GPS NAVIGATION RESULTS FROM THE LOW POWER TRANSCEIVER CANDOS EXPERIMENT ON STS-107

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ABSTRACT

This paper presents the Global Positioning System (GPS) navigation results from the Communications and Navigation Demonstration on Shuttle (CANDOS) experiment flown on STS-107. The CANDOS experiment consisted of the Low Power Transceiver (LPT) that hosted the GPS Enhanced Orbit Determination Experiment (GEODE) orbit determination software. All CANDOS test data were recovered during the mission using the LPT's Tracking and Data Relay Satellite System (TDRSS) uplink/downlink communications capability. An overview of the LPT's navigation software and the GPS experiment timeline is presented. In addition, this paper discusses GEODE performance results, including comparisons with the Best Estimate of Trajectory (BET), NASA Johnson Space Center (JSC) real-time ground navigation vectors, and post-processed solutions using the Goddard Trajectory Determination System (GTDS).

INTRODUCTION

The ITT Industries' Low Power Transceiver (LPT) is an advanced signal processing platform that offers a configurable and reprogrammable capability for supporting communications and/or navigation functions of mission applications ranging from single unit, non-real time operation to multi-unit, real-time formation flying. The LPT is the result of extensive collaborative research under NASA Goddard Space Flight Center's (GSFC) Advanced Technology Program and ITT's internal research and development efforts. Its modular, multi-channel design enables transmitting and receiving communication signals on L- or S-band frequencies and processing Global Positioning System (GPS) L-band signals for precision navigation. The LPT also includes the GPS Enhanced Orbit Determination Experiment (GEODE) version 5.4 flight software for performing real-time orbit determination.

This paper presents the GPS navigation results from the LPT Communications and Navigation Demonstration on Shuttle (CANDOS) experiment on STS-107. The STS-107 mission timeline provided four periods of at least two orbits without orbiter reorientation maneuvers for the GPS experiments. The CANDOS objectives for these GPS experiment periods were to:

- Maintain track of at least four GPS satellites
- Achieve GEODE convergence
- Demonstrate the use of an uplinked attitude timeline to select the satellites to track

- Demonstrate GEODE propagation during GPS outages and subsequent filter processing when at least four GPS satellites come back into view
- Compare the GEODE solution to the ground navigation solution provided by the NASA Johnson Space Center (JSC)
- Compare the GEODE solution to the JSC's post-flight Best Estimate of Trajectory (BET) solution

All objectives were met and the results are discussed in this paper. In addition, post-flight data analysis was performed to better assess the accuracy of the GPS point solutions and GEODE solutions that were computed onboard and to identify approaches for improving these solutions.

LPT NAVIGATION SOFTWARE OVERVIEW

The LPT navigation software is comprised of four main functions: 1) point solution, 2) orbit determination, 3) channel assignment, and 4) data logging. The point solution function is a standard weighted least-squares algorithm for computing the position and clock bias when at least four GPS satellites are tracked. The velocity and clock drift are computed using a polynomial fit to three successive position/bias solutions. The point solution algorithm was designed for both ground and orbital scenarios.

The GEODE flight software, developed at NASA GSFC, provides the orbit determination function [Reference 1]. GEODE consists of an extended Kalman filter that estimates the receiver's position, velocity, atmospheric drag coefficient, clock bias, and clock drift. It also provides high-fidelity force models for the geopotential, atmospheric drag, and Solar and lunar gravitational perturbations. The expected GEODE position accuracy is about 20 meters (m) (one-sigma) during periods without orbiter maneuvers. GEODE can compute a state vector update using only one measurement at a given time and can accurately propagate the receiver state vector during measurement outages. However, for CANDOS, GEODE was constrained to process pseudorange measurements only at times when a point solution was computed.

The channel assignment function determines which GPS satellites are to be tracked. When fewer than four satellites are tracked and either a GEODE solution or GPS almanac is not available, this function performs an open-sky search until at least four satellites are tracked. When four or more satellites are tracked and a GEODE solution is available, the channel assignment function uses the current position, GPS almanac, and current orbiter attitude to determine which satellites are in view and then commands the LPT to track them. An initial GPS almanac file is available onboard the LPT and is updated as new data are received from the GPS constellation. For CANDOS, an uplinked attitude timeline file provided the orbiter's attitude based on the mission timeline. This file provides the orbiter's attitude via roll-pitch-yaw angles as a function of time, which the software uses to determine the direction that the GPS antenna is pointing with respect to the GPS constellation.

The data logging function logs various database messages for post-flight analysis. The message types and logging frequency are determined by a configuration file that can be uplinked to the LPT. All available messages were logged during the GPS experiments (typically every 30 seconds), but only a minimal set was logged at other times to conserve disk space on the LPT.

