REAL-TIME GPS ATTITUDE DETERMINATION SYSTEM BASED ON EPOCH-BY-EPOCH™ TECHNOLOGY

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ABSTRACT

There are many civilian and military applications requiring precise attitude determination. Geodetics Inc. has demonstrated high-accuracy GPS attitude 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). One of the most significant advantages of EBE technology over conventional GPS Real-Time Kinematic (RTK) algorithms is in its instantaneous initialization and re-initialization capability. This capability eliminates re-initialization delays due to losses-of-lock, such as occur during high-dynamic maneuvers. This paper provides empirical data that was gathered during a test program, sponsored by Eglin Air Force Base, to assess the performance in real time of EBE technology as it applies to attitude determination. Using simulated data from a high-dynamic (9'g) maneuver, EBE yielded real-time attitude with accuracy better than one tenth of a degree (0.038 - 0.083 degrees, one standard deviation), utilizing geodetic quality GPS receivers operating in dual- or single-frequency mode with antenna separation of 2 meters. GPS geodetic receivers with only single frequency capability yielded attitude with accuracy of between 0.044 - 0.176 degrees after 1.3% - 2.5% of the solutions were rejected as data outliers.

INTRODUCTION

The Air Force has been funding the Technology Insertion Risk Reduction Program (TIRR) to determine the feasibility of new technologies and methodologies for future T&E investment. The objective of one TIRR funded project, the Enhanced Time Space Position Information (ETSPI) project, is to develop a low cost, miniature, real-time TSPI system to provide accurate position, pitch and heading, in real-time, on air-to-ground weapons throughout their entire flight envelope on land or water ranges.

As part of the ETSPI effort, the performance of EBE technology as it applies to attitude determination was evaluated. During the program, the EBE software package was tested in simulated tests, under dynamics of up to 9g's. The results of these tests were then analyzed, focusing on attitude solutions utilizing both dual and single frequency pseudorange and carrier phase measurements.

This paper begins with a description of EBE technology, followed by EBE attitude test results for a simulated dynamic maneuver utilizing both dual and single frequency measurements, and a summary that includes future work.

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 a,b]. 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 reduced 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). 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 inertial measurement unit (IMU).

The EBE algorithms are designed to 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 data, compensating for outages when sight to the satellites is blocked. This results in a robust and more reliable system.

Precise GPS positioning data provided by EBE is also used to provide platform attitude data. This can be accomplished by multiplexing a single receiver among three antennas on the platform, or by deploying three complete GPS systems. Only two antennas are necessary to compute two of the three attitude angles. Attitude can be determined to an accuracy of about 0.02 degrees (with inter-antenna distances of 2.0 meters). Note that multipath is a limiting factor for attitude determination. This paper presents results obtained in testing the EBE approach to attitude determination.

EBE attitude determination requires tracking a common set of five or more satellites and providing simultaneous single- or dual-frequency phase and pseudorange (code) data. Single-frequency applications are limited to short ranges (5 km or less) as is the case for attitude determination. Normally one of the receivers is stationary but this is not a requirement.

Epoch-by-Epoch™ offers numerous benefits such as:

- *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. end-game scoring), cannot see the satellites until launch, and have short flight duration.
- *A re-initialization 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 the Air Force is considering EBE for 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 code and phase observations. However, it must be mentioned that many of the GPS receivers in use by the military today do not support this requirement; hence, those systems could not realize the maximum benefit of EBE.

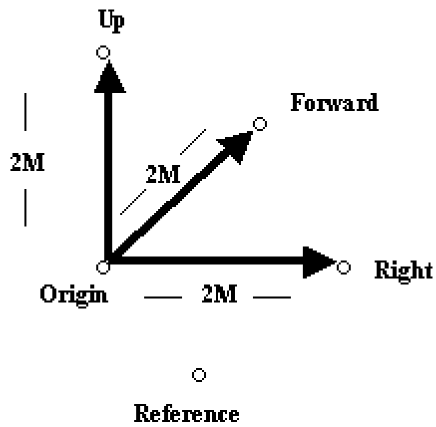
TEST SETUP

Geodetics' Vector™ software package with EBE attitude determination was tested on a simulated maneuver employing an omni-directional antenna model. The maneuver 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 simulated scenario consisted of a single stationary reference receiver and moving rigid platform upon which four antennas were mounted in a right-handed Cartesian coordinate system with inter-antenna spacing of 2 meters. For the purposes of this paper, the antennas are labeled as shown in figure 1 below.

