American Astronautical Society
Rocky Mountain Section

AAS 09-056

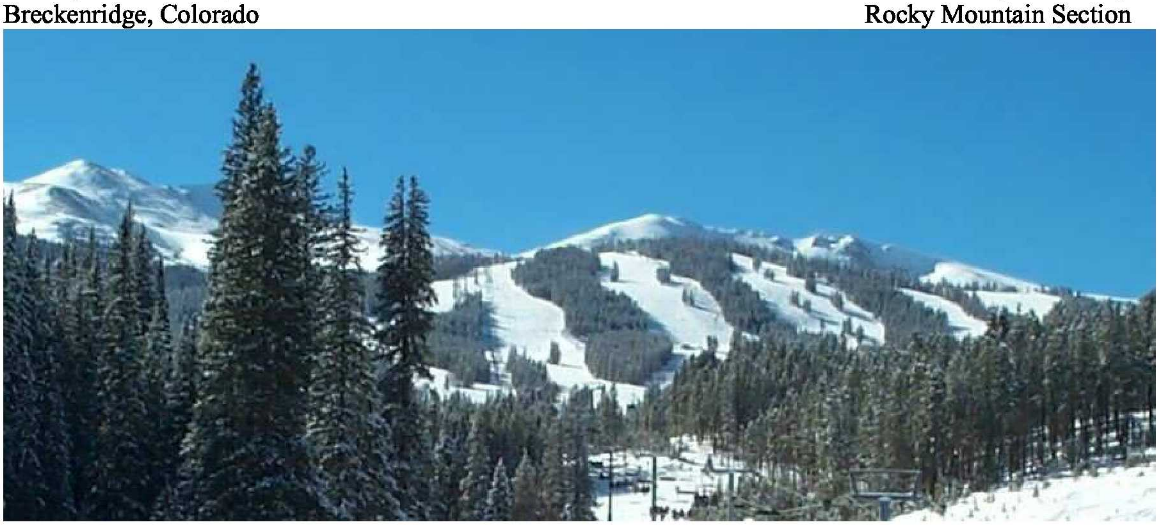
Navigating the Return Trip from the Moon Using Earth-Based Ground Tracking and GPS

Taesul Lee, Anne Long – a.i. solutions
Kevin Berry, Russell Carpenter, Michael C. Moreau -
NASA Goddard Space Flight Center
Greg N. Holt, NASA Johnson Space Center

32nd ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

January 31 - February 4, 2009
Breckenridge, Colorado

Sponsored by
Rocky Mountain Section



AAS Publications Office, P.O. Box 28130 - San Diego, California 92198

AAS 09-056

NAVIGATING THE RETURN TRIP FROM THE MOON USING EARTH-BASED GROUND TRACKING AND GPS

Taesul Lee, Anne Long[*]
Kevin Berry, Russell Carpenter, Michael C. Moreau[†]
Greg N. Holt[‡]

NASA's Constellation Program is planning a human return to the Moon late in the next decade. From a navigation perspective, one of the most critical phases of a lunar mission is the series of burns performed to leave lunar orbit, insert onto a trans-Earth trajectory, and target a precise re-entry corridor in the Earth's atmosphere. A study was conducted to examine sensitivity of the navigation performance during this phase of the mission to the type and availability of tracking data from Earth-based ground stations, and the sensitivity to key error sources. This study also investigated whether GPS measurements could be used to augment Earth-based tracking data, and how far from the Earth GPS measurements would be useful. The ability to track and utilize weak GPS signals transmitted across the limb of the Earth is highly dependent on the configuration and sensitivity of the GPS receiver being used. For this study three GPS configurations were considered: a "standard" GPS receiver with zero dB antenna gain, a "weak signal" GPS receiver with zero dB antenna gain, and a "weak signal" GPS receiver with an Earth-pointing direction antenna (providing 10 dB additional gain). The analysis indicates that with proper selection and configuration of the GPS receiver on the Orion spacecraft, GPS can potentially improve navigation performance during the critical final phases of flight prior to Earth atmospheric entry interface, and may reduce reliance on two-way range tracking from Earth-based ground stations.

