DG14 are capable of tracking up to two geostationary satellites and utilizing the SBAS ranging and differential corrections in the navigation solution. DG16 can track SBAS satellites in either automatic or manual mode.

User can select single or dual automatic mode of operation. In either mode, DG16 uses intelligent algorithms for selecting and tracking best available SBAS signals. In single automatic mode, the best signal is available on channel 1. Channel 2 tracks the second best available signal. In dual automatic mode, DG16 tracks the best two available signals. Likewise, user can also select single manual mode or dual manual mode to specify SBAS satellite(s) to be tracked. In single manual mode, user can select one SBAS satellite to be tracked by the receiver on channel 1. Channel 2 tracks the other best available SBAS signal. Using dual manual mode user can select two SBAS satellites to be tracked by the receiver.

In any of the above SBAS modes, the DG16 is capable of utilizing SBAS data from either or both channels tracking SBAS satellites. A number of features are available to control SBAS operation and use of SBAS data.

Beacon

DG16 is also capable of tracking up to two beacon signals in the 300 KHz range using the on-board beacon circuitry. Similar to the SBAS operation, the DG16 can track 1 or 2 beacon signal using automatic or manual modes.

Beacon automatic and manual modes are very similar to the SBAS automatic and manual modes. In automatic modes, the beacon receiver automatically selects and tracks the best Beacon signal(s) utilizing it's own position information. In the manual modes, the DG16 can track the Beacon station(s) specified by the user.

The DG16 maintains a DGPS beacon directory in a battery-backed memory. The beacon directory contains a list of default beacon stations from ROM, list of stations received from RTCM Type 7 and user entered stations. User can make changes to the beacon directory and save the contents. User can also reset the beacon directory to revert to the default directory.

DG16 is capable of using beacon data for DGPS positioning and can also output the beacon data through serial ports.

Integrated Differential Optimization

DG16 is capable of using multiple sources of differential corrections in the navigation solution. Using the Integrated Differential Optimization feature, the user can specify the corrections to be used in the differential solution. User can either select Primary-Secondary or Multi-Base processing. In the Primary-Secondary scenario, the navigation solution always utilizes a single source of corrections. The user can specify the primary and secondary sources manually or let the receiver automatically select the primary and secondary sources of corrections based on an internal set of criteria for the "best" correction source. In multi-base processing mode, multiple sources of corrections can be used in the navigation solution using weighted multi-base solution (weight factors include: age of correction, distance to base, satellite elevation at base, etc.)

If the SBAS or beacon is set to Dual Mode, each channel serves as a separate source of corrections. If multiple serial corrections are available, each set of corrections (based on reference station ID) serves as a separate source of corrections.

EGNOS Test Description

The test was conducted in Moscow, Russia on 4th of July 2001. The test duration was 15 hours and the DG16 receiver used WAAS PRN 120 that was transmitting GPS corrections. The standard DG16 receiver data output included current navigation solution (position fix); number of locked satellites with PRN number, azimuth, elevation and signal strength for each locked satellite; WAAS/EGNOS channel status and RTCA 229 250-bit data stream containing the differential corrections.

The collected data was analyzed using the Ashtech software utility SOPHIST™. This utility program processes recorded files and plots 2-dimensional position, position components (latitude, longitude, altitude) versus time in addition to statistical analysis to the output data and other useful information.

Conducting the test was somewhat challenging in the difficult environment in Moscow as the EGNOS satellite rarely broadcast the full set of corrections during the course of the test. Often, there were no differential corrections at all. It was also difficult to collect and analyze data in Moscow as the current broadcast of ionospheric corrections only covers the European regions west of Moscow. This is indicated in Figure 3 below, which shows the ionospheric delay correction zones (satellite signal pierce-point grid) provided by EGNOS. Moscow location is indicated as a star.

