Computer Sciences Corporation **CSC-5547-05**

Autonomous Navigation of Geosynchronous Satellites Using GPS: Maneuver Recovery Study

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
Greenbelt, Maryland 20771

CONTRACT GS 35F-4381-G
Task Order No. S-15614-Y

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Abstract

This report provides the results of an assessment of the autonomous navigation performance achievable for geosynchronous spacecraft using standard Global Positioning System (GPS) pseudorange measurements. In particular, this report addresses the navigation accuracy achievable immediately following typical momentum unloads, East-West station-keeping maneuvers, and North-South station-keeping maneuvers. The sensitivity of the navigation performance is evaluated with respect to the GPS receiver's signal acquisition threshold, receiving antenna gain, and the accuracy of any available thrust acceleration data.

Contents

1.0 Introduction

The Guidance, Navigation, and Control Center (GNCC) at the Goddard Space Flight Center (GSFC) has successfully demonstrated high-accuracy autonomous navigation for near-Earth spacecraft using the Global Positioning System (GPS). GNCC is developing the PiVoT (Position Velocity and Time) GPS receiver for use as an improved navigation sensor in orbits with very high apogees. This receiver is intended to expand the range of missions for which GPS can be reliably used as the primary orbit determination sensor to include the wide range of orbit designs being considered for most future Earth-orbiting missions. The PiVoT receiver hosts the GPS Enhanced Onboard Navigation System (GEONS) flight software (Reference 1). GEONS provides high accuracy navigation using an extended Kalman filter with realistic process noise models and a high-fidelity orbit propagator.

This report presents the results of a study to characterize the navigation performance that is achievable for a geosynchronous satellite using the high accuracy GPS navigation algorithms available in GEONS. In particular, this report assesses the absolute navigation accuracy achievable immediately following typical momentum unloads, East-West station-keeping maneuvers, and North-South station-keeping maneuvers. The sensitivity of the navigation performance is evaluated with respect to the GPS receiver's signal acquisition threshold, the user antenna characteristics, and the accuracy of any available thrust acceleration data.

This study is motivated by a request from Donald Chu of Swales to determine if PiVoT/GEONS can support the navigation requirement for future GOES missions, which is on the order of 100 meters (Reference 2). Therefore, the spacecraft orbital characteristics are based on the GOES spacecraft and the momentum unloads and maneuvers are modeled based on GOES mission experience. GEONS is used to process realistically-simulated GPS pseudorange measurements, representative of those provided by a typical single-frequency civilian GPS space receiver, and the estimated trajectory is compared with the truth trajectory used in the measurement simulation.

This study demonstrates that the following autonomous navigation accuracies are achievable for a geosynchronous spacecraft:

- Excluding maneuver recovery periods, position accuracies of better than 15 meters root-mean-square (RMS) and 60 meters maximum can be achieved using a typical GPS space receiver with a high-gain antenna.

- During the first 5 hours following momentum unloads, position errors remain below 50 meters RMS and 110 meters maximum if the thrust magnitude is included in the state covariance propagation and GPS measurements are available immediately following the maneuver.

- During the first 5 hours following an East-West station-keeping maneuver, position errors remain below 150 meters RMS and 250 meters maximum if the thrust acceleration is included in the state propagation, the thrust magnitude is included in the state covariance propagation, and GPS measurements are available immediately following the maneuver.

- During the first 2 hours following the start of a 90-minute North-South station-keeping maneuver, the maximum position errors increase to 2 kilometers but during the next 5 hours reduce to less than 100 meters RMS and 200 meters maximum if the thrust acceleration is included in the state propagation, the thrust magnitude is included in the state covariance propagation, and GPS measurements are available immediately following the maneuver. Preliminary indications are that the initial errors can be reduced by processing measurements during the maneuver.

To assure near-continuous availability of GPS measurements for a geosynchronous mission, it is recommended that a combination of a receiving antenna gain and a GPS receiver acquisition threshold be selected that will acquire signals from the first side-lobe of the GPS broadcast signal.

Section 2 of this document discusses the navigation scenarios and assumptions that are the basis for this study. Section 3 describes the measurement simulation procedures used in this study. Section 4 presents the navigation performance analysis during periods of free-flight and immediately following momentum unloads and maneuvers. Sections 5 and 6 discuss the sensitivity of the navigation performance to the GPS receiver's signal acquisition threshold and the receiving antenna's gain, respectively. Section 7 summarizes the primary conclusions produced by this study.

2.0 Navigation Scenarios

Three types of maneuvers are typically performed on a GEO spacecraft. Momentum unloads are performed frequently, e.g. daily. East-West station-keeping maneuvers are performed less often to maintain the spacecraft within a specified longitude tolerance, e.g. monthly. North-South station-keeping maneuvers are performed less frequently to maintain the spacecraft within a specified latitude tolerance, e.g. yearly. Table 2-1 lists the magnitudes of the maneuvers and associated delta-V errors (5 percent hot) assumed for this analysis (Reference 2).

Table 2-1 Maneuver Duration, Direction and Execution Errors

Maneuver Type	Delta-V magnitude	Direction	Duration	Delta-V Error (5%)
Momentum Unload	2 cm/sec	Along-track	5 minutes	1 mm/sec
East-West Maneuver	2 m/sec	Along-track	9 minutes	10 cm/sec
North-South Maneuver	20 m/sec	Cross-track	90 minutes	100 cm/sec

In the case of a momentum unload, the net delta-V is assumed to be all in the along-track direction (worst case), although it could be in other directions.

Table 2-2 lists two approaches available in GEONS for modeling the thrust acceleration in the trajectory propagation and the thrust uncertainties in the covariance propagation, along with the associated operational impacts. The approaches are listed in order of increasing accuracy/complexity. The objective of the analysis is to find the simplest approach for handling each type of maneuver that meets the GOES navigation goals.

Table 2-2   Thrust Modeling Approaches

Approach	Thrust Acceleration Model	Thrust Uncertainty Model	Operational Impact
Unmodeled acceleration/ modeled uncertainty	None	Add thrust covariance consistent with total predicted delta-V	Maneuver start and end times and predicted total delta-V are uploaded prior to the maneuver
Modeled acceleration/ modeled uncertainty	Predicted/measured thrust accelerations are included	Add thrust covariance consistent with predicted/measured thrust errors	Predicted/measured thrust accelerations are provided to GEONS Maneuver times and thrust error are computed based on predicted/measured thrust accelerations

The last approach can be achieved by either uploading a predicted thrust profile prior to the maneuver or using real-time input from the onboard propulsion system or an accelerometer. This approach has been used successfully to autonomously support perigee-raising maneuvers and a large inclination change maneuver on the low-altitude EOS Terra spacecraft, which uses the TDRSS Onboard Navigation System (TONS) for navigation. On Terra, the thrust accelerations are computed onboard using the commanded thruster on/off times and calibrated thruster information, which are uploaded to the spacecraft prior to the maneuvers.

3.0 Measurement Simulation Procedure

This section discusses the trajectory and measurement simulation procedures and the associated error models.

3.1 GOES Truth Ephemeris Characteristics

Table 3-1 lists the GOES orbit characteristics and the truth ephemeris force model parameters used for this study. The GOES truth ephemeris was generated using the Goddard Trajectory Determination System (GTDS) with the epoch elements and force model parameters listed in Table 3-1. Delta-V's due to various maneuvers are modeled in GTDS as finite burns. Several maneuver truth ephemerides were generated using the full magnitude of the delta-V's. The magnitudes and durations of these maneuvers are given in Table 2-1.

