Epoch-by-Epoch™ Real-Time GPS Positioning in High Dynamics and at Extended Ranges

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Civilian and military applications increasingly require precise positioning. Geodetics, Inc. has demonstrated centimeter-level position solutions using their Epoch-by-Epoch™ (EBE) technology. EBE technology provides computational algorithms for instantaneous differential GPS processing of raw GPS measurement data (pseudorange and carrier phase) from one or more base stations and one or more rovers. EBE has been shown to have significant advantages over conventional GPS Real-Time Kinematic (RTK) algorithms in several ways, including 1) no initialization or re-initialization delays, 2) extended ranges over which dual-frequency GPS receivers can provide precise positioning, and 3) graceful degradation when a full set of measurement data is not available. This paper will provide empirical data that were gathered during a test program, sponsored by the Office of the Secretary of Defense, to assess the performance in real time of EBE technology on realistic Advanced Range Data System (ARDS) maneuvers.

The Central Test & Evaluation Investment Program (CTEIP), which resides within the Office of the Director, Operational Test and Evaluation / Resources and Ranges (DOT&E/RR) within the Office of Secretary of Defense (OSD), has been funding a program to evaluate the performance of EBE technology for test and evaluation instrumentation applications.[1] During the program, Geodetics integrated its EBE software package with a number of commercial and SAASM-based receivers. These receivers were then tested in both live and simulated tests, under strenuous environments, including high dynamics and extended range. The results of these tests were then analyzed. The first part of the analysis focused on position solutions utilizing pseudorange and carrier phase measurements at high dynamics.

This paper begins with a background discussion of T&E applications requiring precision GPS. This is followed by a description of the EBE technology, EBE test results for four simulated high-dynamic maneuvers, and a summary that includes future work.

1. Background

T&E Applications Requiring Precision GPS – In the 1970's, OSD recognized that use of GPS-based TSPI, i.e., tracking, offered excellent advantages over conventional TSPI instrumentation. In fact, GPS offered the potential to support an unlimited number of participants in a 'world wide range'. In 1979, OSD conducted a major study to evaluate the potential of GPS as a TSPI source for the test and training range communities. The survey evaluated TSPI requirements at 22 major ranges of the three Services. GPS was evaluated considering such factors as real-time and post-mission TSPI and scoring accuracy, supportable vs. required data rates, number of participants, and coverage area. The OSD final report was submitted on 31 December 1982. *The report concluded that GPS could be used as a cost-effective real-time TSPI source for 95 percent of all TSPI requirements.*

Range Applications Program (RAP). As a result of this report, a tri-Service program was initiated to develop the assets for the real-time GPS-based positioning of low, medium, and high dynamic platforms. These assets were to be put in place at the major DoD test and evaluation ranges. The training community initially deferred the introduction of GPS-based TSPI; they are now in the process of converting most of their major range instrumentation to GPS.

GPS has undergone significant hardware and software enhancements during the last ten years. The advances have primarily focused on miniaturization of the GPS package and improvement in the accuracy of the GPS solution. Nonetheless, RAP initial production equipment is now ten years old. It is now believed that GPS can cost-effectively address the remaining 5% of unmet TSPI requirements that were called out (in the above mentioned) 1982 OSD report. For that reason, EnRAP is being pursued to provide the next generation RAP instrumentation.

Enhanced RAP Program (EnRAP). The EnRAP program is a CTEIP initiative to upgrade the basic RAP system in four areas: 1) Enhanced data link spectrum efficiency and capacity, 2) Higher accuracy GPS/inertial TSPI, 3) Miniaturization of modules, and 4) Development of a plug-and-play architecture.

EnRAP provides TSPI for a number of land, sea and air platforms, with the most stressing environment

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[1] This is the second of two papers written on EBE assessment. See [*Macdonald*, 2001] for the first paper.

being that of a fighter aircraft (~10 g's). EnRAP has a stringent requirement to enhance the *real-time* accuracy of today's GPS instrumentation to meet the test needs of advanced weapon systems. Test instrumentation must provide a factor of ten enhanced accuracy when compared to the system-under-test (SUT). This translates to EnRAP (level III) TSPI requirement of 30 cm real-time and 10 cm post-mission. It should be noted that the required TSPI performance must be provided real time over a range area that can extend some 200 miles. Based on the test results presented in this paper, EBE has the potential to meet this real-time requirement for the next generation TSPI suite of instrumentation.

Multi-Service Target Control System (MSTCS) Project. CTEIP is also funding the MSTCS project to develop the next generation target control system. MSTCS is a GPS-based system that will replace and upgrade the **Gulf Range Drone Control System** (GRDCS), which is the Air Force's ground-based multilateration target control system (TCS) that operates at the Gulf Range, FL, the **Drone Formation Control System** (DFCS), which is the Army's ground-based multilateration TCS that operates at White Sands Missile Range (WSMR), NM, and the **Integrated Target Control System** (ITCS), which is the Navy's radar-based TCS that operates at Pt. Mugu, CA.

MSTCS has a requirement for formation control of airborne targets and auto landing of full-scale drones such as the QF-4. Precise *real-time* GPS would support more realistic presentations of closely spaced airborne targets, and would provide a cost-effective GPS-only instrumentation package for auto-landing. Real-time accuracy on the order of 30 cm is required. As opposed to EnRAP, however, precision TSPI is only warranted in low dynamic applications, i.e., formation flight, auto-landing. The MSTCS range of operations can extend 200 miles from the control center. Based on the test results presented in this paper, EBE is able to meet the requirements for the next generation MSTCS.

Joint Advanced Missile Instrumentation (*JAMI) Project.* The JAMI project is another key CTEIP-funded program. JAMI is developing modular instrumentation packages for missile applications. The JAMI package supports three functions: 1) Missile termination, 2) TSPI, and 3) Vector-Scoring.