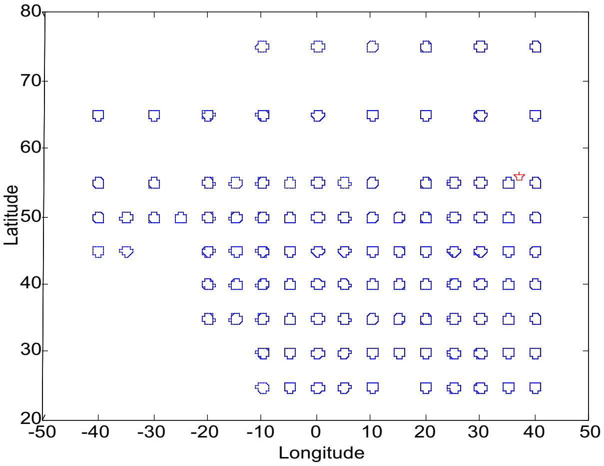


Figure 3: EGNOS Ionospheric zones

Results and Analysis

Typical test results are shown in Figures 4 through 9. Illustrated in Figures 4, 5 and 6 is the positioning accuracy attainable over a period of fifteen hours in Moscow using EGNOS full corrections, meaning the test data included all satellites for which full corrections were available as well as all satellites with no ionospheric component; i.e. ionosphere-free corrections.

In Figure 4, horizontal positioning results are shown with the corresponding error statistics. Horizontal position accuracy (1 σ) is 1.7 m and maximum error is 4 m. In Figure 5, the latitude error is shown to range between –3m to +3.5 m. In Figure 6, the longitude error is shown to vary from –2.5m to +3.5m. In Figure 7, the altitude error is shown to range between –5m and +5m. In Figure 8, the overall positioning statistics are shown for the same data set demonstrating horizontal and vertical positioning accuracy of 2.87m and 3.98m (95%), respectively. Finally in Figure 9, the variation in ground speed and vertical speed are shown. Maximum ground speed is 0.2 knots and maximum vertical speed is 0.2m/s.