The simulation moved the rigid platform through two sets of maneuvers, one set occurring while the rigid platform was stationary, and the second occurring while the rigid platform was translating along a linear path. During each maneuver set, the platform underwent three 360-degree rotations one rotation about each of the three axes of rotation (yaw, pitch and roll). Each rotation achieved a maximum of 9g's. Fifteen minutes of static data were collected prior to the start of the first maneuver set, and five minutes of static data were collected after the end of the second maneuver set.

Raw GPS measurement data from each of the five antennas in the simulation (1 stationary and 4 mounted on the rigid platform) were collected using both a Novatel Millennium dual-frequency receiver and an Ashtech G12 single-frequency receiver. Figure 2 illustrates the test setup.



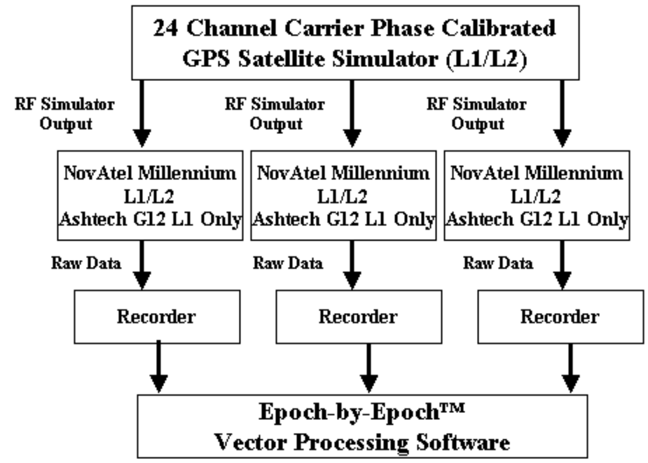


Figure 1. Antenna Configuration **Figure 2**. GWEF Test Setup

For the purposes of extracting autonomous attitude data, it was only necessary to utilize data from three of the five available receivers. The three receivers used, all on the rigid platform, were "Origin", "Forward" and "Right". The "Up" antenna was not needed. Further, the leading and trailing static sections were not included in the analysis, which focused on the dynamic parts of the simulation.

The tests involved comparing the Vector™ EBE attitude output for three different data sets (Novatel Millennium using both L1 and L2 data, Novatel Millennium in Vector™ L1 only mode where Vector™ ignores all L2 data present and processes only L1 data, and Ashtech G12) with the 'truth' simulator attitude output. Although conducted in "post-processing", the EBE analysis was conducted as if the data were collected in real time.

TEST RESULTS

Figures 3 – 5 compare unedited Vector™ EBE rigid platform attitude outputs with the 'true' attitude from the simulator for the maneuver, for the Novatel Millennium (both L1/L2 and L1 Only) and the Ashtech G12. Figure 6 compares edited attitude outputs with the 'true' attitude from the simulator for the Ashtech G12, where statistical outliers were manually edited out of the EBE solutions. In order to isolate and characterize outliers, the median and interquartile range for the deviations from truth were calculated, 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, the outlier criteria were selected to be 4 times the IQR (this criteria corresponds to approximately 3σ, if the single-epoch solutions were normally distributed).

Table 1 provides statistics (mean, standard deviation) for deviations from truth for the Novatel Millennium and Ashtech G12 data and additional robust statistics (median, interquartile range) for the edited (outliers removed) Ashtech G12 data.