The TSPI and Vector-Scoring will be accomplished with a GPS (and inertial) engine on both the missile and target. Although TSPI must be provided in real time, the accuracy requirement is moderate (several meters). The vector-scoring requirement, on the other hand is precise (< 30 cm), but can be accomplished post mission. Because post-mission processing is allowed, existing RTK algorithms can be used for this purpose. However, operational considerations and excellent performance data (discussed in this paper) suggest that EBE technology may be the preferred approach meeting the vector-scoring requirement.

2. Epoch-by-Epoch™ Technology

Geodetics, Inc. has developed a new class of instantaneous, real-time precise GPS positioning and navigation algorithms, referred to as Epoch-by-Epoch™ (EBE) [*de Jonge* et al., 2000, *Bock et al.*, 2003]. Compared to conventional RTK, integer-cycle phase ambiguities are independently estimated for each and every observation epoch. Therefore, complications due to cycle-slips, receiver loss of lock, power and communications outages, and constellation changes are minimized. There is no need for the initialization period (several seconds to several minutes) required by conventional RTK methods. More importantly there is no need for re-initialization immediately following loss-of-lock problems such as occurs when a mobile GPS receiver passes under a bridge or other obstruction, or loses satellite visibility during an aerial maneuver.

In addition, EBE provides precise positioning estimates over longer reference receiver-to-user receiver baselines than conventional RTK. This feature supports testing for long-range operations, for example, positioning aircraft landing on a ship at sea (i.e., the reference receiver is on the ship).

Precise GPS positioning data provided by EBE is also used to provide platform attitude data. This can be accomplished by multiplexing a single user receiver among three antennas on the platform, or by deploying three complete GPS systems. Only two antennas would be necessary if only two of the three attitude angles were desired. Attitude can be determined to an accuracy of about 0.05 degrees (antenna distances of 1.5 meters).

EBE requires the use of a minimum of two receivers, each of which is tracking a common set of five or more satellites and providing simultaneous dual frequency carrier phase data. Normally one of the receivers is stationary but this is not a requirement. It is anticipated that EBE technology would support end game scoring between a missile and an airborne platform. In this case the two receivers would be located on highly dynamic platforms.

EBE has been proven utilizing dual frequency receivers and operating at distances of up to 50 km from the nearest base station in unaided mode, and up to 250 km in aided mode. Aided mode requires reasonable knowledge of a-priori position (meter level) such as provided by a coupled IMU. Additionally the EBE algorithms operate in a network environment and make optimal use of all GPS measurement data at each epoch, gracefully degrading the position accuracies when some measurement data are not available. Further, the system will make use of IMU system, compensating for outages when sight to the satellites is blocked. This results in a robust and more reliable system.

OSD has seen sufficient static and low dynamic performance data to be convinced that the EBE concept deserves serious consideration for test applications. A test program is required because the scenarios of interest typically involve high dynamic platforms, and there is minimal data for these scenarios.

Epoch-by-Epoch™ promises numerous benefits including:

- *Computationally efficient algorithms* that provide a position estimate based on a single epoch in several milliseconds. This allows the real-time position estimate to be computed on the user platform (assuming reference station data is sent to the user platform).
- *An initialization period is not required*. Since RTK requires some period of time (that can be measured in seconds to minutes) to perform ambiguity resolution, this is an important capability for platforms that: Require high accuracy (e.g., for end game scoring); cannot see the satellites until launch; and have short flight duration.
- *A reinitialization period following loss-of-lock is not required*, unlike RTK, which needs to restart the integer-cycle phase ambiguity resolution process. This is another important capability because OSD is considering EBE for many high dynamic applications where loss of lock and loss of data are likely.

Currently, there *are* receivers in production that will support the EBE requirement for simultaneous dual-frequency code and phase observations. Hence, it is not envisioned that a receiver development effort would be required if the dynamic test results prove favorable. However, it must be mentioned that many of the GPS receivers in use by the test (and training) community today do not support this dual frequency requirement. Hence, those systems could not realize the maximum benefit.

3. Test Setup

The RTD ("Real Time Dynamics") software package with EBE positioning was tested using four high-dynamic simulations based on realistic ARDS maneuvers developed as part of the TSPI study. An omni-directional antenna simulation was utilized for each of the maneuvers. The maneuvers and antenna model were programmed into the Guided Weapons Evaluation Facility (GWEF) satellite simulator. The GWEF simulator is a model 2400 GPS Constellation Simulator from Interstate Electronics Corporation, and was phase calibrated using the procedures outlined in [*Anthony* et al., 2001]. The NovAtel OEM4 was selected as the test receiver (see Figure 1). For three maneuvers, reference data were collected from both a near and far reference receiver. The near reference receiver was located at distances of less than 10 km from the rover. The far reference receiver was located at distances of 88-96 km from the rover. The tests involved comparing the RTD EBE output positions for the rovers to the 'true' simulator positions for characterization of EBE accuracies. Although conducted in "post-processing" the EBE analysis was conducted as if the data were collected in real time. The fourth test involved comparing the RTD EBE output positions with those of a post-processing package to characterize the re-initialization timing characteristics of the EBE algorithms.