Table 3-1 GOES Orbit Characteristics and Truth Force Model Parameters

Parameter	Value
Epoch date	October 5, 2001 00:00:00
Semimajor axis	42165.53489973196 kilometers
Eccentricity	0.000242180213355
Inclination	0.261670198454318 degrees
Argument of perigee	323.7379634263601 degrees
Right ascension of ascending node	200.1726425289057 degrees
Mean anomaly	33.33525100396508 degrees
Spacecraft cross-sectional area	54 meters^2
Spacecraft mass	2100 kilograms
Nonspherical Earth gravity model	70x70 Joint Gravity Model (JGM)-3
Solar and lunar ephemeredes	DE200
Spacecraft area model	Spherical
Solar radiation pressure coefficient	1.4
Maneuver delta-V	See Table 1

3.2 GPS Measurement Simulation Characteristics

For a GPS user in a GEO orbit, the number of GPS signals that can be acquired by the GPS receiver is limited due to the direction and strength of the GPS broadcast signal, the field of view and gain of the receiving antenna, the signal acquisition threshold of the receiving GPS antenna, and the interference of the Earth. Figure 3-1 illustrates the broadcast signal geometry for a GEO user with respect to a single GPS Space Vehicle (SV). Figure 3-2 shows the number of GPS SV signals that can be acquired over one day period. This visibility was computed using a signal acquisition model developed by M. Moreau of GSFC. This computation assumed that GOES flies a typical GPS space receiver (i.e., with a signal acquisition threshold of 35 dB-Hertz) and one nadir-pointing high-gain antenna. At this altitude, using a receiver that has an acquisition threshold of 35 dB-Hertz, only GPS signals within the primary beam of the GPS antenna pattern can be acquired. To minimize the impact of ionospheric delay, measurements were excluded for which the height of the ray path (HORP) is less than 1000 kilometers. In this case, no GPS SV is visible to the user for approximately 32 percent of the time. Most of the time, only one or two GPS SVs are visible. The number of GPS SVs visible to the user is three only for approximately 7 percent of the time.

GPS pseudorange measurements were simulated using the GPS Data Simulation program (Reference 3). Table 3-2 lists the parameters used in the measurement simulation. The additional pseudorange error of 2 meter (1σ) is included to account for errors in the broadcast GPS SV ephemeris and clock predictions. User clock bias and bias rate errors are simulated using a simple two-dimensional clock model. The Allan Variance parameters (h_0 and h_{-2}) used to simulate the user clock errors correspond to a high quality clock (close to Rubidium standard). Several sets of measurements were simulated using different GOES trajectories to evaluate GEONS performance for the maneuver cases listed in Table 2-1, as well as the maneuver free case.

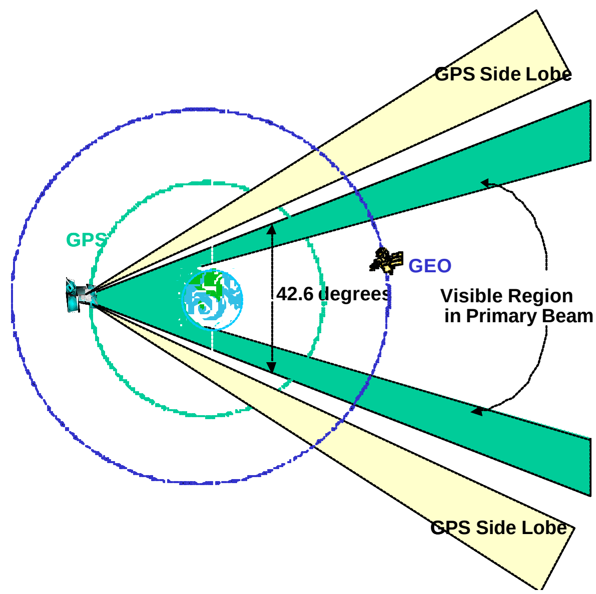

Figure 3-1 GEO Satellite Geometry With Respect to a GPS Broadcast Signal

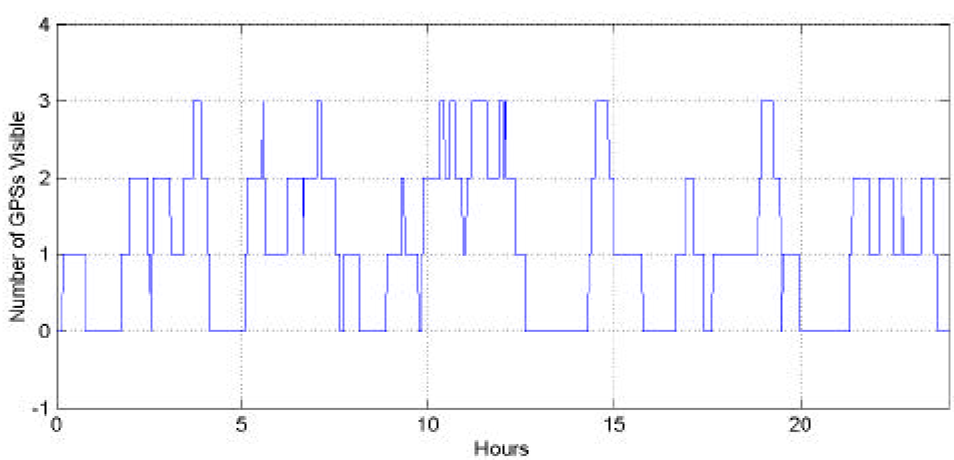

Figure 3-2 Nominal GPS SV Visibility With HORP=1000km

Table 3-2 GPS Measurement Simulation Parameters

Parameter	Value
Simulation time span	4 days
Measurement data rate	Every 60 seconds from all visible GPS SVs
GPS SV ephemerides	Broadcast ephemerides for October 5-October 12, 2001
User antenna model	Nadir-pointing high gain antenna
GPS receiver signal acquisition threshold	35 dB-Hertz
Visibility constraints	Earth blockage with HORP=1000 kilometers GPS SV antenna beamwidth (42 degree main beam)
Ionospheric delay error	4.5 meters maximum with HORP=1000 kilometers
Pseudorange random noise	2 meters (1σ)
Additional pseudorange error	2 meters (1σ) to account for GPS SV ephemeris and clock errors
Allan Variance parameters used to model user clock bias and bias rate errors	$h_0 = 4.808\times10^{-20}$ $h_{-2} = 1.321\times10^{-29}$

4.0 Navigation Performance

GEONS Release 1.1 was used to process the simulated GPS measurements generated using the procedure described in Section 3. Table 4-1 lists the GEONS processing parameters:

Table 4-1 GEONS Processing Parameters

Parameter	**Value**
Nonspherical Earth gravity Model	30x30 Joint Gravity Model (JGM)-2
Solar and lunar ephemeris	Analytical ephemeris
Spacecraft area model	Spherical
Solar radiation pressure coefficient (C_R)	1.47
Thrust acceleration model	105% of the truth thrust model
Estimated state	User position and velocity GPS receiver time bias and time bias drift
GPS SV ephemerides	Broadcast ephemerides for October 5-October 12, 2001
Measurement processing rate	All visible GPS SVs at 1-minute intervals
State process noise rate: Radial velocity In-track velocity Cross-track velocity User clock bias User clock bias rate	 10^{-9} meter^2/second^3 10^{-10} meter^2/second^3 10^{-10} meter^2/second^3 10^{-4} meter^2/second 10^{-6} meter^2/second^3
Pseudorange measurement noise weight	25 meters

It should be noted that some of the force model parameters selected for the GEONS filter in Table 4-1 are different from those used for the GTDS truth ephemerides (see Table 3-1). The differences between the solar radiation pressure coefficients and the thrust accelerations are intentional. The solar radiation coefficient C_R is normally estimated for spacecraft such as GOES, but it was decided not to estimate it in this study. Instead, an error of 5 percent is assigned to it, fixing it at 1.47. This decision was made based on the following results from a preliminary investigation:

- Usually C_R is known to better than 5 percent for spacecraft in geosynchronous orbits
- Steady state results obtained with C_R fixed at 1.47 are very similar to those obtained from estimating C_R
- The filter converges faster with C_R not estimated: the filter initially took approximately 15 hours to converge when C_R is not estimated, while the filter initially took approximately 27 hours to converge when C_R is estimated.