I. INTRODUCTION

NASA's Constellation Program is developing the preliminary designs for the Orion spacecraft and other systems that will enable a human return to the Moon late in the next decade. From a navigation perspective, one of the most critical phases of a lunar mission is the series of burns performed to leave lunar orbit, insert onto a trans-Earth trajectory, and target a precise re-entry corridor in the Earth's atmosphere. Studies have been conducted to examine sensitivity of the navigation performance during this phase of the mission to the type and availability of tracking data from Earth-based ground stations, and sensitivity to key error sources, in order to plan support from Earth-based communications and tracking infrastructure. This paper describes analysis that considers the use of GPS pseudorange measurements during the Earth return

[*] a.i. solutions, Inc.

[†] Goddard Space Flight Center, National Aeronautics and Space Administration

[‡] Johnson Space Center, National Aeronautics and Space Administration

trajectory, to augment or replace some of the Earth-based ground tracking that would otherwise be required.

The actual Moon to Earth transfer time is one of the variable parameters in the mission design, but is typically between 3-4 days in duration. Figure 1 shows the sequence of events beginning with the trans-Earth injection (TEI) burn, followed by the first of three trajectory correction maneuvers (TCM) approximately 16 hours following TEI. Additional TCMs may be performed 16 hours and 5 hours prior to Earth entry interface (EI) to refine the EI angle target. Throughout the trans-Earth period, the spacecraft is tracked by one or more Earth-based ground stations and the Constellation Mission Operations Center performs orbit determination functions and provides navigation state updates to the spacecraft. The spacecraft passes the altitude of the GPS constellation a little over one hour prior to EI; therefore, to make any significant use of GPS, the receiver must track weak signals from GPS satellites that reach the Orion spacecraft after crossing over the limb of the Earth.

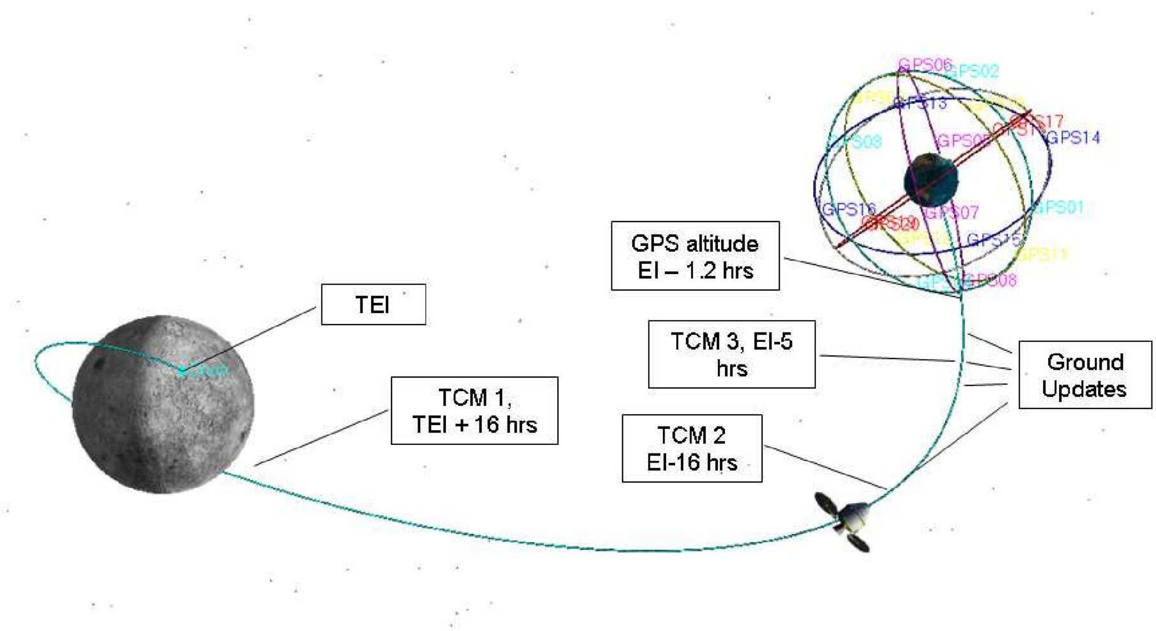
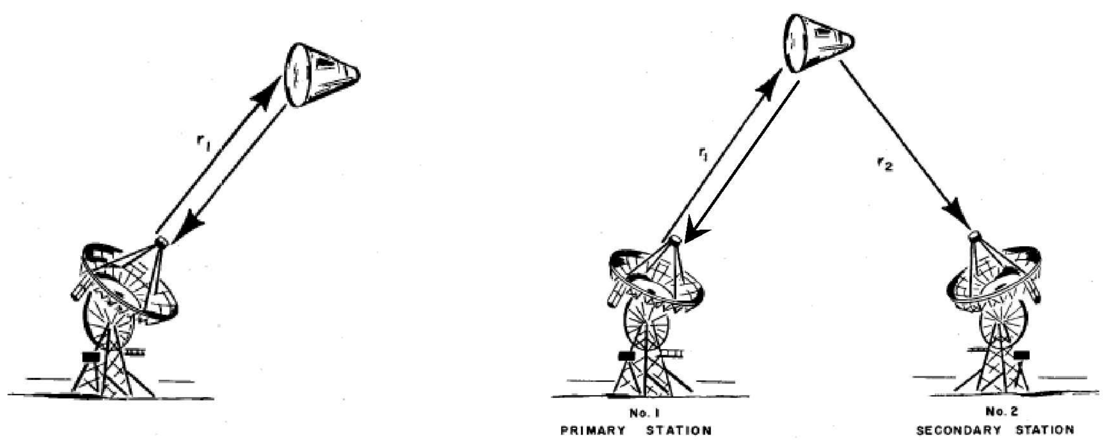