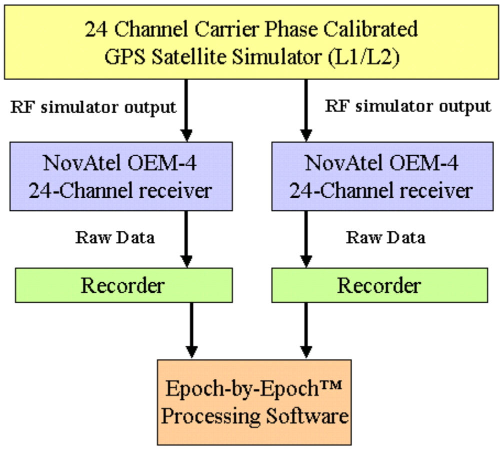

Figure 1. Guided Weapons Evaluation Facility

4. Test Maneuver Descriptions

The three selected maneuvers used for EBE accuracy characterization were: 1) Split S – Cuban 8 – Split S (~4 g's), 2) Post Hole (~3.8 g's) and 3) 9g Turns (~9 g's). Each maneuver contained three segments; a 15 second straight and level segment followed by the maneuver followed by another 15 second straight and level segment. The maneuvers are shown graphically in Figures 2-4. The first two maneuvers provided sufficient data (visibility to 5 or more common satellites) for phase processing with ambiguity resolution. The third maneuver was analyzed in 'graceful degradation' mode since only 4 satellites were available for about 50% of the time, including the entire first 720° turn. In this mode, RTD uses only pseudorange (code) measurements when the number of common satellites fall less than the minimum 5 required for EBE processing. The fourth maneuver, used to characterize EBE re-initialization characteristics, was a barrel roll

5. Test results

Figures 5-10 compare the EBE rover position output with the 'true' simulated positions for each of the three accuracy maneuvers, for both 'near' and 'far' reference stations. Table 1 provides standard (mean, standard deviation) and robust (median, interquartile range) statistics for the deviations from truth in each of the experiments. In order to isolate and characterize outliers, we calculate the median and interquartile range for the deviations from truth, which are less affected by outliers than standard statistics. The interquartile range (IQR) is defined as the range of the middle 50% of the data. From experience with many real and simulated data sets, we select the outlier criteria to be 4 times the IQR (this criteria corresponds to approximately 3σ, if the single-epoch solutions were normally distributed).

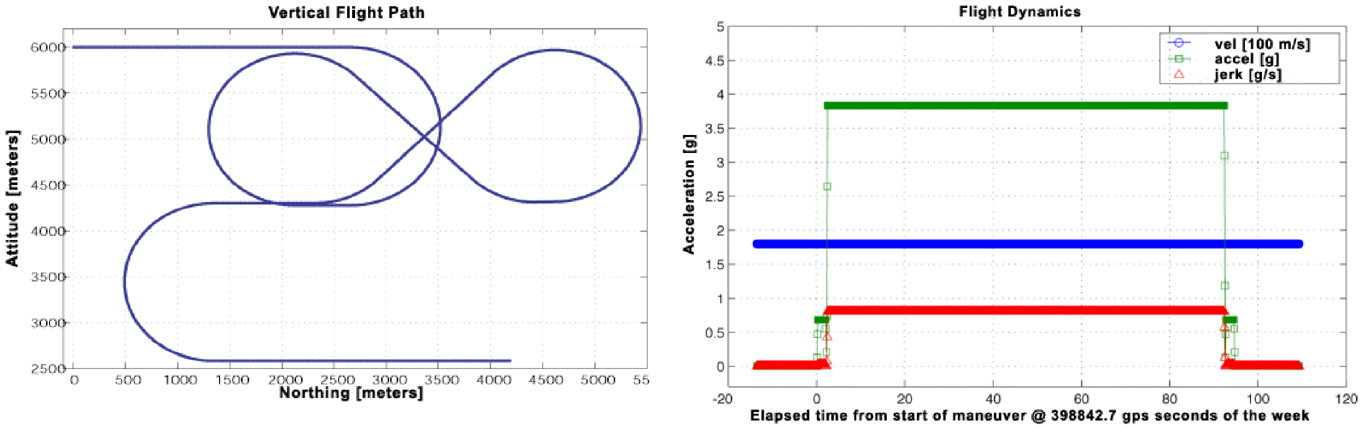

Figure 2. Rover flight path and dynamics of the “Split S-Cuban 8-Split S” maneuver with up to 4g’s of acceleration. The velocity was kept constant at 100m/s, while the acceleration and jerks were varied.

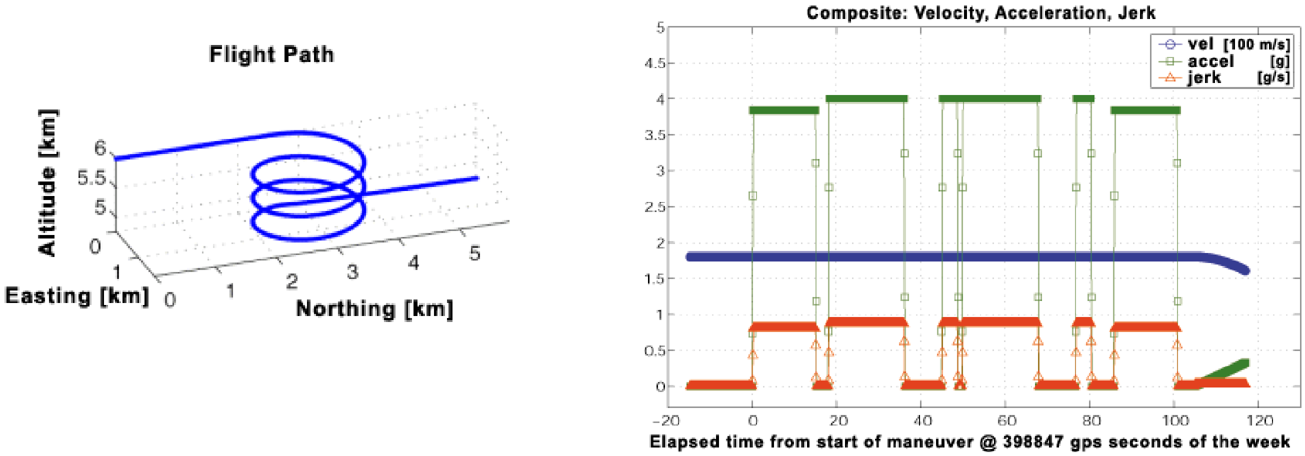

Figure 3. Rover flight path and dynamics of the “Post/Hole” maneuver with up to 4g’s of acceleration. The velocity is kept constant at 100m/s, while the acceleration and jerks were varied.