With these differences in the force model parameters, the difference between the GTDS truth and GEONS ephemerides is approximately 55 meters over one day. The propagated position errors due to the delta-V errors are much larger. Position errors arising from the force model difference between GTDS and GEONS are summarized in Table 4-2. They represent the root-sum-square (RSS) position errors obtained by propagating the maneuver errors. Position errors are primarily in the along-track direction in the cases of momentum unload and East-West maneuvers and in the cross-track direction in the case of the North-South maneuver.

Table 4-2 Magnitudes of Propagated Position Errors

Error Source	Maximum Position Error [over one-day propagation]
GTDS and GEONS difference (without any maneuver errors)	55 meters [growing in time]
5% of momentum unload maneuver error (0.1 cm/sec in along-track direction)	300 meters [growing in time]
5% of East-West maneuver error (10 cm/sec in along-track direction)	30 kilometers [growing in time]
5% of North-South maneuver error (100 cm/sec in cross-track direction)	14 kilometers [amplitude of the sinusoidal variation]

4.1 Maneuver-Free Solutions

The GPS pseudorange measurements simulated for this case are based on the GPS visibility shown in Figure 3-2 and a maneuver-free GTDS GOES truth ephemeris. With the limited GPS visibility shown in Figure 3-2, standard point solutions (geometrical solutions), which require four simultaneous GPS measurements, cannot be obtained. GEONS, however, can generate stable solutions because it includes a high-fidelity propagator and an extended Kalman filter. The solar radiation pressure parameter (C_R) is not included in the solve-for parameter set. Instead, five percent of the value of C_R is included as a force model error. A reference free-flight filter solution was obtained using the filter parameters listed in Table 4-1. This solution was obtained starting with large initial state errors of 1 kilometer and 0.1 meters/sec in each direction and a correspondingly large initial covariance. Solutions obtained from widely different a priori state errors and covariances yielded similar convergence behaviors and steady-state error statistics. The steady-state error statistics for these solutions are summarized in Table 4-3. The position errors and root-sum-variance associated with this solution are shown in Figure 4-1.

Table 4-3 Steady-State Errors Statistics for the Maneuver-Free Reference Solution

State Parameter	Mean	Standard Deviation	RMS	Maximum
Position (meters)	10.2728	5.0037	11.4266	32.0347
Velocity (mm/sec)	0. 7741	0.4953	0.9190	3.0757
Clock bias (meters)	-1.0053	8.9528	9.0090	30.4632
Clock bias rate (mm/sec)	0.2854	3.5695	3.5809	11.0208
Residuals (meters)	0.0204	3.4995	3.4995	30.1961

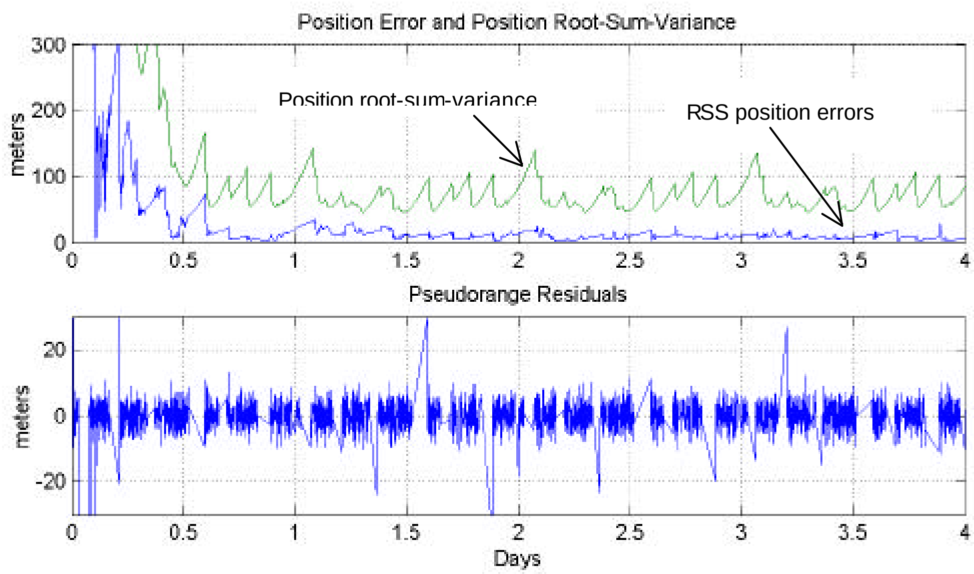

Figure 4-1 GEONS Position Errors and Pseudorange Residuals for Maneuver-Free Reference Solution

4.2 Maneuver Recovery Solutions

Post-maneuver recovery solutions were studied at two different times, T1 and T2, to evaluate performance with typical and poor GPS visibility following the maneuver. T1 was selected such that one or two GPS SVs are visible to the GEO user following the maneuver, whereas T2 was selected such that no GPS SV is visible for 1.6 hours following the maneuver. GPS pseudorange measurements for GOES were simulated based on the truth GTDS trajectories that included 100 percent of the delta-V applied at T1 or T2. Here T1 and T2 indicate the end of the burn. Figure 4-2 shows the location of these maneuver times.

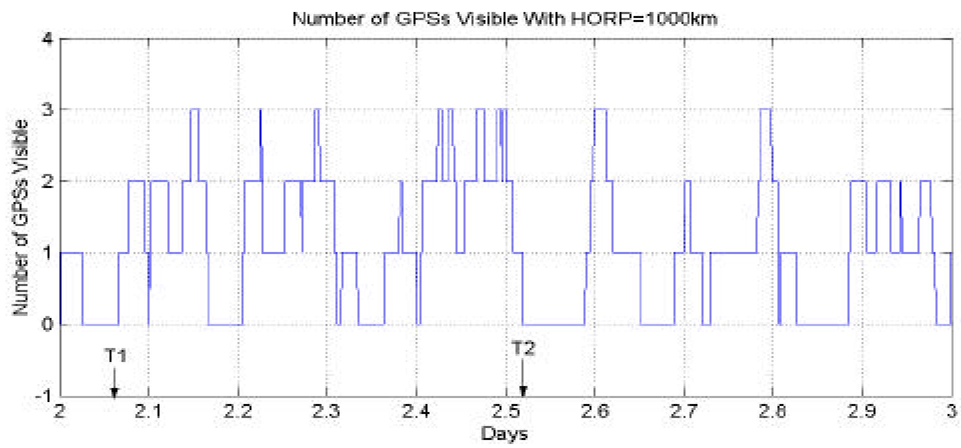

Figure 4-2 Location of Maneuver End Times (T1 and T2)

For several representative cases, results from Monte Carlo (MC) simulations are presented. In these cases, ensemble error statistics were accumulated for navigation solutions obtained by processing 25 sets of simulated pseudorange measurements that were created by varying the random number seeds for random noise, GPS SV ephemeris and clock errors, and user clock errors.