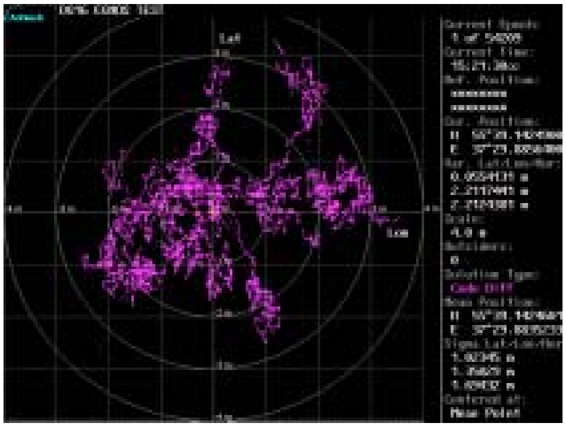


Figure 4: Horizontal Positioning Results

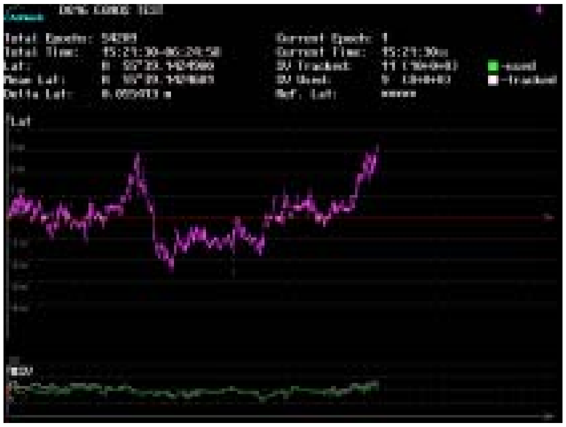


Figure 5: Latitude Error Results

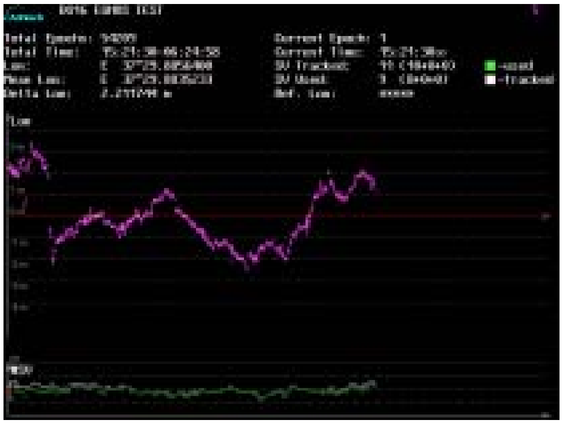


Figure 6: Longitude Error Results

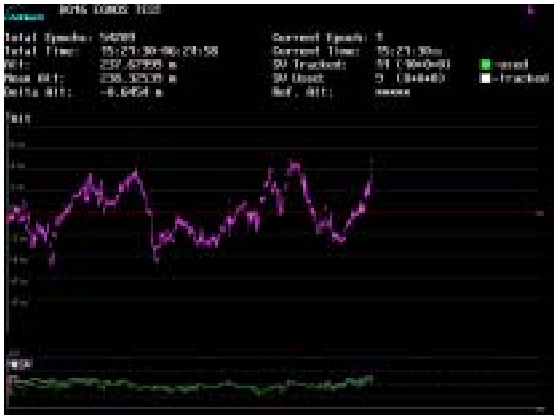


Figure 7: Altitude Error Results

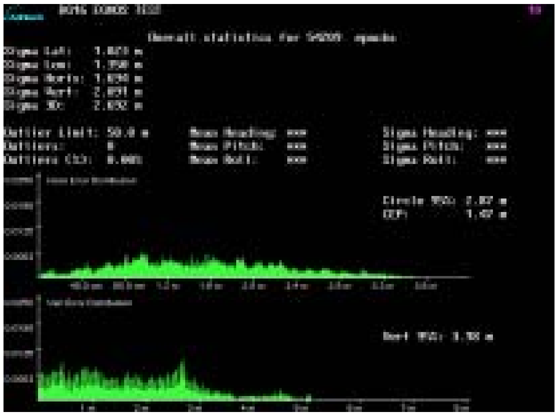


Figure 8: **Overall Statistics**

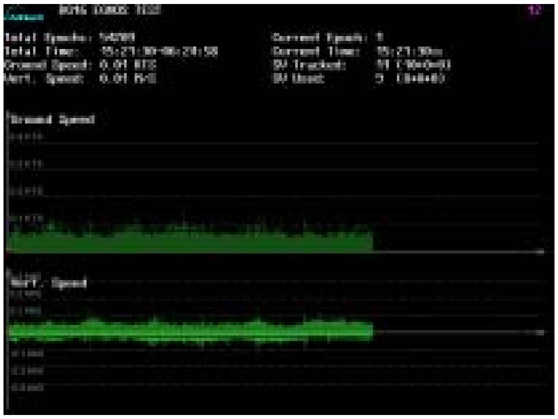


Figure 9: Ground and Vertical Speed Results

SBAS Test Results

Position Accuracy Statistics

	CEP (50%)	95%
Horizontal	1.47 m	2.87 m
Vertical	1.64 m	3.98 m

Velocity Accuracy Statistics

	CEP (50%)	95%
Horizontal	0.01 m/s	0.026 m/s
Vertical	0.01 m/s	0.04 m/s

Beacon Test

The beacon test was conducted at Mission College, Santa Clara, CA, U.S.A. on 19th of July 2001. The test duration was 7 hours and the DG16 receiver used signals from beacon station at Pigeon Point, CA. The beacon station ID is 267 and the signal was being transmitted at 287 KHz. The standard DG16 receiver data output included current navigation solution (position fix); number of locked satellites with PRN number, azimuth, elevation and signal strength for each locked satellite; RTCM base station data and statistical data on satellite range measurements and antenna position.

The collected data was analyzed using the Ashtech software utility SOPHIST™. This utility program processes recorded files and plots 2-dimensional position, position components (latitude, longitude, altitude) versus time in addition to statistical analysis to the output data and other useful information.

Selecting the site for conducting the beacon test was quite challenging as most of the sites had multi-path environment making it difficult to analyze performance results.

Results and Analysis

Typical test results are shown in Figures 10 through 15. Illustrated in Figures 10, 11 and 12 is the positioning accuracy attainable over a period of seven hours in Santa Clara, CA using corrections from beacon station at Pigeon Point, which is approximately 50 KM from the test site.