Figure 1 – Earth return trajectory and key events between Trans Earth Injection (TEI) and Earth atmospheric Entry Interface (EI)

Human lunar missions face some unique navigation challenges. Most significant among these are accelerations introduced by the presence of the human crew, such as periodic venting of the environmental control systems, attitude thruster firings, and even waste dumps. Because these forces are very difficult to model, and in many cases are below the threshold that would be detectable by the onboard inertial navigation system, within the Constellation Program we have adopted the term "FLAK" (from "unFortunate Lack of Acceleration Knowledge") to refer to these perturbations. Experience from the Apollo missions indicates that although the magnitudes of the perturbations are small, the FLAK effects are a significant error source, potentially resulting in hundreds of meters per hour of growth in the predictive state error. The combination of FLAK with compressed timelines between critical events requires a robust tracking capability to meet the navigation requirements of the mission.

Previous analysis examined the navigation problem for Constellation Lunar missions and defined a baseline concept for supporting the trans-lunar cruise phases using a network of three primary (two-way) and three or more secondary (three-way) Earth-based tracking stations. The two-way tracking sites are assumed to provide two-way Range and two-way Doppler tracking observables. These sites also provide the command uplink and telemetry downlink functions for the spacecraft. The three-way sites provide three-way Doppler measurements, by tracking the return-link signal from the spacecraft while it is being coherently tracked by one of the two-way sites. Figure 2 illustrates the signal path and geometry associated with two-way and three-way Doppler measurements. By adding three-way sites, tracking data can be obtained from two to three geometrically distributed sites simultaneously. The availability of tracking data from multiple sites that provide North-South and East-West baselines has been shown to be required to provide adequate short-arc navigation solution capabilities in the presence of FLAK [Reference 2].



a.) two-way Doppler

b.)two-way Doppler at No.1, three-way Doppler at No.2

Figure 2 Comparison of a.) two-way and b.) three-way Doppler tracking [Ref. 1]

In this paper, navigation solutions computed using Earth-based ground tracking measurements with and without GPS pseudorange measurements are compared. Additionally, solutions are generated using different combinations of Earth-based ground stations, and with and without two-way Range data from Earth-based ground stations. Three different sets of assumptions are considered for the performance and capabilities of the GPS receiver and antenna design on the Orion spacecraft, which result in more or less availability of GPS signals.

II. APPROACH

This analysis was performed based on a reference trajectory for a Constellation Lunar Sortie mission to an equatorial lunar landing site. The Goddard Enhanced Onboard Navigation System (GEONS) software [Reference 3] was used to simulate a reference trajectory that included accurate force models including modeled non-gravitational accelerations. The DatSim program [Reference 4] was used to simulate tracking measurements from two-way tracking stations located at Madrid, Spain; Canberra, Australia; and White Sands, New Mexico, and three-way stations located at Goldstone, California; Dongara, Australia; and Hartebeesthoek, South Africa, as shown in Figure 3. Additionally, GPS pseudorange measurements were simulated using DatSim for three different possible GPS receiver/antenna configurations on the Orion spacecraft: 1. a "typical" GPS receiver (35 dB-Hz sensitivity) and no better than zero dB antenna gain, 2. a "weak signal" GPS receiver (25 dB-Hz sensitivity) and zero dB antenna gain, and 3. a "weak signal" GPS receiver (25 dB-Hz sensitivity) with an Earth-pointing direction antenna (providing 10 dB additional gain). Navigation solutions were obtained by processing different combinations of simulated ground tracking data and GPS measurements in an extended Kalman Filter (EKF) implemented in GEONS. The measurements were processed in a manner consistent with how the Constellation Mission Operations Center might perform orbit determination in support of an actual mission.