Momentum Unload Maneuvers

For a momentum unload maneuver, the delta-V is small. For this case, the unmodeled thrust acceleration/modeled thrust uncertainty approach listed in Table 2-2 was used. The delta-V was not modeled in the GEONS filter, such that the full delta-V of 2 cm/sec is a thrust acceleration error. A command was uplinked prior to each maneuver to open up the GEONS covariance enough to accept measurements following the maneuver. Measurements were not processed during the maneuver. Figure 4-3 shows the MC simulation error statistics for momentum unloads at T1.

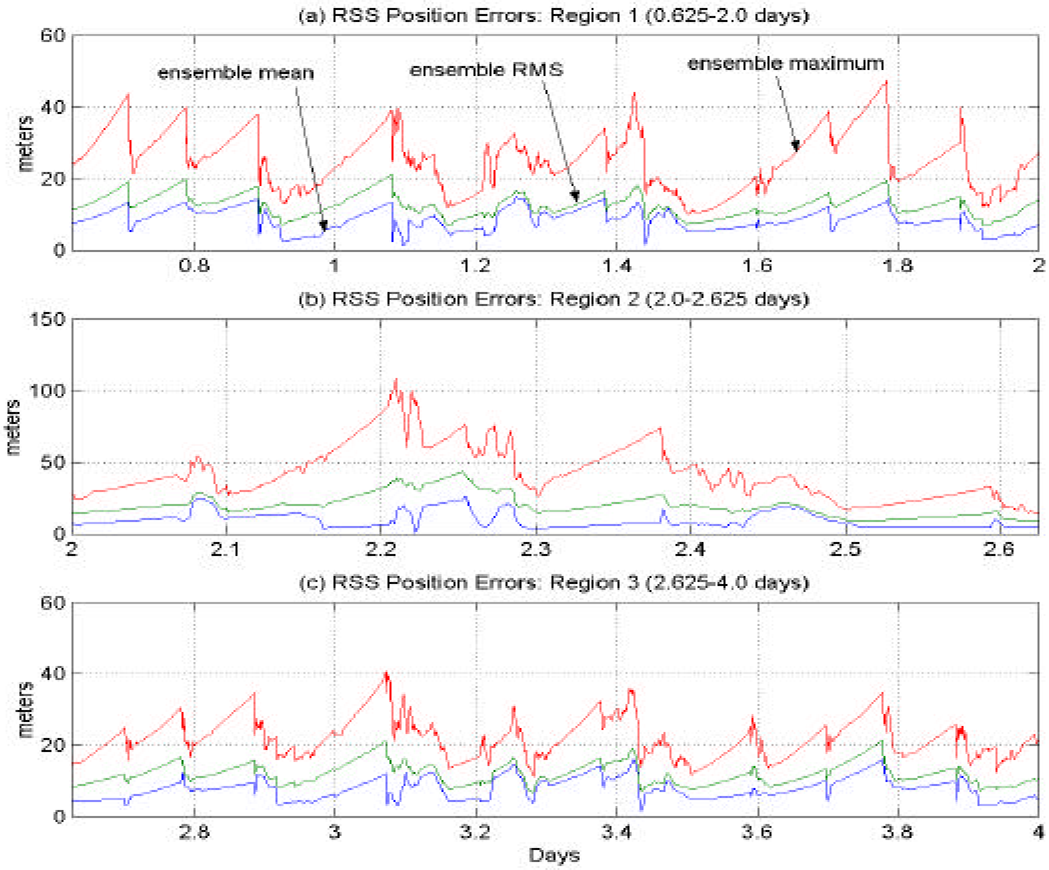

Figure 4-3 MC Error Statistics for Momentum Unload at T1

The maximum, RMS and mean of the RSS ensemble position errors from 25 solutions are shown in the three figures. Figure 4-3(a) shows the pre-burn steady-state period, Figure 4-3(b) the post-burn transient period, and Figure 4-3(c) the post-burn steady-state period. In each figure, the top curve represents the ensemble maximum, the middle curve the ensemble RMS, and the bottom curve the ensemble mean. The time-wise RMS of the RSS ensemble position errors for the three regions is 12.9, 21.3, and 12.3 meters, respectively. The maneuver recovery time is approximately 10 hours. Steady-state statistics in regions 1 and 3 are similar to those of maneuver-free case (Table 4-3).

The GOES definitive orbit determination performance goal is to maintain the maximum RSS position errors under 100 meters (Reference 2). The Monte Carlo simulation results presented here indicate that, in the case of a momentum unload maneuver, the overall position errors can be maintained below 100 meters, although the ensemble maximum RSS position error briefly goes over 100 meters during the maneuver recovery period.

Note that these GEONS filter solutions were obtained without using any thrust acceleration data to model the maneuver. The only maneuver information provided to GEONS is the start and end times of the momentum unload and an approximate maneuver magnitude (used to model the thrust uncertainty). In the case of the T1 maneuver, the quality of the solutions can be improved only marginally by using thrust acceleration data in GEONS (i.e., the modeled acceleration/modeled uncertainty approach in Table 2-2).

However, in the case of the T2 maneuver where there are no GPS SVs visible for approximately 1.6 hours following the maneuver, using the thrust acceleration data significantly improves the solutions. Using the thrust acceleration data, the position error statistics of T2 maneuver solutions were found to be similar to those of T1 maneuver solutions. However, without using the thrust acceleration data, T2 maneuver solutions have peak-errors reaching several hundred meters for a few hours during the post-maneuver recovery period. Thus, acceptable post-burn recovery period solutions can be obtained without including thrust acceleration data if the maneuver times are selected such that good visibility from the GPS constellation occurs after the maneuver.

An estimate of GOES prediction errors is shown in Figure 4-4. These position RSS errors were obtained by propagating the last filtered state from the post-maneuver steady-state period for 1 day. It is seen from the results that the maximum RSS position error (out of 25 solutions) stays under 100 meters.

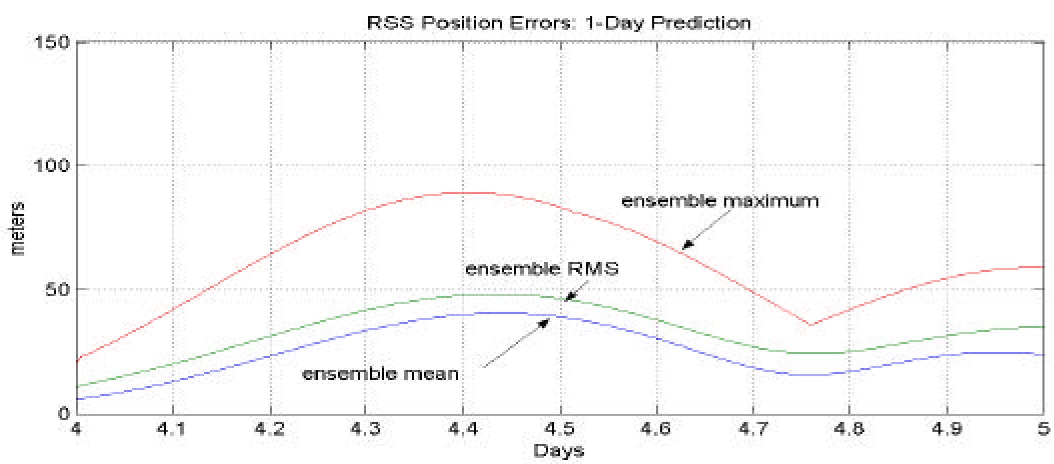

Figure 4-4 One-Day Prediction Errors

East-West Maneuvers

A Monte Carlo simulation was performed for an East-West maneuver at T1. In this case, all 25 GEONS filter solutions were obtained by including thrust accelerations corresponding to 105 % of the true delta-V (i.e., the modeled acceleration/modeled uncertainty approach in Table 2-2). Measurements were not processed during the maneuvers. The MC results of T1 East-West maneuver solutions are shown in Figure 4-5.