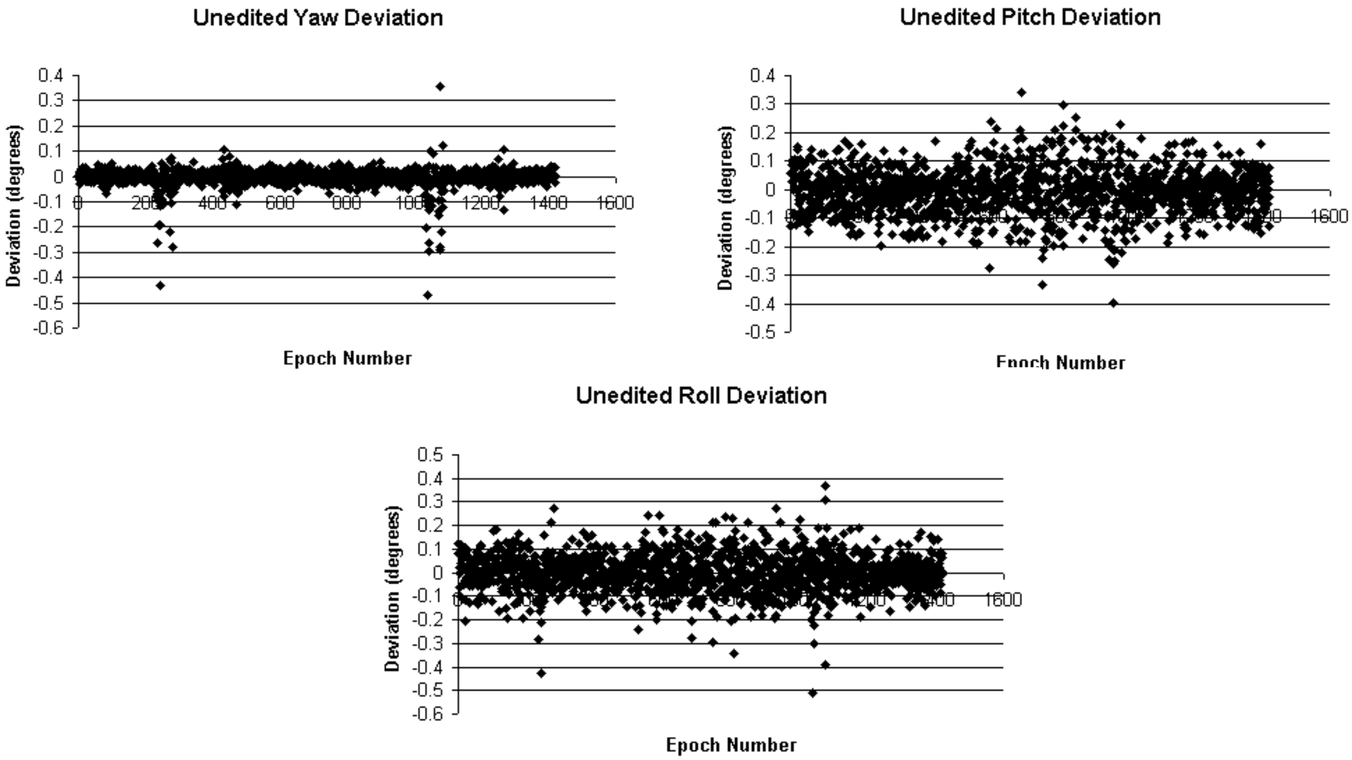


Figure 3. Novatel Millennium - Angular deviation utilizing L1/L2.