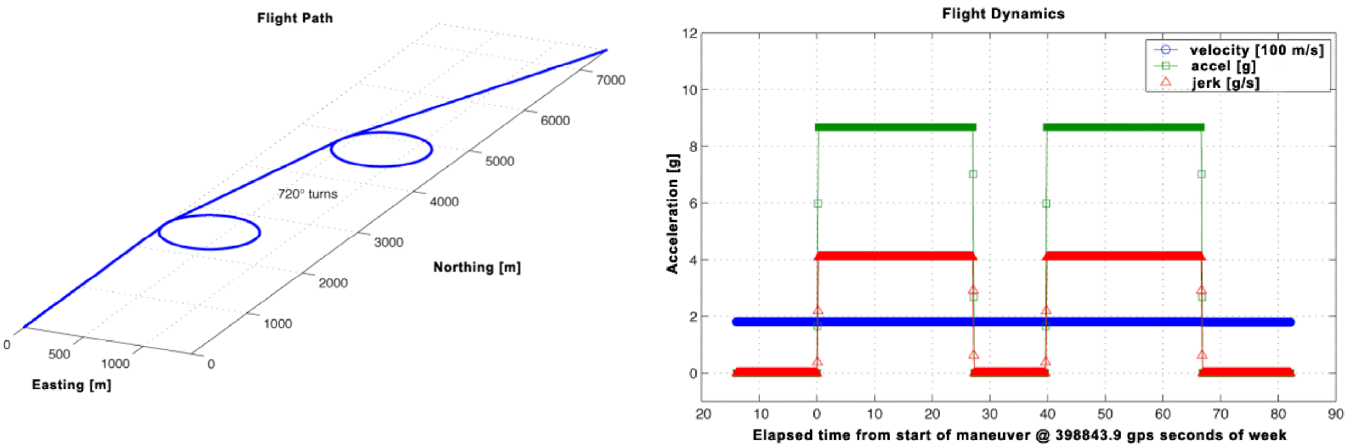

Figure 4. Rover flight path and dynamics of the “9g Turns” maneuver with up to 9g’s of acceleration. The velocity is kept constant at 100m/s, while the acceleration and jerks were varied.