The maximum, RMS and mean of the RSS ensemble position errors from 25 solutions are shown in the three figures. The time-wise RMS of the RSS ensemble position errors for the three regions is 12.9, 46.0, and 13.0 meters, respectively. During the maneuver recovery period (approximately 13 hours), the ensemble maximum errors reach 230 meters and stay above 100 meters for a few hours. Even the ensemble RMS errors are higher than 100 meters for a couple of hours. Steady-state statistics in regions 1 and 3 are similar to those of the maneuver-free case (Table 4-3).

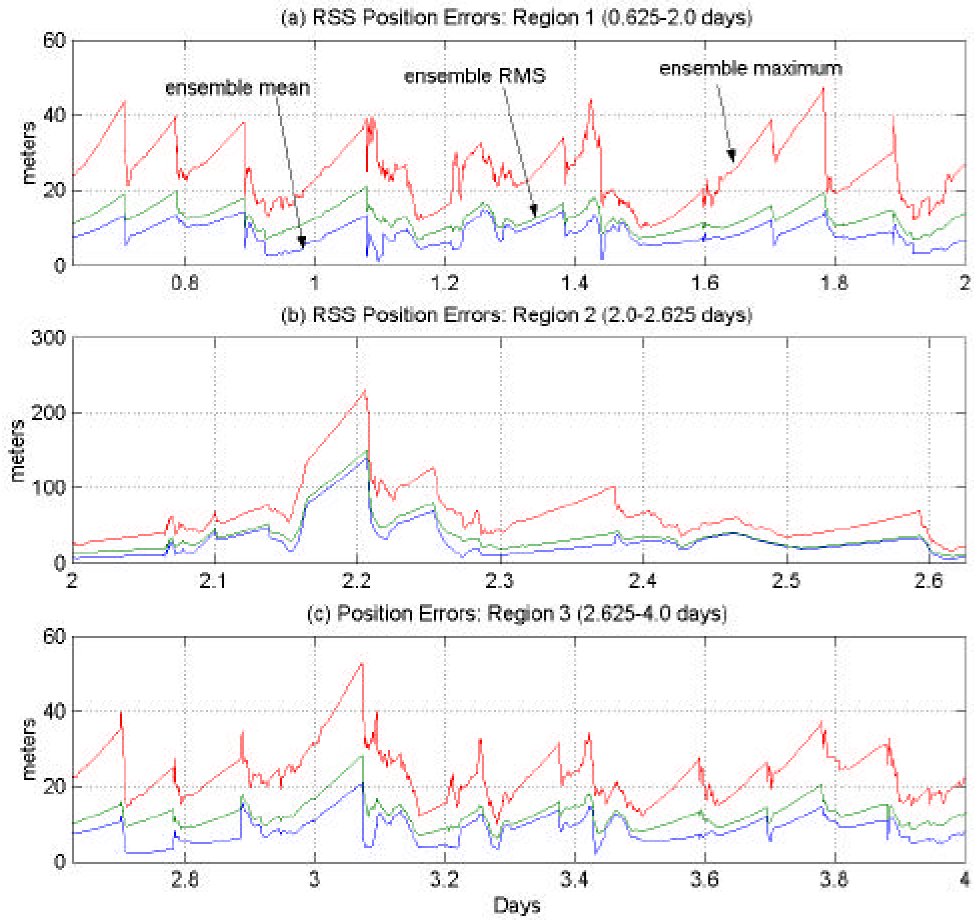

Figure 4-5 MC Error Statistics for East-West Maneuver at T1

A single GEONS solution was obtained without using the thrust acceleration data (i.e., using the unmodeled acceleration/modeled uncertainty approach in Table 2-2). The entire East-West maneuver delta-V of 2 m/sec was treated as an unmodeled acceleration error. The results were similar to those obtained using the acceleration data except that the peak error during the maneuver recovery period is about 618 meters.

A maneuver recovery solution for an East-West maneuver at T2 was obtained using the thrust acceleration data. The peak position errors reached 700 meters for the first couple of hours in the post-maneuver period, and continued to stay above 100 meters for another few hours. Thus, for the first 5 to 6 hours of the post-maneuver recovery period, the position errors will stay above 100 meters in the case of T2 maneuvers.

North-South Maneuvers

A Monte Carlo simulation was performed for a North-South maneuver performed at T1. All 25 GEONS filter solutions were obtained including thrust accelerations corresponding to 105 percent of the true delta-V for the North-South maneuvers. For these MC filter solutions, no measurements were processed during maneuvers. The MC error statistics for the T1 North-South maneuver solutions are shown in Figure 4-6.

The time-wise RMS of the RSS ensemble position errors for the three regions is 12.9, 302.5, and 12.4 meters, respectively. During the maneuver recovery period (approximately 10 hours), the ensemble maximum errors reached 2 kilometers and generally stay above 100 meters for several hours, although the period of 2-kilometer peak errors was less than 2 hours. Ensemble RMS errors, however, stay higher than 100 meters for only about 2 hours. Preliminary indications are that the peak errors can be reduced by processing measurements during the maneuver, which was assumed to last for 90 minutes in the case of North-South maneuvers. More work is planned in this area. The steady-state statistics in regions 1 and 3 are similar to those of the maneuver-free case (Table 4-3).