GPS EXPERIMENT OVERVIEW

Table 1 summarizes the four GPS experiment periods, along with two unscheduled GPS tracking opportunities (during orbits 64 and 156). As shown, the orbiter provided a stable attitude for tracking the GPS constellation during each of the four experiment periods. The attitude column shows which orbiter body axis is in the direction of the local vertical (LV), which points toward the Earth, and which is in the direction of the velocity vector (VV). The orbiter body coordinates convention is the +X axis points out the orbiter's nose, the +Y axis points out the right wing, and the +Z axis, which points out the bottom of the orbiter, completes the right-hand system. The GPS antenna boresight is along the orbiter's -Z body axis (outward from the payload bay), with a field of view of approximately ± 70°. Note that as a result of the antenna's location, the visibility of the GPS constellation was typically limited to eight or fewer satellites, whereas twelve or more GPS satellites would typically be in view from a low altitude orbit. The experiment start and stop times are listed in both Greenwich Mean Time (day of year (DDD)/hour (HH):minute (MM):second (SS) and GPS time (GPS week/time of week (TOW)).

Table 1. GPS Experiment Timeline

GPS Experiment Period	Shuttle Attitude	Start Time (DDD/HH:MM:SS GPS Week/TOW)	Stop Time (DDD/HH:MM:SS GPS Week/TOW)	Duration (H:MM)
#1	+ZLV -YVV	20/00:15:00 1202/87313	20/03:22:00 1202/98533	3:07
#2	+ZLV +YVV	22/20:19:00 1202/332353	23/00:29:00 1202/347353	4:10
#3	+ZLV +YVV	23/20:14:00 1202/418453	23/23:24:00 1202/429853	3:10
#4	+ZLV +YVV	24/19:57:42 1202/503875	24/23:59:00 1202/517753	3:51
Orbit 64	-Z Solar Inertial	20/13:45:00 1202/135913	20/15:43:00 1202/142993	1:58
Orbit 156	-XLV +YVV	26/11:50:00 1203/42613	26:14:10:00 1203/51013	2:20

Prior to each GPS experiment period, any necessary files were uplinked (e.g., updates to the navigation configuration, attitude timeline, or logging configuration). At the beginning of each GPS experiment period, the navigation software was initialized from a cold-start. Once the open-sky search algorithm acquired at least four GPS satellites, a point solution was computed and used to initialize the GEODE filter.

All experiments were run with the same navigation configuration except the first one. For the first experiment period, the GEODE drag coefficient's a priori variance and process noise variance rate were constrained to suppress estimation of a correction to the atmospheric drag coefficient. For the other experiment periods, the atmospheric drag coefficient's a priori variance and process noise variance rate were increased so that GEODE would estimate the drag coefficient correction.

JSC GROUND NAVIGATION VECTOR COMPARISONS

JSC provided the current orbiter's ground navigation batch solution vector once per orbit for comparison with the GEODE estimate. Table 2 shows the vector comparisons for each of the experiment periods. The one-sigma JSC vector accuracies are approximately 360 m in position and 0.314 meters per second (m/s) in velocity (for 2 hours following an attitude maneuver). The GEODE solution was not corrected for the distance between the GPS antenna and the orbiter's center of mass for these comparisons. All but one of the root-sum-square (RSS) GEODE-JSC vector differences were within the 1-sigma uncertainty of the JSC vectors, with the first comparison of the fourth experiment period being within the 2-sigma uncertainty.

Table 2. GEODE-JSC Vector Comparisons

Orbit	GPS Experiment Period	GPS Time (GPS Week/TOW)	RSS Position Difference (m)	RSS Velocity Difference (m/s)
55	1	1202/88813	179.0	0.170
56	1	1202/94633	149.6	0.186
57	1	1202/100453	248.0	0.270
64	–	1202/137714	47.1	0.063
101	2	1202/341594	25.1	0.078
102	2	1202/347893	97.8	0.122
116	3	1202/423271	132.4	0.141
117	3	1202/429126	225.2	0.283
132	4	1202/509701	439.8	0.520
133	4	1202/515532	243.2	0.212
156	–	1202/636373	80.2	0.154
157	–	1202/642193	110.6	0.071

JSC BET COMPARIONS

The GEODE state vectors were compared to the JSC BET, officially referred to as the Postflight Attitude and Trajectory History [Reference 2]. The estimated accuracy of the BET's position and velocity in radial, intrack, and crosstrack components is listed in Table 3 [Reference 3]. Because of the large uncertainties in the BET relative to expected GEODE accuracies, corrections for antenna location or shuttle attitude were not applied to the GEODE states. The BET solution was generated using a filter/smoother to process all available Tracking and Data Relay Satellite System (TDRSS) Doppler and Ground Network (GN) tracking measurements. Solutions from the orbiter's GPS receiver were not available during the orbital phase of the mission.