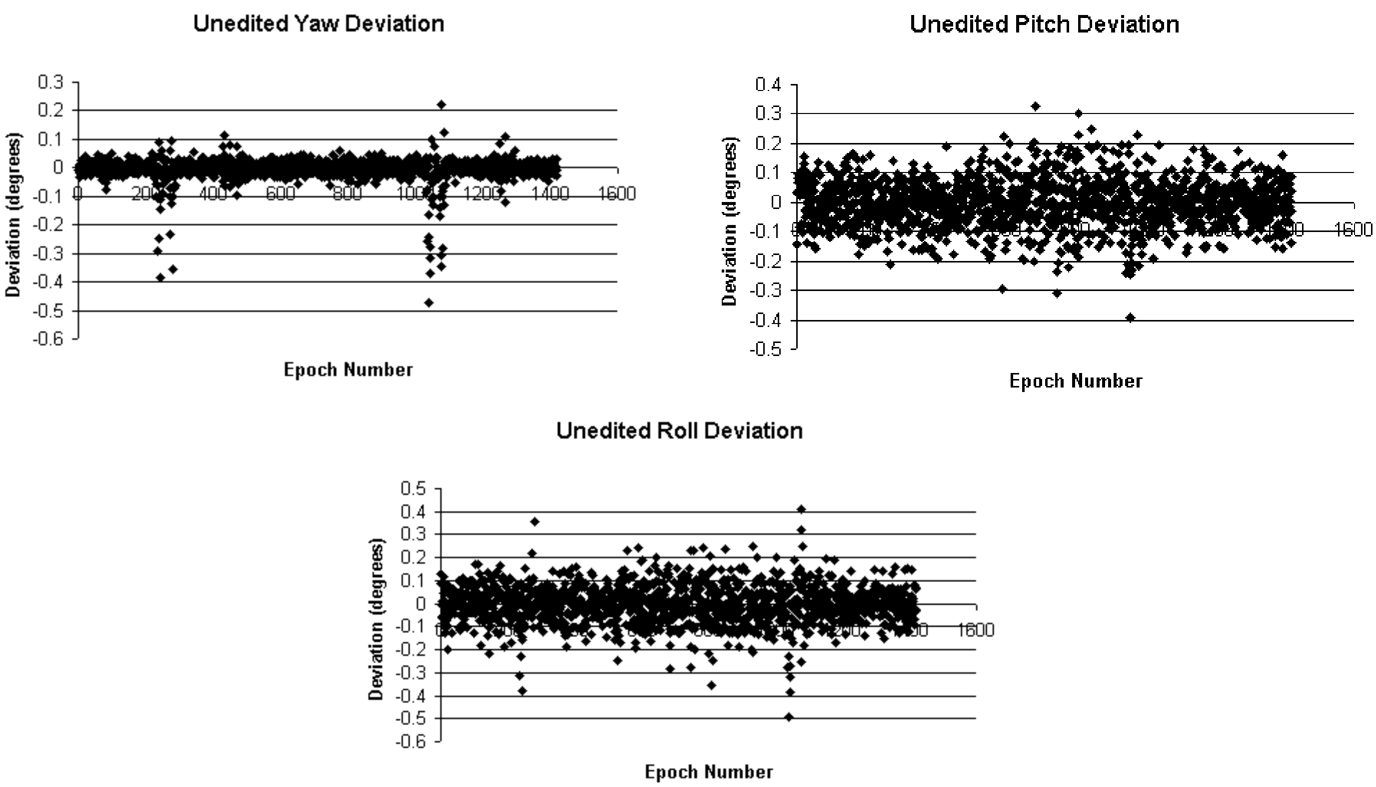


Figure 4. Novatel Millennium - Angular deviation utilizing L1 only.