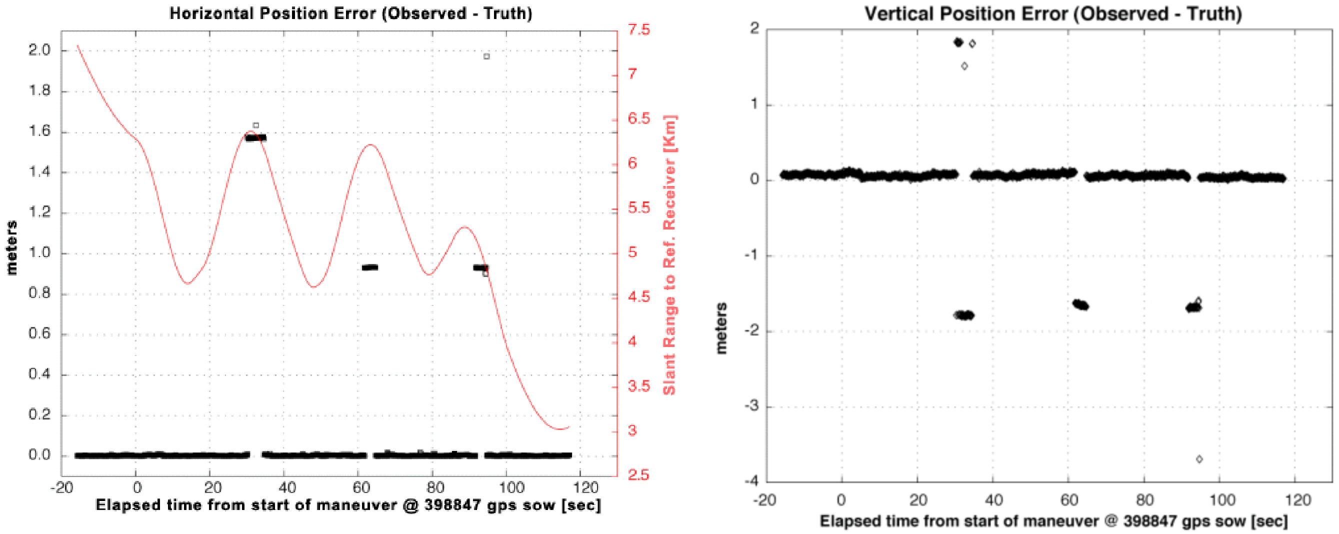

Figure 5. Near position errors for “Split S-Cuban 8-Split S” maneuver

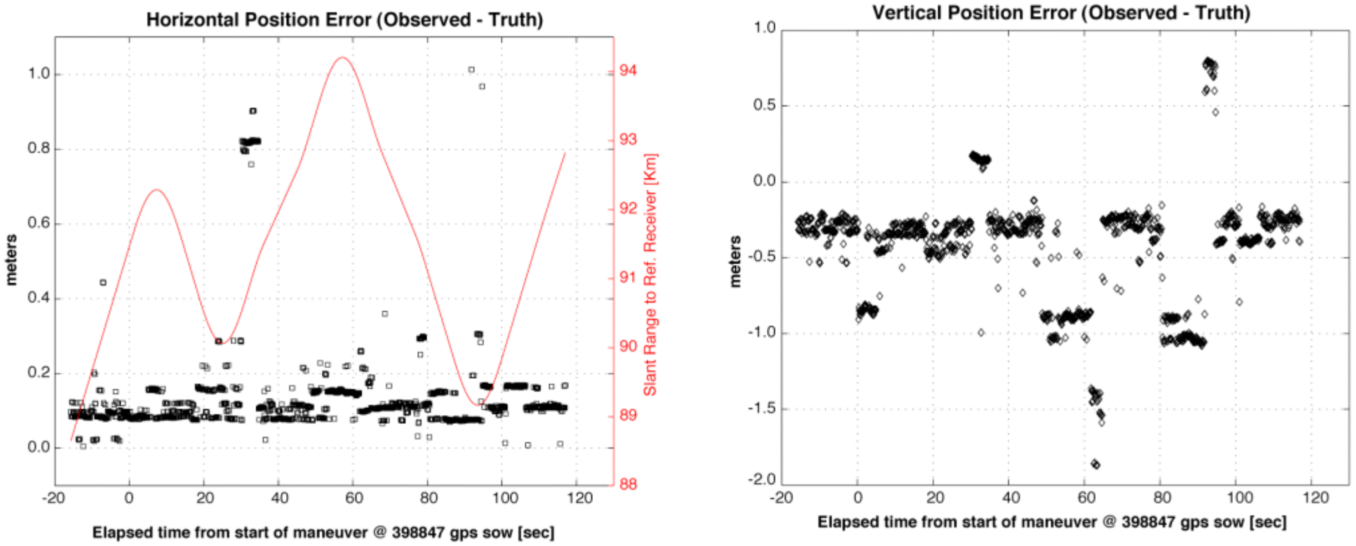

Figure 6. Far position errors for “Split S-Cuban 8-Split S” maneuver

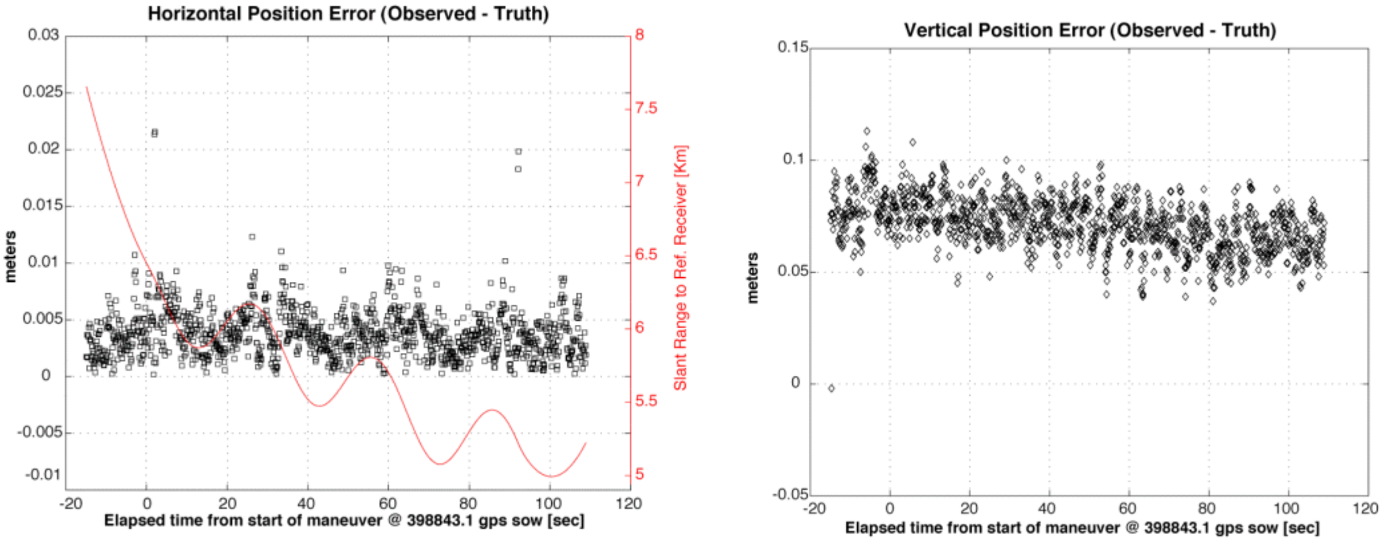

Figure 7. Near position errors for “Post Hole” maneuver