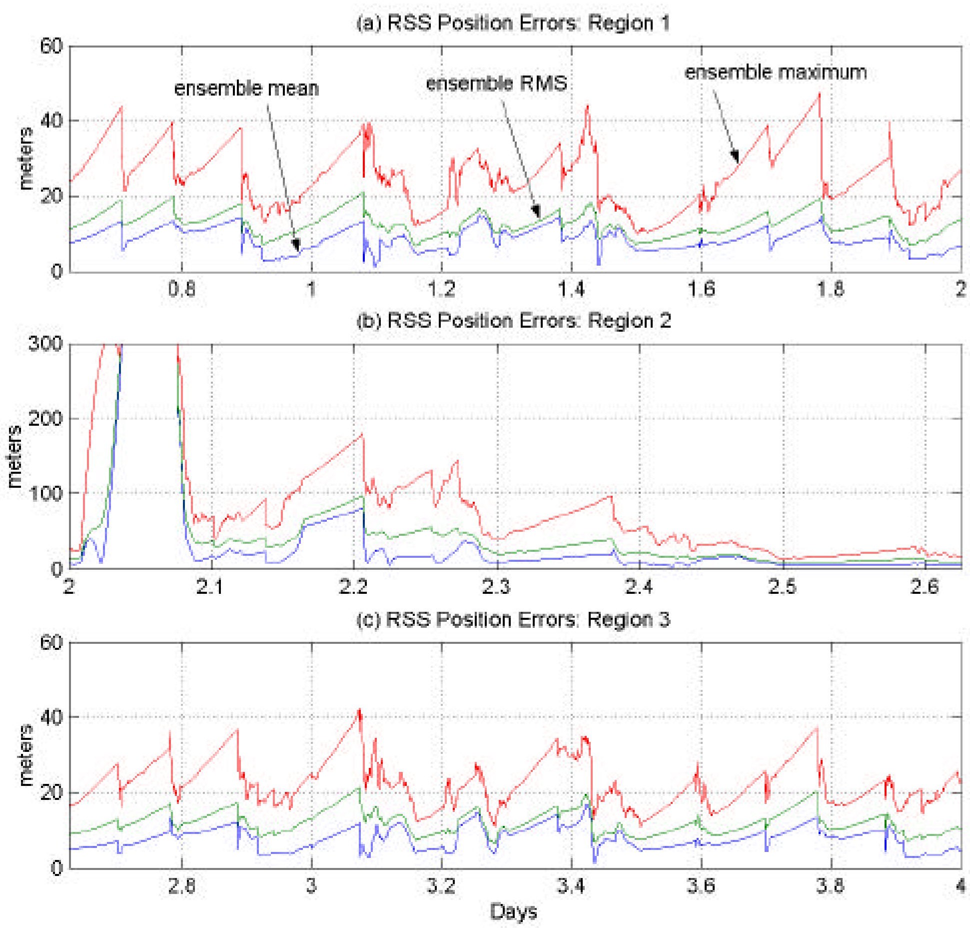

Figure 4-6 MC Error Statistics for North-South Maneuver at T1

A solution was also obtained without using the thrust acceleration data (i.e., using the unmodeled acceleration/modeled uncertainty approach in Table 2-2). The entire North-South maneuver delta-V of 20 m/sec was treated as an unmodeled force model error. The results were similar to those obtained using the acceleration data except that the peak error during the maneuver recovery period reached 53 kilometers. The peak error period was about 2 hours and the errors were reduced to approximately 150 meters as soon as GPS measurements were processed.

A maneuver recovery solution for a North-South maneuver at T2 was obtained using the thrust acceleration data. The peak position errors reached 8.3 kilometers for the first 3 hours in the post-maneuver period, and continue to stay slightly above 100 meters for another 3 to 4 hours. Thus, for the first 6 to 7 hours of the post-maneuver recovery period, the position errors will stay above 100 meters in the case of T2 maneuvers. In this case, there was a period of approximately 3 hours without measurement processing: 1.5 hours of burn time followed by 1.6 hours of measurement gap. During this time, the state was propagated with the maneuver delta-V errors assumed in the simulation.

5.0 Sensitivity to Receiver Acquisition Threshold

The results presented in Section 4 indicate that the quality of the post-maneuver recovery solutions depends strongly on the number of GPS SV signals that are acquired immediately following the maneuver. This number can be increased by using an enhanced GPS receiver with a reduced acquisition threshold such that the GPS side-lobe signals are acquired. GNCC is currently developing enhancements to the PiVoT receiver to improve signal acquisition at high altitudes. These include modified tracking loops to acquire and track the weaker side-lobe signals of the broadcast GPS satellites; tighter integration of a Kalman filter state estimator with the tracking loops; and improved search algorithms to account for this orbital geometry.

Figure 5-1 shows the variation in the strength of the GPS broadcast signal provided to a receiver at GEO altitude assuming a high gain receiving antenna. A 35dB-Hertz acquisition threshold corresponds to a typical GPS space receiver. By lowering the receiver's acquisition threshold from 35 dB-Hertz to 33 dB-Hertz, the mean visibility increases by nearly 200 percent because at 33.7dB-Hertz, signals from the first side lobe can be acquired. With a 31dB-Hertz acquisition threshold, the mean visibility increases more than four times as compared with that of a typical GPS space receiver. Large visibility gaps disappear with a 33dB-Hertz threshold, and no visibility gaps exist with a 31dB-Hertz threshold. Therefore, if the receiver's signal acquisition threshold can be lowered to 33dB-Hertz, maneuver scenarios such as the T2 maneuver, discussed in Section 4, will be eliminated.

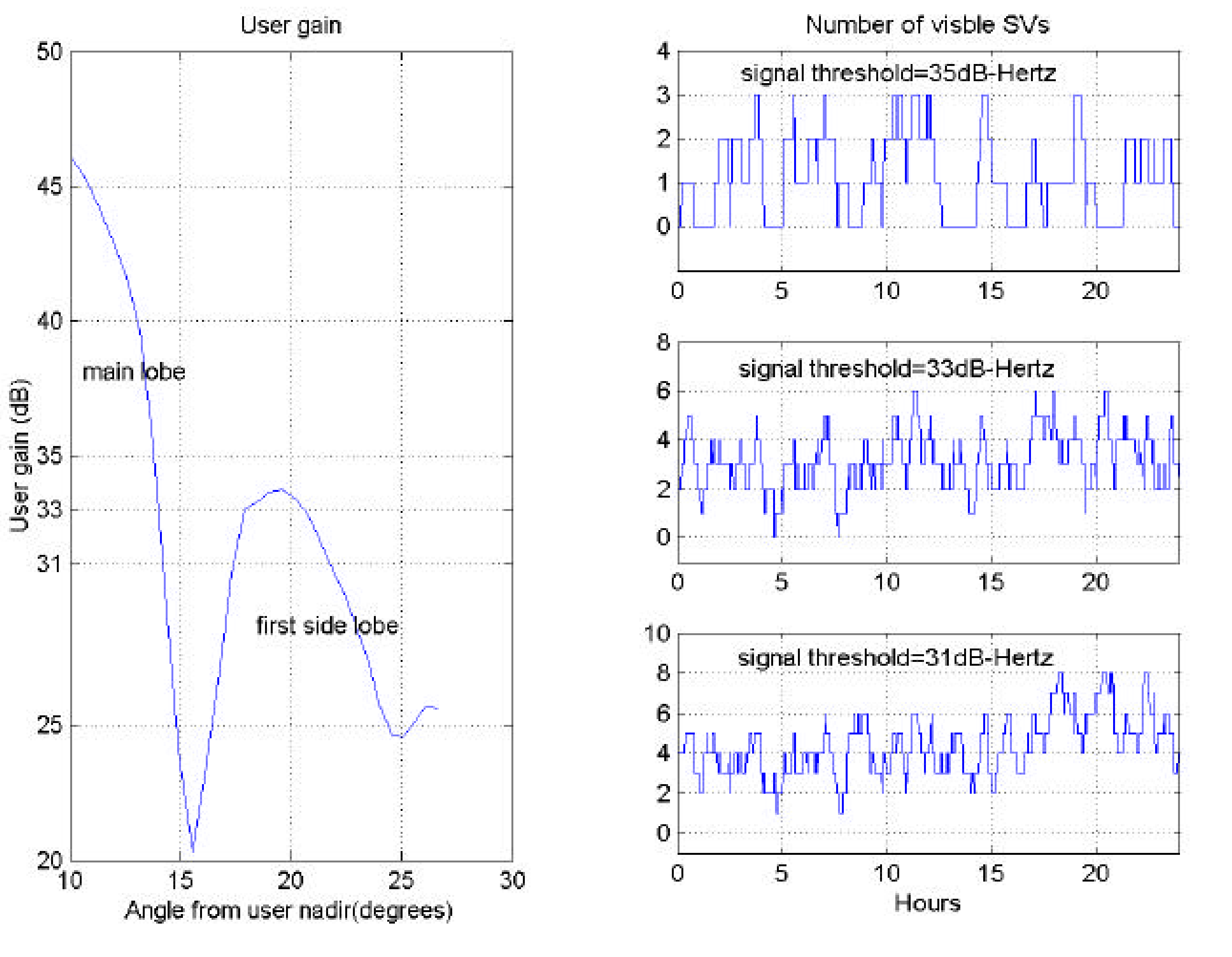

Figure 5-1 GPS Broadcast Signal Strength at the Receiver and GPS Visibility for a GEO User

Additional Monte Carlo simulations were performed for the case of the East-West maneuvers at T1, including thrust accelerations and using different GPS visibilities based on reducing acquisition thresholds to 33dB-Hertz and 31dB-Hertz. The results are compared in Figure 5-2. Only the solutions for the post-maneuver recovery regions are shown in this figure. A gradual but clear overall decrease in the RSS position errors can be seen in these graphs by reducing the threshold from 35dB-Hertz to 31dB-Hertz. In addition, the maneuver recovery time reduces from about 13 hours to 7 hours.