Table 3. BET 3-Sigma Accuracies

Component	Position (m)	Velocity (m/s)
Radial	200	0.45
Intrack	450	0.20
Crosstrack	200	0.25

Figures 1 and 2 present statistics for the radial (R), intrack (I), and crosstrack (C) components of the position and velocity differences between the BET and GEODE for the four GPS experiment periods and the data collected during orbits 64 and 156. Also shown are the averaged statistical values over all the data spans (horizontal solid line), along with the predicted BET 3-sigma uncertainties listed in Table 3. In Experiment period 4, which produced the largest differences from the BET, all three components of position and velocity exceeded the predicted BET thresholds, with the crosstrack component having the largest difference. The crosstrack position and velocity differences also exceeded the expected BET uncertainties in Experiment 3. All other periods were well bounded by the BET uncertainty thresholds.

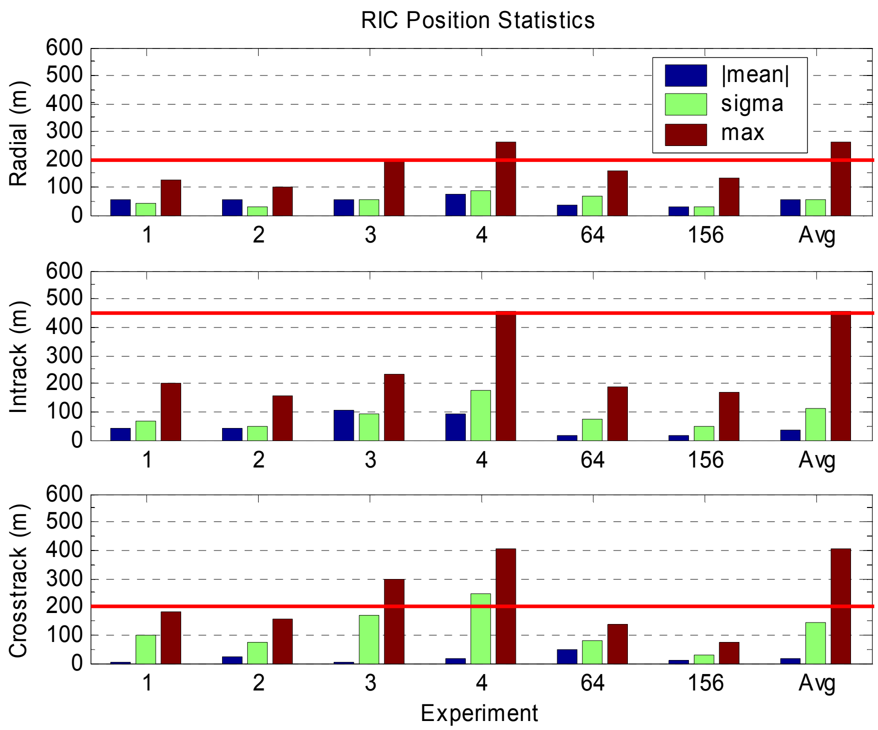

Figure 1. GEODE-BET Position Difference Statistics

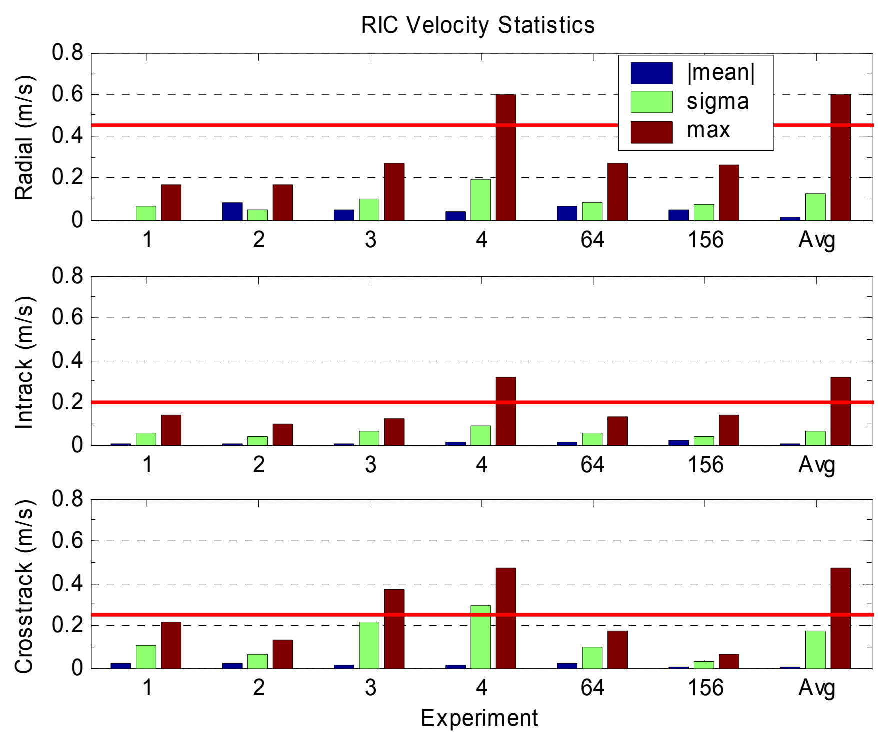

Figure 2. GEODE-BET Velocity Difference Statistics

As an example of GEODE's performance, Figures 3 and 4 show the RIC position and velocity differences with the BET for the second GPS experiment period. The orbiter's attitude is indicated along the top of the figure, and the "x" symbols on each curve indicate where GEODE's estimated root-variances exceeded convergence tolerances of 100 m and 0.2 m/s. Even though the experiment was only for the duration of the +ZLV +YVV attitude hold, the subsequent –XLV –YVV attitude hold allowed the LPT to track enough satellites to maintain GEODE convergence for an additional 2.5 hours. At the end of this period, the navigation software continued to propagate for an additional 9 hours (shown in Figure 5). The orbiter's attitude was not favorable for tracking at least four GPS satellites after the –XLV –YVV attitude hold, and the GEODE position error increased as a result of unmodeled translational forces from multiple attitude maneuvers during this timeframe. GEODE's intrack position error relative to the BET grew to 9 kilometers before the LPT again tracked four or more GPS satellites, and within 13 minutes, GEODE had returned to steady-state performance. This demonstrated the ability of GEODE to propagate through extended outages and return to steady-state performance when new measurements were available.