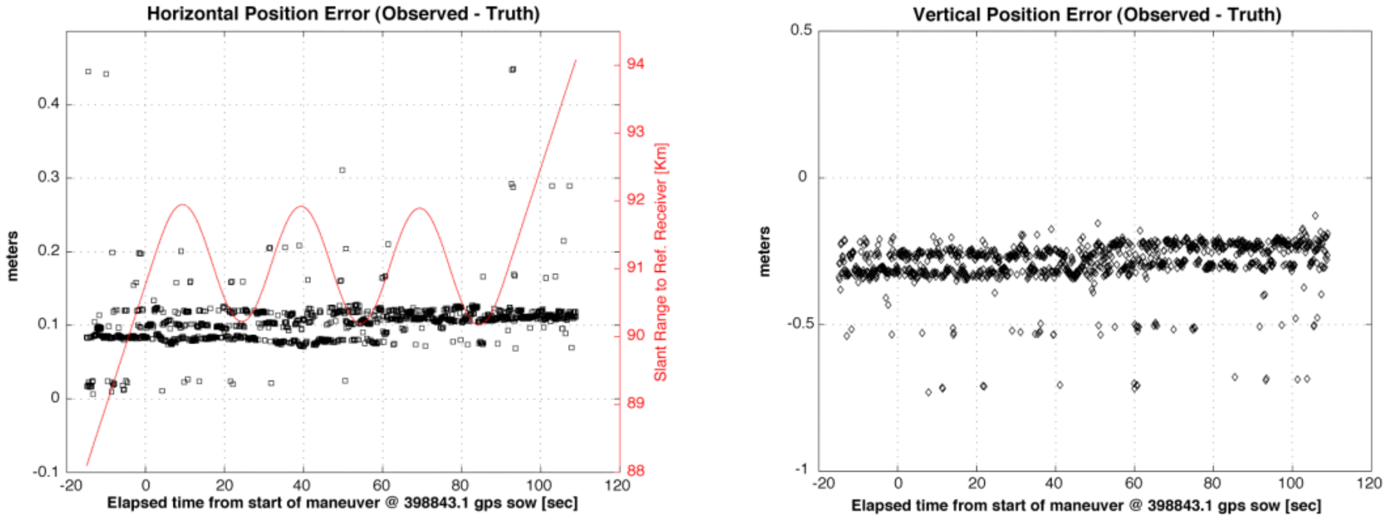

Figure 8. Far position errors for “Post Hole” maneuver

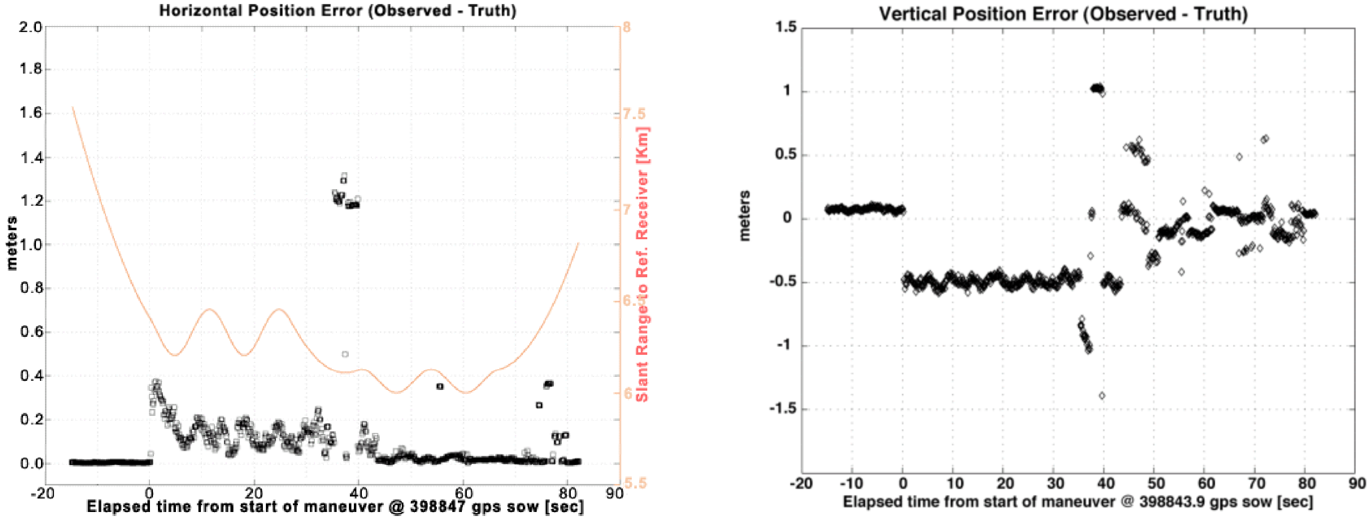

Figure 9. Near position errors for “9g Turns” maneuver in graceful degradation mode

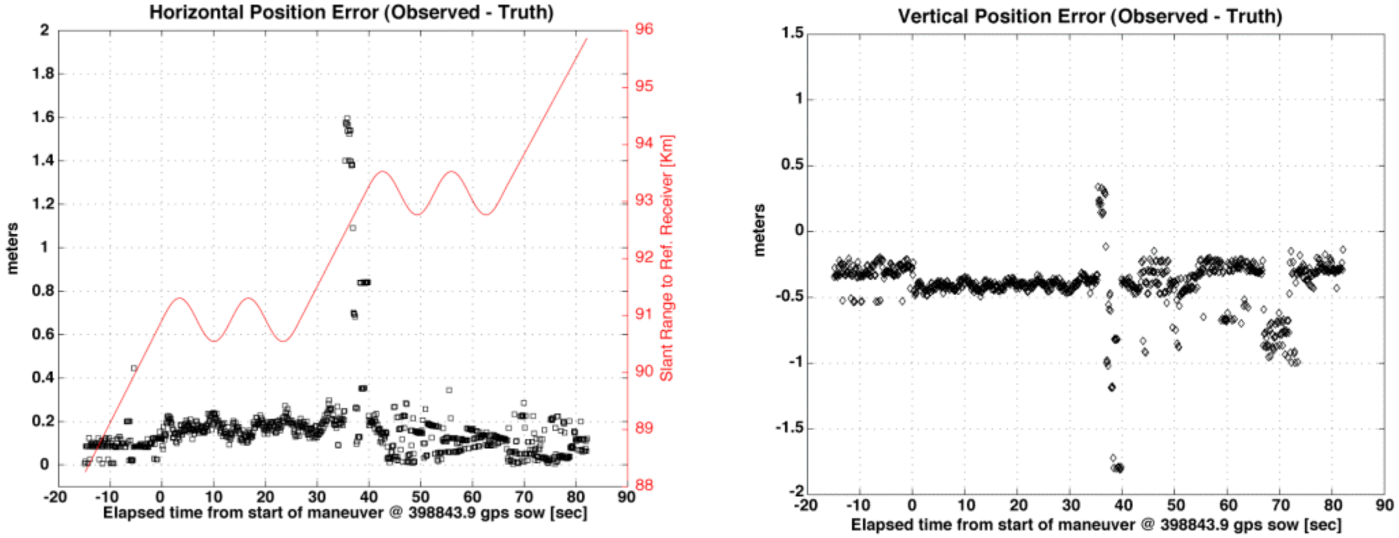

Figure 10. Far Position errors for “9g Turns” maneuver in graceful degradation mode