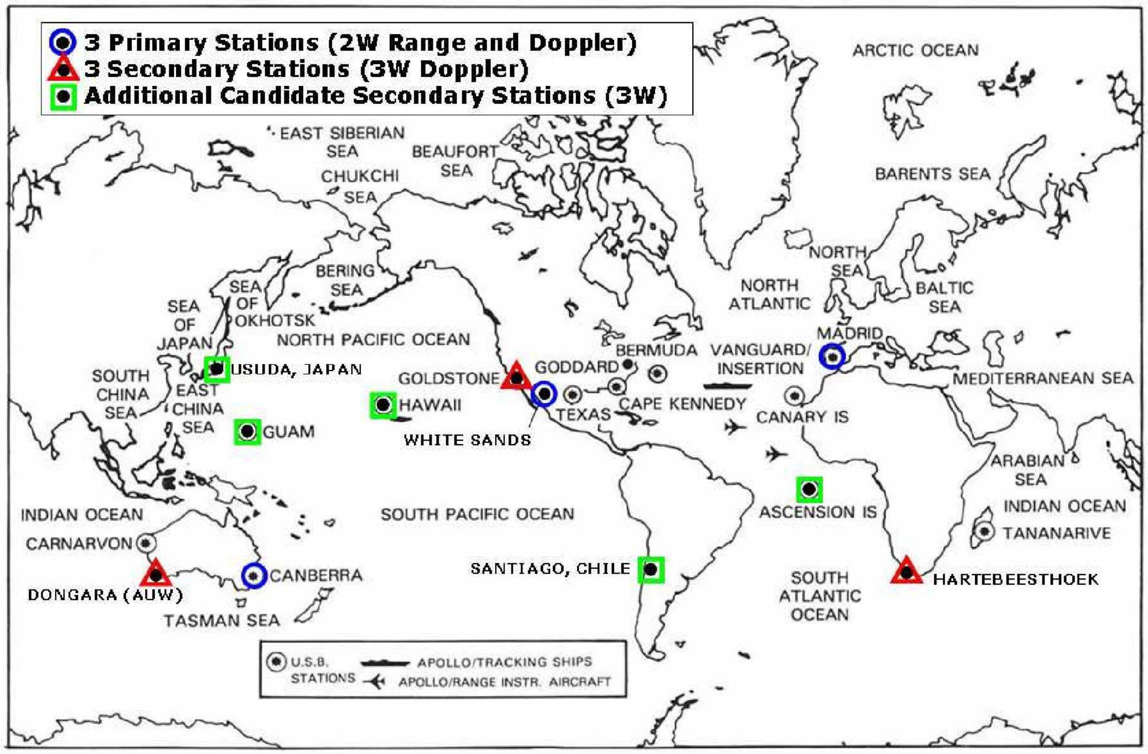


Figure 3 – Ground tracking stations considered in this analysis, overlaying map of Apollo 17 tracking network

Truth Trajectory and GEONS Filter Model Assumptions

The truth trajectories for the Earth return trip used for the data simulation were generated using GEONS based on the epoch and initial state vector given in Table 1. The force models used to generate the truth trajectories are summarized in Table 2.