In the cases of long-burn maneuvers such as GOES North-South maneuvers, more significant improvement is expected with reduced thresholds of 31 dB-Hertz or 33 dB-Hertz, if measurements are processed during the maneuvers.

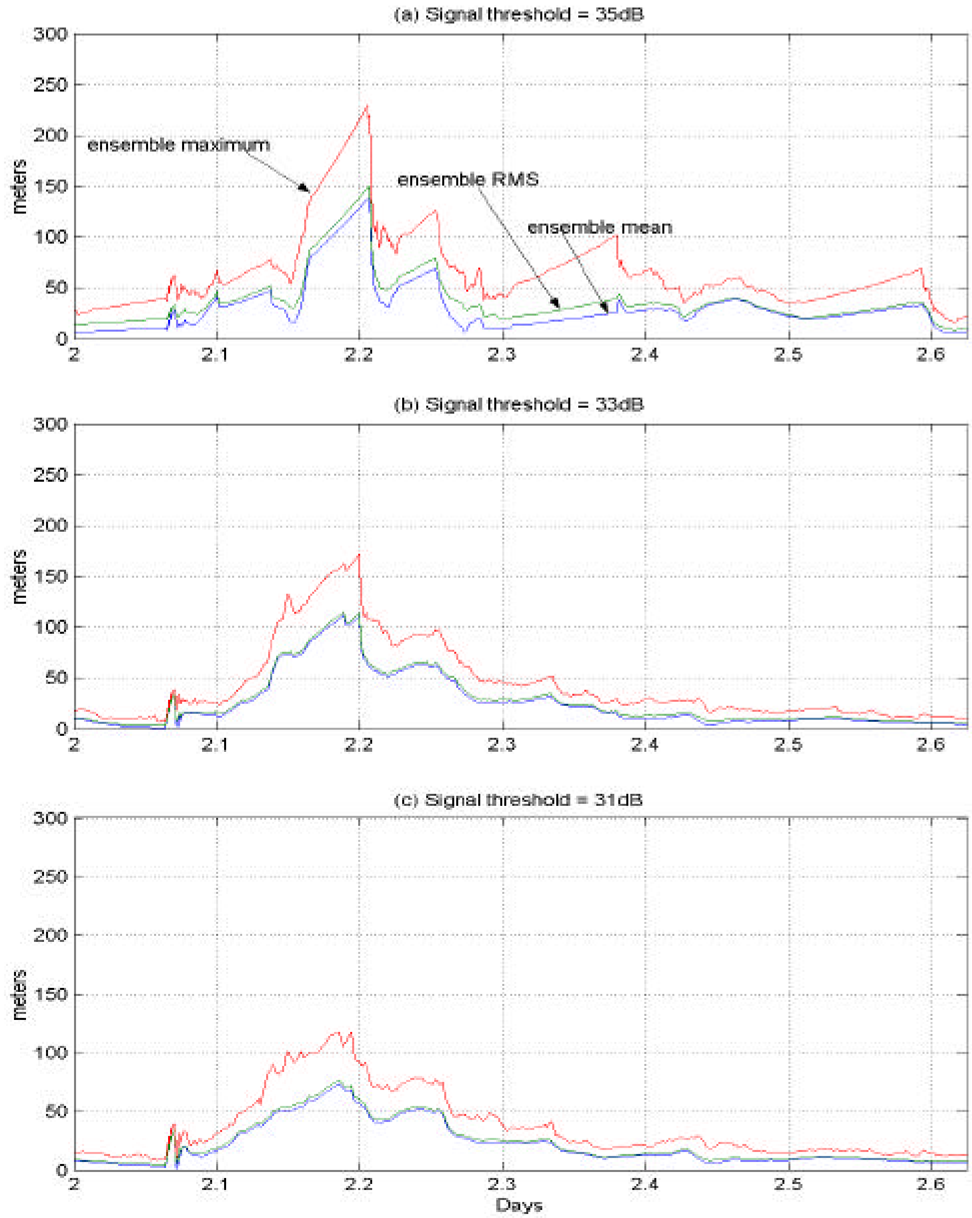

Figure 5-2 Post-Maneuver Recovery RSS Ensemble Position Errors for East-West Maneuver at T1

6.0 Sensitivity to User Antenna Gain

The results provided in Sections 4 and 5 used GPS visibilities based on a high-gain user antenna. This section evaluates the impact on performance of flying a less costly hemispherical antenna. Figure 6-1 compares the GPS signal strength at the GEO receiver using a hemispherical antenna with the strength using a high gain antenna. This comparison indicates that the high gain antenna increases the signal strength at the receiver by approximately 3 dB-Hertz. Table 6-1 lists the mean number of GPS SV signals that can be acquired at GEO using the two antenna types, averaged over a 2 day interval.