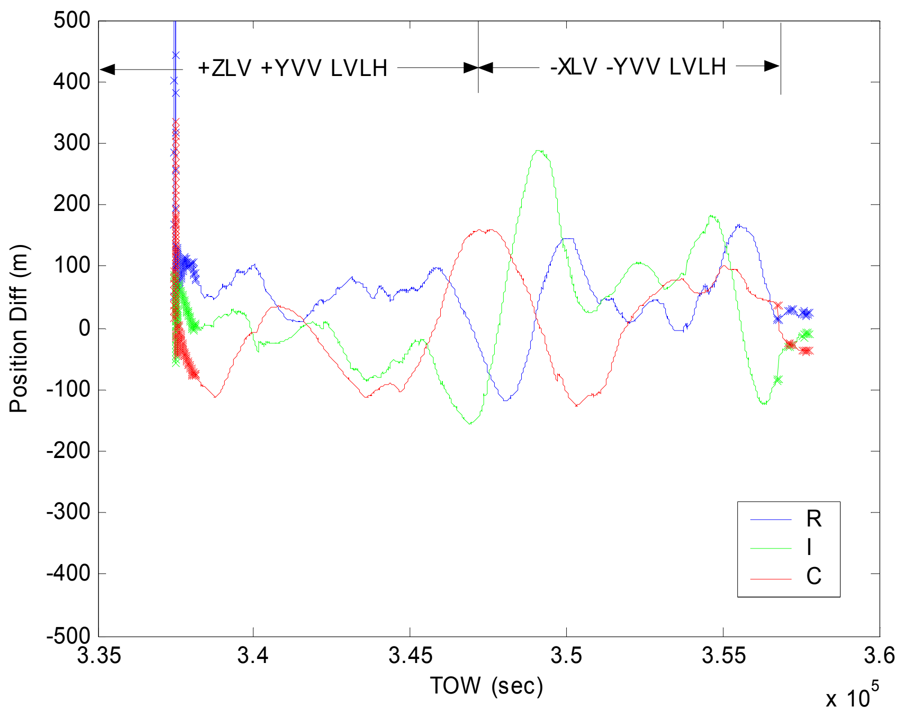

Figure 3. Experiment 2 GEODE-BET Position Difference

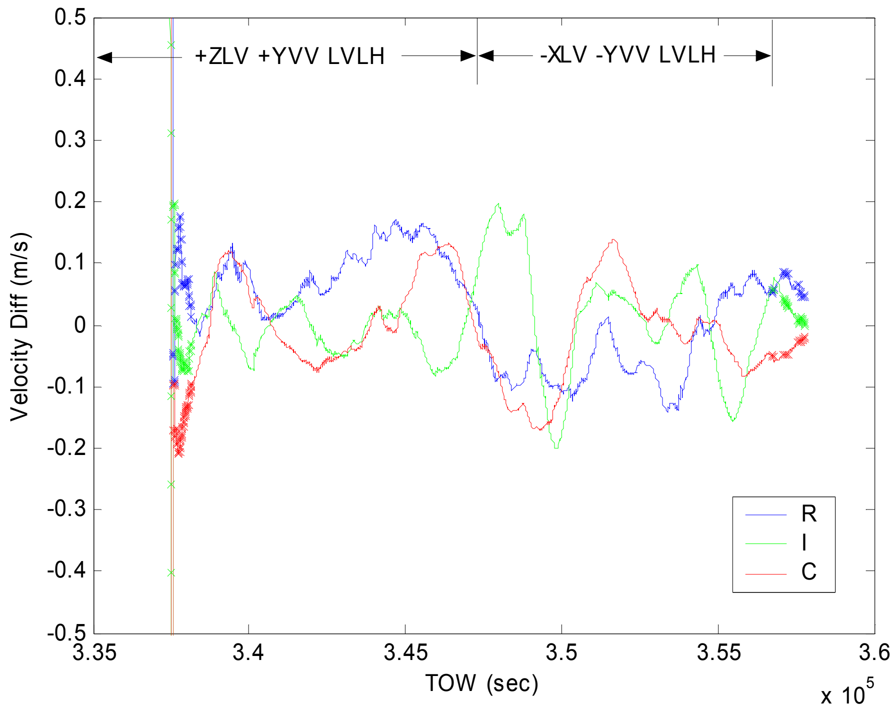

Figure 4. Experiment 2 GEODE-BET Velocity Difference

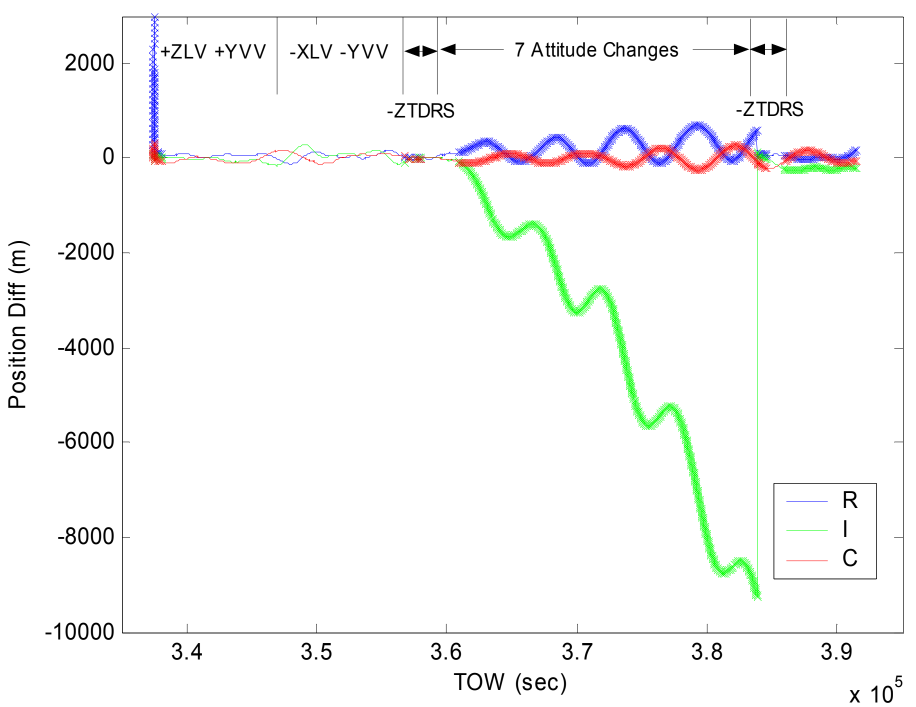

Figure 5. Extended Experiment 2 GEODE-BET Position Difference

NAVIGATION TELEMETRY PROCESSING

The pseudorange residual statistics, which are shown in Table 4 for each GPS experiment period, provide another measure of GEODE's performance. The 95% value was computed as the 95% point of the absolute residuals when ranked in ascending order. The first measurement at each processing epoch included significant errors from the LPT clock prediction (up to 600 m) and was excluded from the statistics. The near-zero mean and approximately 13 m standard deviation indicates that the Kalman filter performed well.

Table 4. Measurement Residual Statistics

GPS Experiment	Mean (m)	Sigma (m)	95% (m)
1	-0.4	12.6	25.3
2	0.2	12.2	24.5
3	-0.9	12.7	25.4
4	1.2	11.4	22.7

POST-FLIGHT DATA ANALYSIS

Additional post-flight analysis was performed to better assess the accuracy of the GPS point solutions and GEODE solutions that were computed onboard and to identify approaches for improving these solutions. GPS measurements from the four experiment periods were reprocessed using the GPS Enhanced Onboard Navigation System (GEONS) flight software, which includes all the capabilities in the GEODE flight software [Reference 4]. The filter parameters were adjusted to provide better clock drift estimation. Point solutions were smoothed using GEONS and used as a GPS-based reference solution for estimation of a lower bound on the accuracy of the GPS-based solutions. Figure 6 shows the root-mean-square (RMS) position and velocity comparison differences between the smoothed point solution versus the onboard point solutions, GEODE filter results, and the retuned GEONS filter results for each experiment period. Figure 7 shows the RMS clock bias and rate comparison differences between the onboard point solutions, GEODE filter results, and the retuned GEONS filter results for each experiment period.

In addition, TDRSS Doppler measurements for the shuttle were processed in the Goddard Trajectory Determination System (GTDS) using definitive tracking spans equal to the experiment time periods. This provides a GPS-independent reference solution for estimation of an upper bound on the accuracy of the GPS-derived solutions. GTDS uses a batch least-squares estimator and includes high-fidelity acceleration models. GTDS was used to generate a "truth" solution because it is the system used at GSFC for prime operational support of most unmanned missions, as well as for backup support for STS missions. Figure 8 shows the RMS position and velocity comparison differences between the GTDS TDRSS solutions versus the onboard point solutions, GEODE filter results, and the retuned GEONS filter results for each experiment period.