Component	Mean (cm)	Std. Dev. (cm	. Dev. w/o Outliers	Median (cm)	IQR (cm)	% Outliers > 4 IQR
Split S-Cuban 8-Split S – Near (Full phase solution with ambiguity resolution)						
North	5.5	2.6	0.3	0.1	0.4	7.83
East	0.6	2.2	0.1	0	0.2	7.83
Up	4.6	4.9	2.1	6.4	3.4	7.83
Split S-Cuban 8-Split – Far (Full phase solution with ambiguity resolution)						
North	3.7	1.3	1.3	1.2	1.9	0.15
East	-5.1	1.3	6.1	-5.9	8.3	3.31
Up	-4.3	3.6	2.9	-3.3	2.4	4.06
Post-Hole - Near (Full phase solution with ambiguity resolution)						
North	0.1	0.2	0.2	0.1	0.3	0.00
East	0.0	0.2	0.2	0.0	0.4	0.32
Up	7.1	1.1	1.1	7.2	1.5	0.08
Post-Hole – Far (Full phase solution with ambiguity resolution)						
North	-1.6	7.7	7.7	-5.2	15.7	0.00
East	-1.4	7.2	7.2	-5.9	14.9	0.00
Up	-2.8	7.5	6.0	-27.5	7.6	1.21
9g Turns - Near (Graceful degradation solution for more than 50% of maneuver)						
North	-7.0	20.3	7.1	-2.1	9.7	4.11
East	-5.9	15.0	6.9	-1.6	8.9	4.11
Up	-8.5	43.1	21.0	-0.4	25.3	2.16
9g Turns – Far (Graceful degradation solution for more than 50% of maneuver)						
North	-9.1	14.0	8.5	-10.3	10.2	3.08
East	-8.6	17.5	7.8	-8.0	9.8	2.67
Up	-40.5	22.6	13.5	-38.4	13.1	4.53

Table 1. Positional accuracy (deviation from truth) of the maneuvers

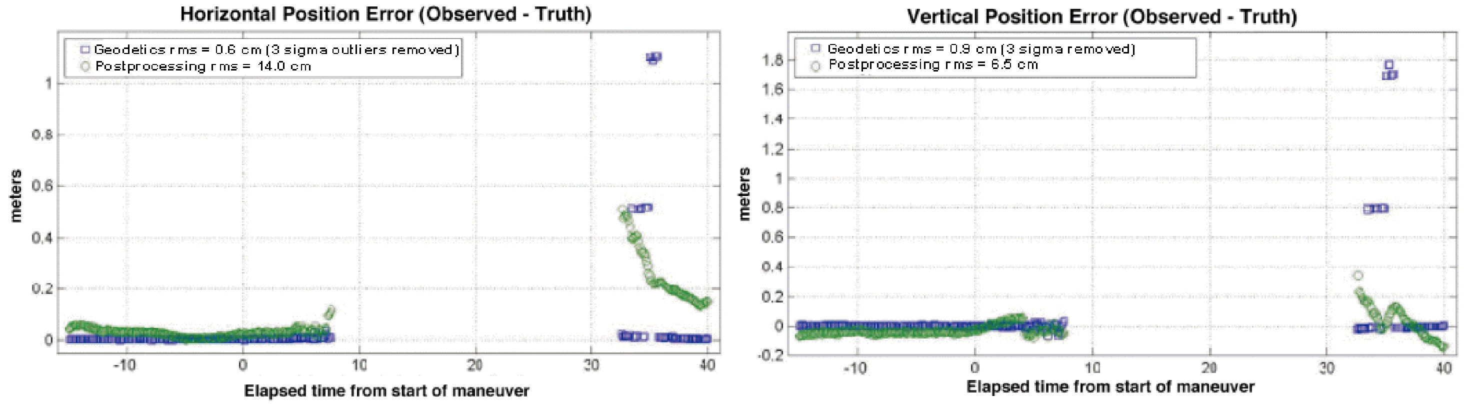

Figure 11. Comparison of re-initialization characteristics of EBE and a post-processing package

Figure 11 shows a loss of lock on all satellites by the GPS receiver due to the inversion of the antenna in the simulation. This occurs approximately 8 seconds after the initiation of the barrel roll maneuver. Satellite track is restored when the antenna rights itself 24 seconds later. The EBE process (blue) initially estimates the integer ambiguities correctly and tracks the truth data accurately until loss of satellites at *t* = 8 seconds. At *t* = 22 seconds, satellite track is restored and the EBE process estimates the ambiguities correctly and produces a few outliers which disappear over the next two seconds. The non-EBE process (green) initially produces an integer ambiguity based solution which tracks the truth data accurately until loss of satellite lock at *t* = 8 seconds. At *t* = 22 seconds, the non-EBE solution produces a float ambiguity solution which is resolved to integer more than 8 seconds after reacquisition of satellites by the GPS receiver.