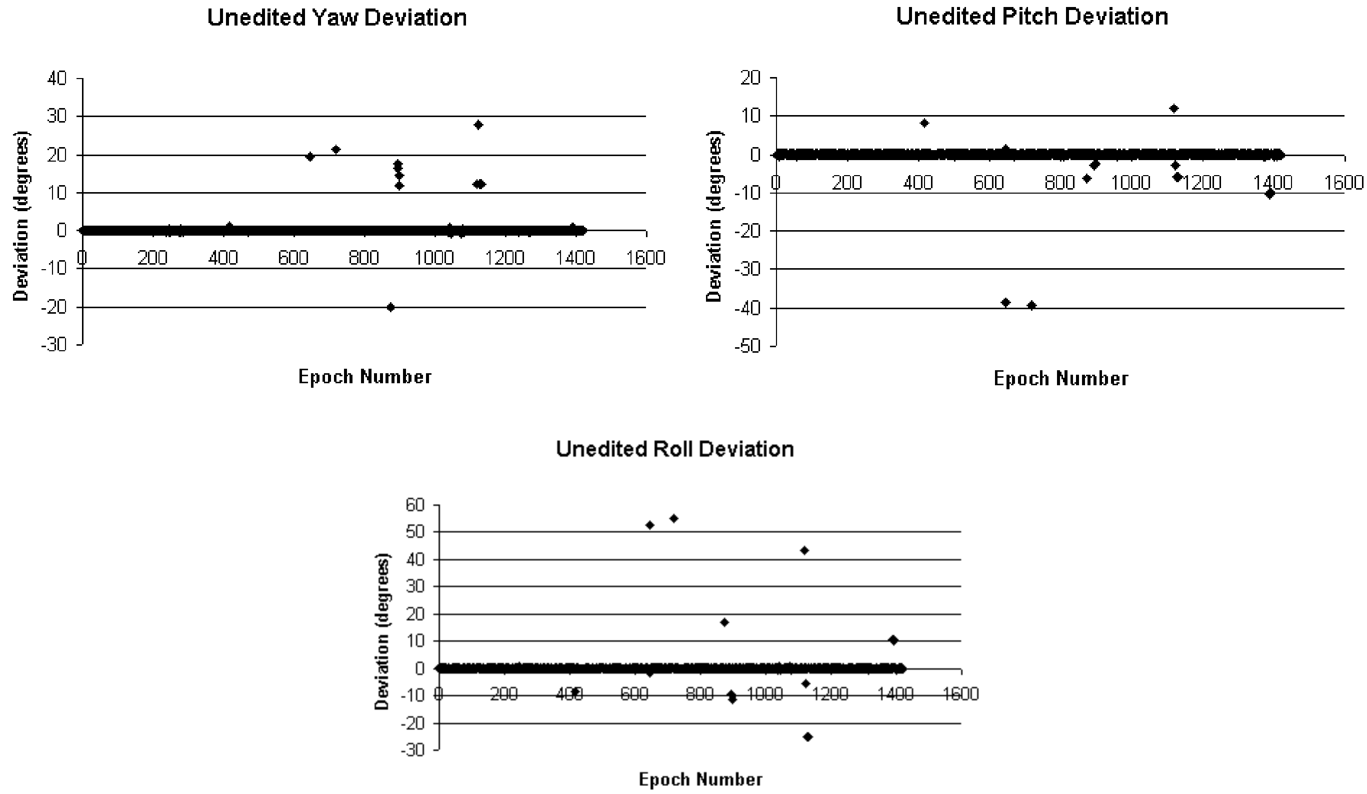


Figure 5. Ashtech G12 - Angular deviation (This is an L1 only receiver).