Onboard Point Solution Accuracy

The accuracy of the onboard point solutions (when compared with the smoothed ground point solutions) was 54 and 12 m RMS (computed as the RMS of the accuracies for each experiment period) for position and clock bias, respectively, and 28.4 and 1.78 m/s RMS for velocity and clock rate, respectively. The velocity differences are primarily due to the fact that the onboard velocity point solution was computed by fitting three position points as a quadratic, which would be sensitive to position spikes. These comparisons provide a lower bound on the accuracy of the onboard point solutions. The accuracy of the onboard point solutions when compared with the GTDS TDRSS solutions were 264 m RMS for position and 3.76 m/s RMS for velocity. These comparisons provide an upper bound on the accuracy of the onboard point solutions.

Onboard GEODE Solution Accuracy

The accuracy of the GEODE filter solutions (when compared with the smoothed ground point solutions) was 34 and 21 m RMS for position and clock bias, respectively, and 0.0449 and 8.9 m/s RMS for velocity and clock rate, respectively. These differences are consistent with the GEODE's estimated state root variances. The velocity differences are less than 0.2% of the point solution velocity differences. The position differences are also smaller than the point solution position differences. The clock differences are larger, due to the small process noise variance rate that was used for the clock drift rate. These comparisons provide a lower bound on the accuracy of the onboard GEODE filtered pseudo-range solutions. The accuracy of the GEODE filter solutions when compared with the GTDS TDRSS solutions were 264 m RMS for position and 0.29 m/s RMS for velocity. These comparisons provide an upper bound on the accuracy of the onboard GEODE filtered pseudo-range solutions.

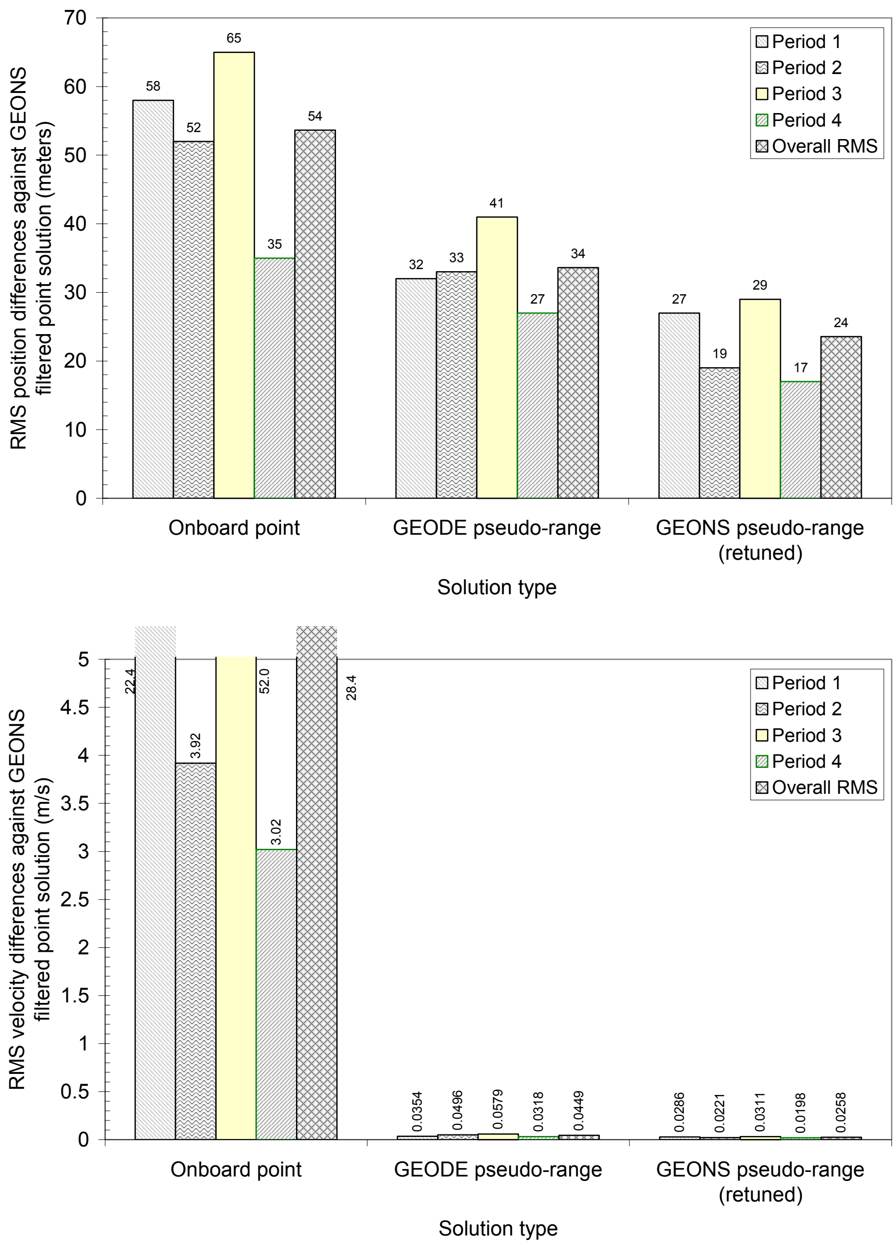

Figure 6. Position and Velocity RMS Differences for Various Comparisons Versus the Smoothed Point Solutions