6. Summary

As shown in Table 1, EBE yields *cm-level real-time* accuracies (1 standard deviation), for the “Split S-Cuban 8-Split S” and “Post Hole” maneuvers where base station distances are up to 10 km. These accuracies are obtained after removing position outliers greater than 4 times the IQR. The “Split S-Cuban 8-Split S” maneuver has about 7% of easily detectable outliers, while the "Post Hole" maneuver has very few outliers (0.0-1.2%). For base station distances of up to 96 km, the accuracies for the "Post Hole" maneuver increase to 6-7 cm in both horizontal and vertical components, and increase to 6-13 cm in the horizontal and 29 cm in the vertical for the "Split S-Cuban 8-Split S" maneuver. Due to long periods where less than 5 common satellites were tracked, results for the "9g turns" maneuvers were computed using graceful degradation techniques and are less accurate, emphasizing the need for aided navigation in these extreme cases.

Outliers and decreased accuracy are a result of a combination of effects, including the ability to track sufficient satellites during high dynamic maneuvers, (as seen in the "9g turns" maneuvers), incorrect integer-cycle phase ambiguity resolution due primarily to ionospheric effects, and the strong coupling between multipath, troposphere and vertical parameter estimation [*Bock et al*., 2000].

Results presented show that with robust data editing, EBE accuracies meet the stringent T&E requirements of 30 cm (RMS) in real-time even at extended ranges from base stations. In these tests, the data were edited manually after the solutions were generated. Robust data editing in real-time is planned for future work. To reduce the number of outliers and improve accuracy we are investigating improved ionospheric modeling and INS/GPS coupling for aided navigation.

The EBE approach was shown to provide an instantaneous integer ambiguity re-initialization as compared to a post-processing package, which required 8 seconds to resolve the integer ambiguity.

These tests provide OSD with sufficient high dynamic performance data to be convinced that the EBE concept deserves serious consideration for deployment in real-time T&E applications.

Dr. Yehuda Bock is the CEO and co-founder of Geodetics Inc. Dr. Bock has over twenty years of GPS experience. He has consulted for GPS manufacturers, state, federal and foreign agencies regarding GPS technology. Dr. Bock holds a B.A. in Mathematics from New York Univ., B.Sc. in Geodetic Engineering from the Technion - Israel Institute of Technology, and M.Sc. and Ph.D. in Geodetic Science from Ohio State University. Dr. Bock has published over 100 papers on GPS and is the recipient of numerous awards. Dr. Bock is also a Research Geodesist and Senior Lecturer at the Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography (SIO), U.C. San Diego. Other current posts include:

Director, Scripps Orbit and Permanent Array Center (SOPAC), the world's premier data facility in support of high precision geodetic, geophysical, and atmospheric measurements using the Global Positioning System

Director, California Spatial Reference Center (CSRC), a public utility for GPS positioning in California, including continuous GPS networks, advanced data processing and analysis capability, and electronic data distribution techniques

Member, SCIGN Executive Committee, The Southern California Integrated GPS Network (SCIGN), a large continuous GPS network in southern California for monitoring crustal deformation and seismic hazards.

Tom J. Macdonald is President of MacroVision, Reading, Massachusetts, a company founded in 1998. Previously with TASC for 22 years, he has more than 26 years of Department of Defense (DoD) experience in the development and analysis of advanced navigation, surveillance and radio frequency (RF) communication systems. His particular focus has been on the use of the Global Positioning Systems (GPS) and advanced datalinks for national test and training range applications. This work experience includes 15 years of support to the Director, Operational Test and Evaluation/Resources and Ranges for the Office of the Secretary of Defense (OSD) and 18 years with the test and training community. Macdonald is an advisor to OSD's Central Test and Evaluation Investment program (CTEIP) Office, for which he provides technical expertise for all. He received a B.Sc. degree in electrical engineering in 1969; a M.Sc. degree in electrical engineering in 1971; and an electrical engineering degree with a major in RF communications in 1975, all from the Massachusetts Institute of Technology. In addition, he has been an instructor with the graduate school of engineering at Northeastern University for 23 years.

John H. Merts started employment with the 46th Test Wing at Eglin AFB in 1982 as an Electronics Design Engineer. He is a previous member of the Range Commanders Council Electronic Trajectory Measurements Group and consults with the group on GPS issues. He is the co-author of a patent on the GPS application of missile / target end-game scoring. His current research topics include precision Time Space Position Information for high dynamic test aircraft, missile end game scoring using GPS raw measurements on missile and target aircraft, and post-mission correction of GPS carrier phase measurements for wrap-around antennae effects on missiles. Mr. Merts received his B.Sc. in Physics from Florida State University in 1979.

Dr. Lydia Bock is the COO and co-founder of Geodetics Inc. Before joining Geodetics, Dr. Bock was an independent business and technology (engineering) consultant. Dr. Bock's experience spans a wide variety of hi-tech industries including electronics, semiconductors, telecommunications, computer (hardware and software), and defense industries. Dr. Bock has 20+ years of industry experience including positions at SAIC and Raytheon.

Dr. Bock holds a B.Sc. from the Technion - Israel Institute of Technology, M.Sc. from Ohio State University and a Ph.D. from the Massachusetts Institute of Technology. Dr. Bock won the Raytheon's Micciolli Scholar award and the American Electric Power "operating ideas" award.

Dr. Jeffrey A. Fayman serves as VP Product Development at Geodetics Inc. Dr. Fayman's experience spans many years with custom software solutions for firms such as Price Waterhouse, Gensia Pharmaceuticals, Science Applications International (SAIC) and Cisco Systems. Dr. Fayman Co-founded and served as VP Business Development for Virtue Ltd. - a startup company developing 3D solutions for the Internet and e-Commerce applications. Dr. Fayman serves on the board of directors for Estimotion Inc. Dr. Fayman holds a B.A. in Business Administration and a M.Sc. in Computer Science, both from San Diego State University. He holds a Ph.D. in Computer Science from the Technion - Israel Institute of Technology where he published over 20 papers in the academic literature in the fields of Robotics, Computer Vision and Computer Graphics.

Endnotes

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