In Figure 10, horizontal positioning results are shown with the corresponding error statistics. It is shown that using beacon corrections and all visible GPS satellites yielded 0.36 m (1 σ) horizontal positioning accuracy. In Figure 11, the latitude error is shown to range between –1.25m to +1.25 m. In Figure 12, the longitude error is shown to vary from –0.8m to +0.8m. In Figure 13, the altitude error is shown to range between –2m and +3m. In Figure 14, the overall positioning statistics are shown for the same data set demonstrating horizontal and vertical positioning accuracy of 0.64m and 1.35m (95%), respectively. Finally in Figure 15, the variation in ground speed and vertical speed are shown. Maximum ground speed is 0.2 knots and maximum vertical speed is 0.2m/s.

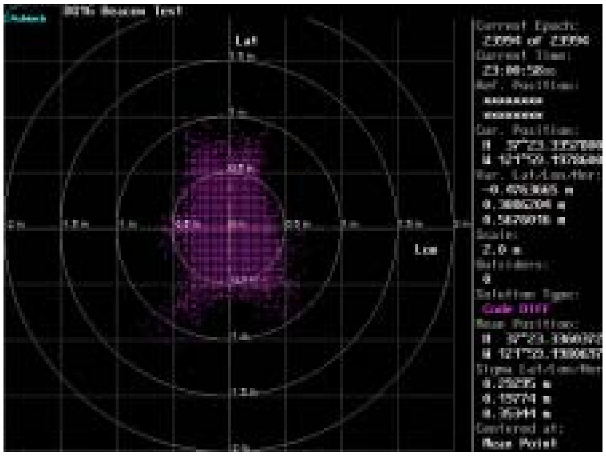


Figure 10: Horizontal Positioning Results

Figure 11: Latitude Error Results

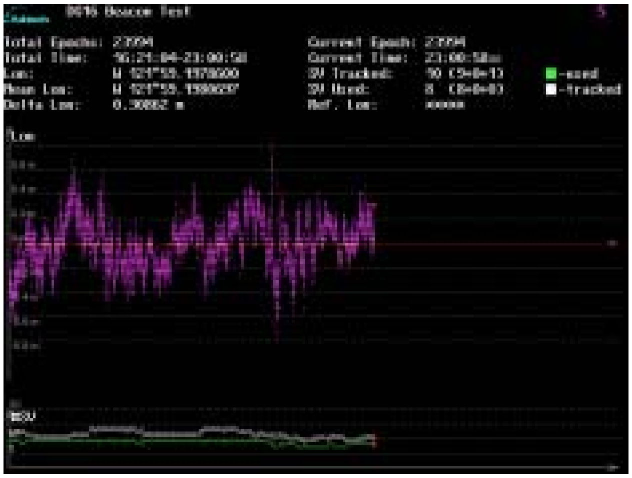


Figure 12: Longitude Error Results

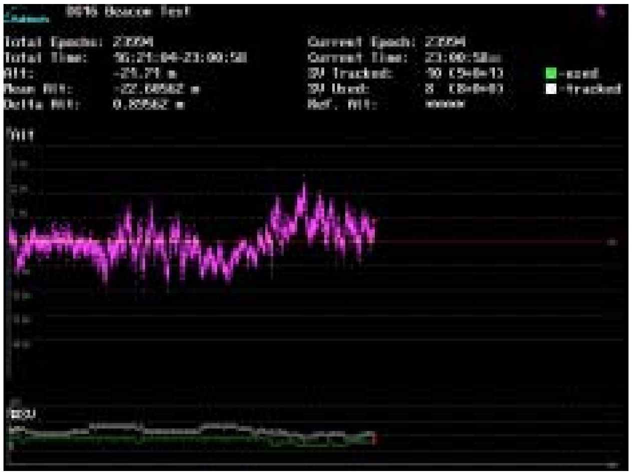
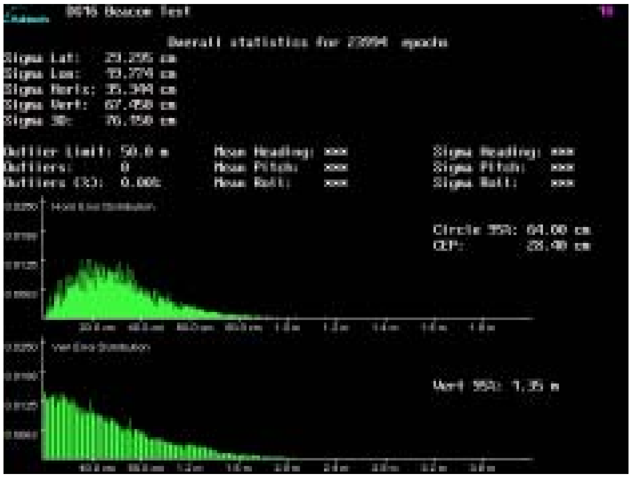