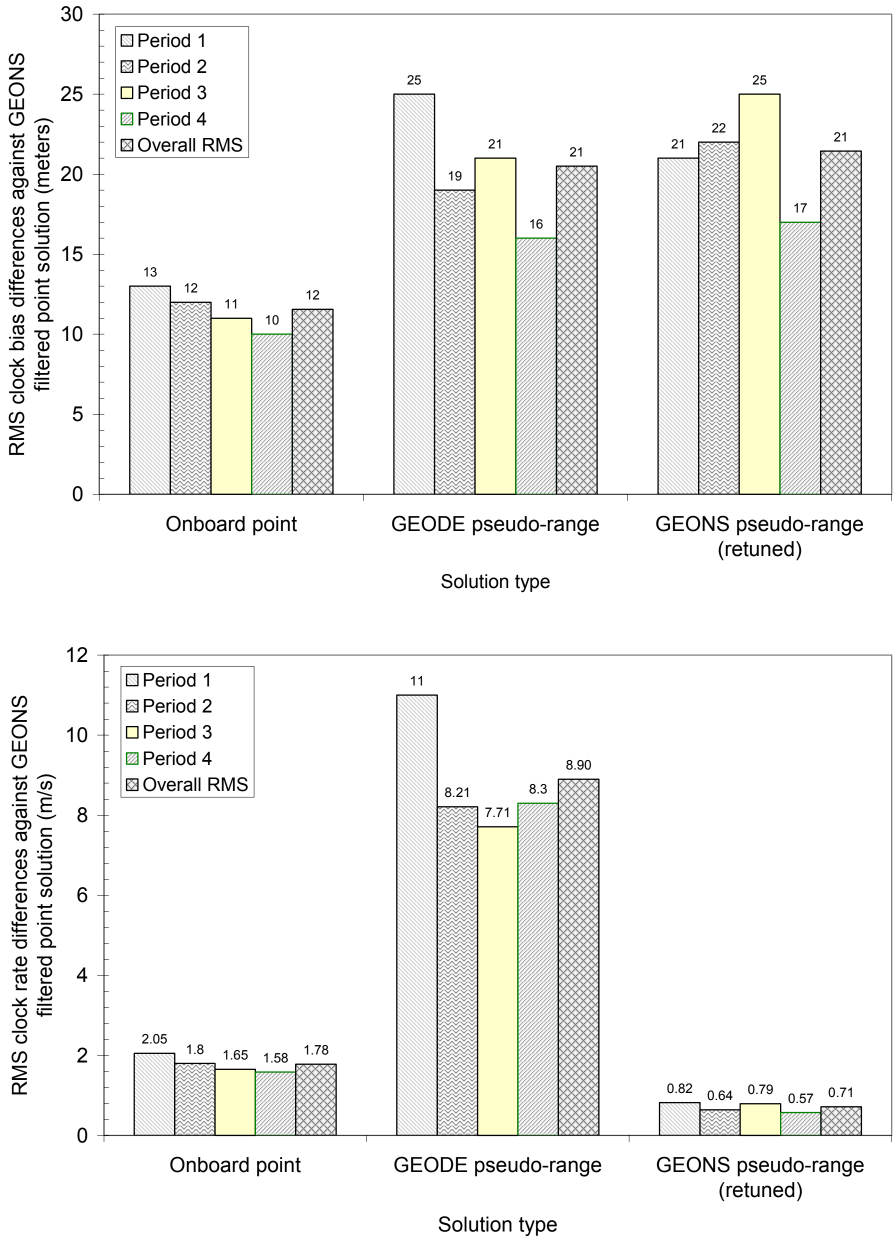

Figure 7. Clock Bias and Rate RMS Differences for Various Comparisons Versus the Smoothed Point Solutions