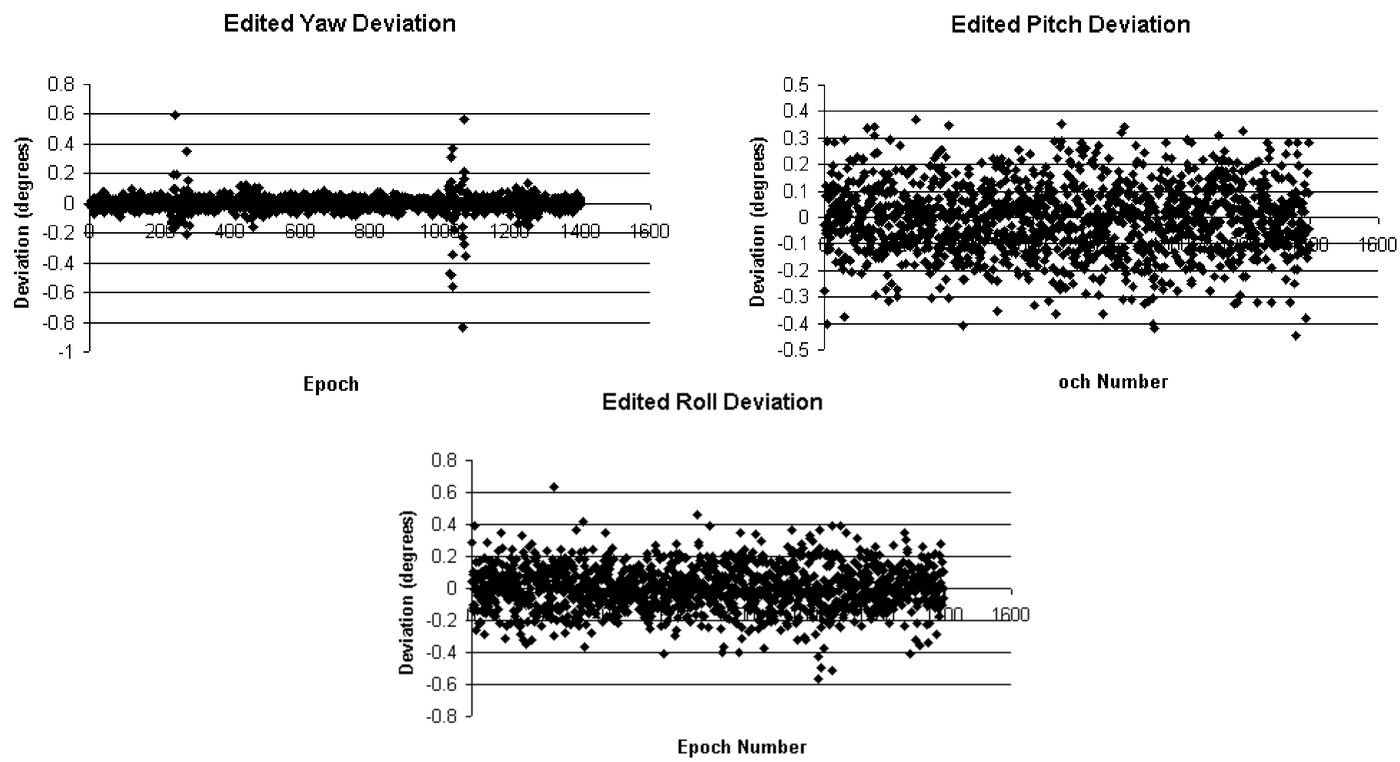


Figure 6. Ashtech G12 - Edited angular deviation (This is an L1-only receiver).

Novatel Millennium Processing Both L1 and L2 data

Component	Mean	Std. Dev.
Yaw	-0.004	0.038
Pitch	-0.005	0.080
Roll	0.001	0.081

Novatel Millennium Processing Only L1 Data

Component	Mean	Std. Dev.
Yaw	-0.005	0.041
Pitch	-0.002	0.080
Roll	-0.001	0.083

Ashtech G12 L1

Component	Mean	Std. Dev.	Std. Dev. w/o Outliers (m	Median	IQR	% Outliers > 4 IQR
Yaw	0.115	1.581	0.039	0.000	0.044	2.535
Pitch	-0.110	1.670	0.130	-0.005	0.173	1.338
Roll	0.066	2.775	0.136	0.001	0.176	1.479

Table 1. Angular accuracy (deviation from truth) of the maneuver (All values are in degrees).

SUMMARY

As shown in Table 1, for this high-dynamic (9'g) maneuver, EBE yields *real-time* attitude with accuracy better than one tenth of a degree (0.038 - 0.083 degrees, one standard deviation), utilizing geodetic quality GPS receivers operating in dual- or single-frequency mode with antenna separation of 2 meters. Single frequency GPS receivers, such as the Ashtech G12, yield attitude in real time with accuracy of between 1.581 and 2.775 degrees (one standard deviation). When 1.3% - 2.5% of the outliers are removed, EBE yields attitude with accuracy of between 0.044 - 0.176 degrees (IQR).

In general, outliers and decreased accuracy are a result of a combination of effects, including the ability to track sufficient satellites during high dynamic 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]. In attitude determination applications where inter-receiver distances are very short, atmospheric effects are not an issue. Real world testing to explore these effects is planned for future work.

Results presented show that when utilizing EBE technology with a high-quality GPS receiver such as the Novatel Millennium in dual- or single-frequency mode, the ETSPI attitude requirements of less than 0.5 degrees accuracy are met in real-time even at dynamics of up to 9g's. Further, the results show these accuracy requirements are met when utilizing EBE technology with a single-frequency receiver such as the Ashtech G12, when robust data editing techniques are employed. Robust data editing in real-time is planned for future work. Further reduction of outliers and improved accuracy can be achieved by coupling IMU and GPS for aided navigation.

REFERENCES

Anthony, K., and S. Mirsky, "Validation of IEC 2400 GPS Simulator for High Dynamic RTK Applications," ION/CIGTF, Albuquerque, NM, June 2001.

Bock, Y., R. Nikolaidis, P. J. de Jonge, and M. Bevis, "Instantaneous geodetic positioning at medium distances with the Global Positioning System," Journal of Geophysical Research, 105, pp. 28223-28254, 2000.

Bock, Y., T. Macdonald, J. Merts, L. Bock, and J. Fayman, "Epoch-by-Epoch™ Real-Time GPS Positioning in High Dynamics and at Extended Ranges," Proceedings of the ITEA Symposium on Test & Evaluation of Advanced Technology Systems, Lihue, Kauai, HI, 2003a.

Bock, Y. P. de Jonge, D. Honcik, and J. Fayman, "Wireless Instantaneous Network RTK: Positioning and Navigation," Proceedings of ION GPS-2003, The Institute of Navigation, Alexandria, VA, 2003b.

De Jonge, P. J., Y. Bock, and M. Bevis, "Epoch-by-Epoch Positioning and Navigation," Proceedings of ION GPS-2000, The Institute of Navigation, Alexandria, VA, pp. 337-342, 2000.