Figure 13: Altitude Error Results



```
DG16 Beacon Test
                 Overall statistics for 23094 epochs
Sigma Lat:   29.235 cm
Sigma Lon:   19.774 cm
Sigma Horiz: 35.349 cm
Sigma Vert:  67.458 cm
Sigma 3D:    76.158 cm

Outlier Limit: 50.0 m      Mean Heading: ***        Sigma Heading: ***
Outliers:      0           Mean Pitch:   ***        Sigma Pitch:   ***
Outliers (%):  0.00%       Mean Roll:    ***        Sigma Roll:    ***

                                                    Circle 95%: 64.00 cm
                                                    CEP:        28.40 cm

                                                    Vert 95%: 1.35 m
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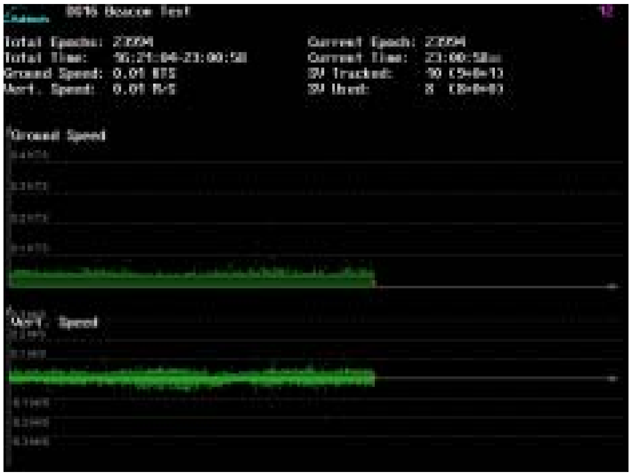
Figure 14: Overall Statistics



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DG16 Beacon Test
Total Epochs: 23094                Current Epoch: 23094
Total Time:   16:21:04-23:00:58    Current Time:  23:00:58
Ground Speed: 0.01 KTS             SV Tracked:    10 (9+0+1)
Vert. Speed:  0.01 M/S             SV Used:       8  (8+0+0)
```

Figure 15: Ground and Vertical Speed Results

Beacon Test Results

Position Accuracy Statistics

	CEP (50%)	95%
Horizontal	0.28 m	0.64 m
Vertical	0.43 m	1.35 m

Velocity Accuracy Statistics

	CEP (50%)	95%
Horizontal	0.010 m/s	0.021 m/s
Vertical	0.010 m/s	0.030 m/s

CONCLUSIONS

THALES Navigation is releasing the new DG16™ GPS receiver. DG16 is the new generation of the renowned Ashtech® G12 receiver. The DG16 is a 16-channel receiver capable of tracking signals from up to 12 GPS satellites, 2 SBAS satellites and 2 different 300 KHz Beacon stations; all fitted on a single 4.25 x 2.30 inch board. The DG16 (GPS+SBAS+Beacon) receiver provides 2.9m (95%) and 0.6m (95%) horizontal positioning using EGNOS and beacon corrections respectively. All SBAS tests were conducted using EGNOS data containing full GPS corrections for partial constellation and ionosphere-free corrections for the remaining constellation. Beacon tests demonstrated that DG16 provides sub-meter accuracy with Beacon station over a 50 KM baseline.

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