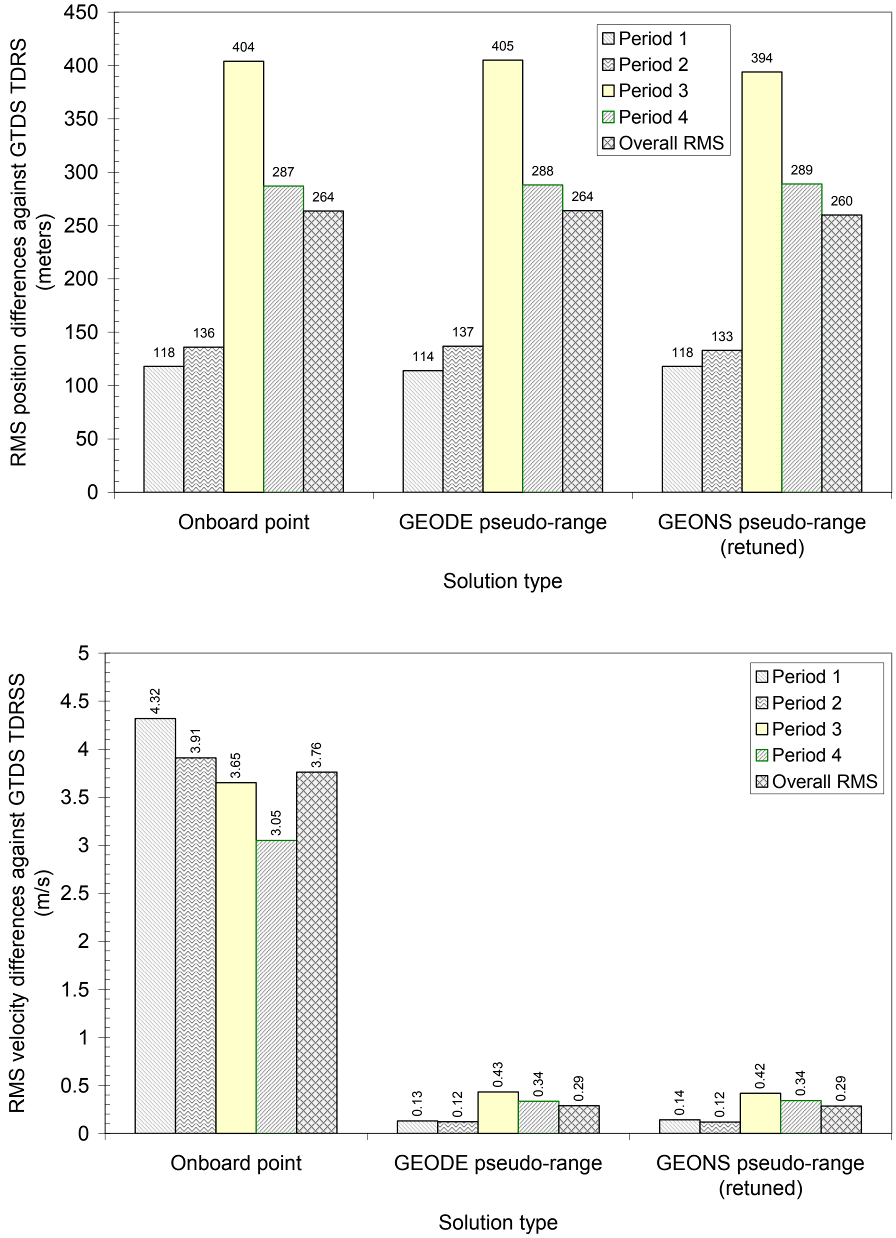

Figure 8. Position and Velocity RMS Differences for Various Comparisons Versus the GTDS TDRSS Solutions

Post-Processed GEONS Solution Accuracy

The accuracy of the retuned GEONS filter solutions when compared with the smoothed ground point solutions (which would indicate how much better the GEODE solutions could have been if the tuning was adjusted) were 24 and 21 m RMS for position and clock bias, respectively, and 0.0258 and 0.71 m/s RMS for velocity and clock rate, respectively. These differences are consistent with the GEONS estimated state root variances. These comparisons provide a lower bound on the accuracy of the filtered pseudo-range solutions with better tuning. The accuracy of the retuned GEONS filter solutions when compared with the GTDS TDRSS solutions were 260 m RMS for position and 0.29 m/s RMS for velocity. These comparisons provide an upper bound on the accuracy of the filtered pseudo-range solutions with better tuning.

The major sources of navigation error in the point sources were probably poor GPS geometry (due to the location of the receiver inside the shuttle bay) and unmodeled ionospheric delays. The major sources of navigation error in the filtered GPS solutions were probably shuttle dynamic modeling errors and unmodeled ionospheric delays (expected to be significant when a single frequency receiver is used at low altitudes). It should be noted that the navigation performance obtained in this experiment represents a worst case for satellite navigation due to the restricted GPS antenna visibility and the difficulty in modeling the shuttle dynamics.

CONCLUSIONS

The differences between GEODE and the JSC ground navigation and BET reference vectors are in general well within the documented uncertainties of the reference solutions, which represent typical solution uncertainties and are not specific to the experiment time spans. However, the uncertainties of the reference sources are much larger than the expected one-sigma uncertainty in GEODE’s position, which is about 20 m. GEODE’s pseudorange residual statistics and GEODE’s estimated position root-variances are consistent with a one-sigma positioning accuracy of 20 m. In addition, the difference between the GEODE solution and a reference solution obtained by smoothing the GPS point solutions is about 35 m, less than the 2-sigma uncertainty. The navigation performance obtained in this experiment represents a worst case for satellite navigation due to the restricted GPS antenna visibility and the difficulty in modeling the shuttle dynamics.

ACKNOWLEGEMENTS

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