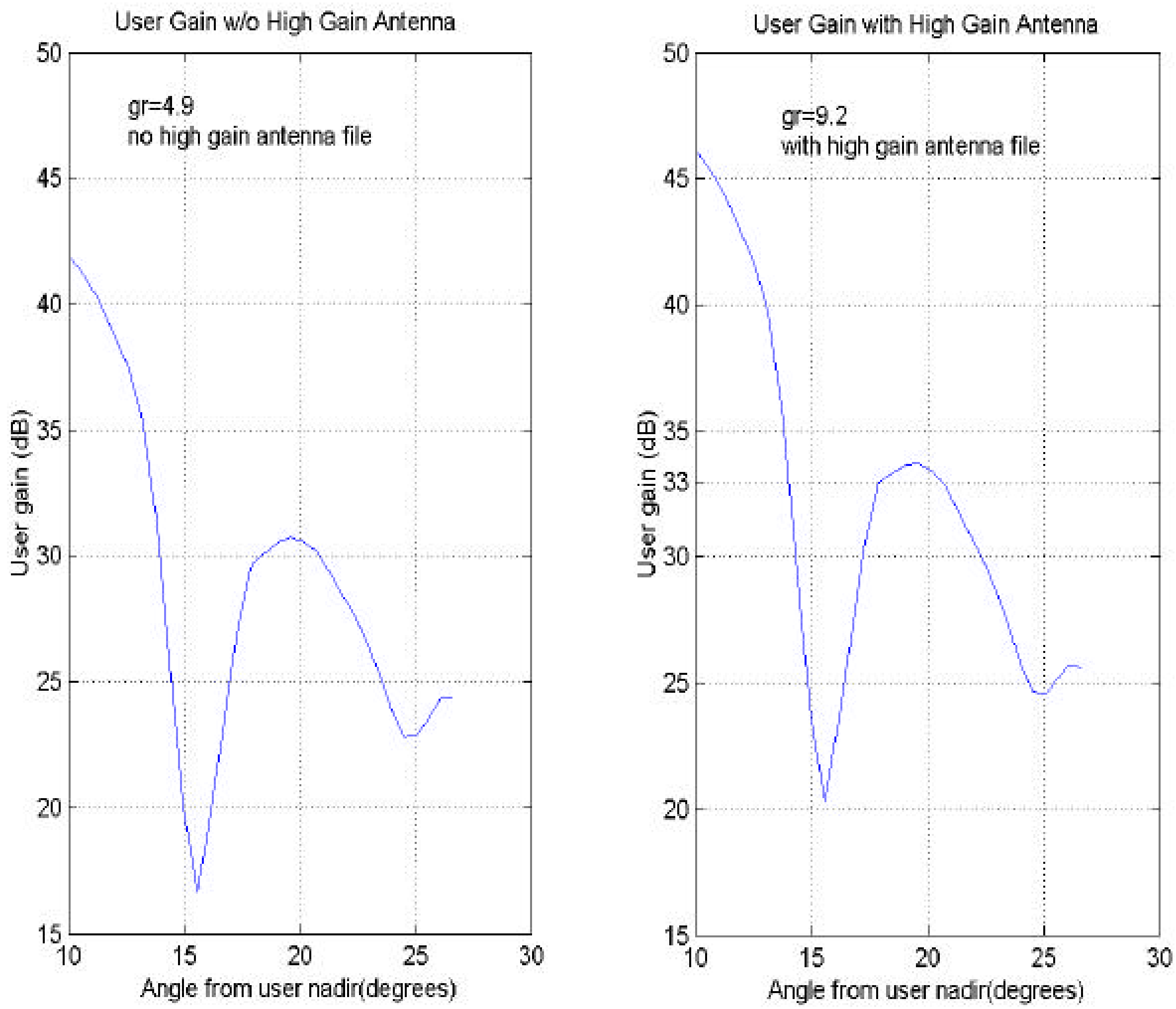

Figure 6-1 GPS Visibility with Hemispherical vs High Gain Antenna

Table 6-1 GOES Mean GPS Visibility

Receiver Acquisition Threshold	Mean Number of GPS SV Signals Acquired at GEO	
	Hemispherical Antenna	High Gain Antenna
35 dB-Hertz	0.95	1.10
34 dB-Hertz	1.00	1.13
33 dB-Hertz	1.04	3.11
31 dB-Hertz	1.11	4.36
30 dB-Hertz	3.00	5.06

Additional Monte Carlo simulations were performed for the case of the East-West maneuvers at T1, including thrust accelerations and using GPS visibilities based on a hemispherical user antenna, for a range of acquisition thresholds. Table 6-2 summarizes these results for both the baseline nadir-pointing high gain antenna and a typical hemispherical antenna. The performance using a hemispherical antenna with either a 35- or 33-dB-Hertz receiver is nearly identical to that using a high gain antenna with a 35-dB-Hertz threshold receiver. To achieve the improved level of performance provided using a high gain antenna with a 33-dB-Hertz receiver, a hemispherical antenna must be used in combination with a 30-dB-Hertz threshold receiver.

Table 6-2 Position Error Statistics For East-West Maneuver Vs. Signal Acquisition Threshold and Antenna Type

Antenna Type	Receiver Acquisition Threshold	Position Error Statistics			
			Region 1*	Region 2*	Region 3*
High-gain	31dB	RMS	9.0	29.8	9.2
		Max	24.8	117.8	31.1
	33dB	RMS	9.3	39.0	9.0
		Max	29.8	172.1	31.9
	35dB	RMS	12.9	46.0	13.0
		Max	47.4	230.2	52.8
Hemispherical	30dB	RMS	9.7	39.6	9.4
		Max	29.2	179.7	31.7
	31dB	RMS	12.8	46.2	13.1
		Max	47.1	232.0	54.5
	33dB	RMS	13.3	46.2	13.6
		Max	47.4	223.3	49.6
	35dB	RMS	13.7	45.9	13.8
		Max	47.4	215.4	51.8

* Region 1: Pre-maneuver steady state period (0.625-2.0 days) Region 2: Post-maneuver recovery period (2.0-2.625 days) Region 3: Post-maneuver steady state period (2.625 –4 days)

7.0 Conclusions

GEONS filter performance was studied for GOES orbit determination support. The objective of the analysis was to find the simplest approach for handling each type of maneuver that will meet the GOES navigation goals of 100 meters at all times. The results are summarized below for each type of maneuver, assuming that GOES flies a typical GPS space receiver and a high-gain antenna.

Momentum unload maneuvers

- If GPS measurements are available immediately following the maneuver, the RMS position errors remain below 100 meters without modeling the thrust acceleration
- If there is a sizable measurement gap following the maneuver (e.g. more than 30 minutes), the RMS position errors remain below 100 meters when the thrust acceleration is modeled
- Monte Carlo ensemble maximum errors briefly reached 100 meters in the beginning of the maneuver recovery region
- About 10 hours is required to reach steady-state performance following the maneuver

East-West maneuvers

- If GPS measurements are available immediately following the maneuver and the thrust acceleration is modeled,
  - Monte Carlo ensemble RMS position errors are generally below 100 meters except for a period of approximately an hour in which they are between 100 and 150 meters.
  - Monte Carlo ensemble maximum position errors are generally below 100 meters except for a period of 2.5 hours during the maneuver recovery in which they stay between 100 and 230 meters
  - About 13 hours is required to reach steady-state performance following the maneuver
- If GPS measurements are available immediately following the maneuver and the thrust acceleration is not modeled, the overall characteristics of position errors statistics are similar to those obtained with the acceleration data except that the peak error during the recovery period reached 618 meters.
- If there is a sizable measurement gap following the maneuver (e.g. more than 1 hour) and the thrust acceleration is modeled, the peak position errors reached 700 meters for the first couple of hours in the post-maneuver period, and continue to stay above 100 meters for another few hours. Except for the first 5 to 6 hours of the post-maneuver recovery period, the position errors will stay below 100 meters.

North-South maneuvers

- If GPS measurements are available immediately following the maneuver and the thrust acceleration is modeled,
  - Monte Carlo ensemble RMS position errors are generally below 100 meters except for a period of approximately 1.5 hours in which they are between 100 and 300 meters.
  - Monte Carlo ensemble maximum position errors are generally below 100 meters except for a peak error period of 2 hours during the maneuver recovery in which the maximum error reached 2.1 kilometers. Errors were reduced from this peak value down below 200 meters, but it took another 5 to 6 hours to get below 100 meters.
- If GPS measurements are available immediately following the maneuver and the thrust acceleration is not modeled, the overall characteristics of position errors statistics are similar to those obtained with the acceleration data except that the peak error during the recovery period reached 53 kilometers.
- If there is a sizable measurement gap following the maneuver (e.g. more than 1 hour) and the thrust acceleration is modeled, the peak position errors reached 8.3 kilometers for the first 3 hours in the post-maneuver period, and continue to stay above 100 meters for another several hours. Even in this case, except for the first 6 to 7 hours of the post-maneuver recovery period, the position errors will stay below 100 meters.

The following two considerations will generally improve the quality of the post-maneuver recovery solutions (especially for long-burn maneuvers such as North-South maneuvers):

1. Place the maneuver at the beginning of a high GPS visibility period and process the measurements during the maneuver
2. Use a GPS receiver with a signal acquisition threshold below 33 dB-Hertz to increase the overall GPS visibility in geosynchronous orbits

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