Table 1: Initial State Vector

		X	Y	Z
	Epoch	2018 08 03 19 59 24.0		
Geocentric MJ2000	**Position (meters)**	3.3468876170E+008	1.9112346746E+008	4.4897658038E+007
	Velocity (meters/sec)	1.2807120000E+003	-8.2256900000E+002	4.4510900000E+002

Table 2: Truth Trajectory Generation and Force Models

Model	Description
Earth gravity model	30x30 truncation of JGM2 70x70 model
Solar Radiation Pressure (SRP)	Mass = 13013.5197kg and area = 60 m^2 (Reference 7) CR = 1.4
Atmospheric Drag	Mass = 13013.5197kg and area = 60 m^2 CD = 2.2 Solar Flux = 150
Point-mass gravity	Sun and Moon
Lunar ephemeris	Derived from DE405
Non-gravitational acceleration errors (FLAK)	Normally distributed random Gaussian acceleration errors applied in all 3 directions with standard deviation of 0.58 mm/sec^2 in each direction
Integration Stepsize	10 seconds

Table 3 compares of some of the force model parameters used in the GEONS truth and in the GEONS filter trajectory propagations. The magnitudes of orbit perturbation due to various dynamic modeling differences are shown in Figure 4. Orbit perturbation due to FLAK is seen to be orders of magnitude larger than perturbations due to other dynamic errors.

Table 3: Truth and Filter Force Models

Error Source	GEONS Truth	GEONS Filter
Earth GM	GM_{Earth}	$GM_{Earth}(1+3x10^{-8})$
Moon's GM	GM_{Moon}	$GM_{Moon}(1-10^{-5})$
Spacecraft Area	60 m^2	100 m^2
Non-gravitational Acceleration Error (FLAK): Normally distributed random Gaussian errors applied in all 3 directions with standard deviation of 0.58 mm/sec^2 in each direction	Included	Not included

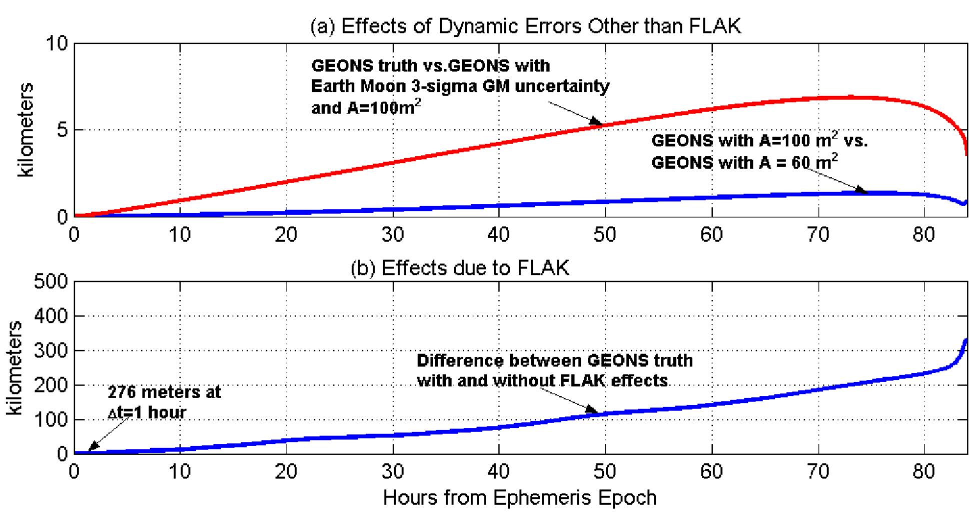


Figure 4 Orbit perturbations due to dynamic error uncertainty (top) and FLAK (bottom)

Simulation of Earth-Based Ground Tracking Measurements

The DatSim program was used to simulate two-way range and Doppler measurements based on the truth trajectory described above. Ground station contacts were simulated whenever the Earth-based station had a physical line-of-site to the spacecraft, without considering s-band antenna locations or attitude of the Orion spacecraft. Because the DatSim program does not provide the capability to simulate and GEONS cannot process three-way Doppler measurements, the three-way Doppler tracking configuration was approximated using two-way Doppler measurements from the three-way stations that are simultaneous with the two-way tracking from the two-way stations. For this preliminary study, the three-way Doppler bias associated with the use of a different frequency standard at the three-way stations was not included. This bias will be small if both the transmit and receive oscillators are of a quality consistent with that of the Deep Space Network tracking sites.

Table 4 lists the measurement error parameters relevant to the current simulation study. Two different levels of tracking measurement errors were simulated. The High Accuracy (HA) values are selected to be consistent with current Deep Space Network site best tracking performance. The Reduced Accuracy (RA) values are selected to study the sensitivity of the navigation performance to larger tracking error levels. The measurements were simulated at 30-second intervals. The two-way range bias is modeled as a random bias based on the first-order Gauss-Markov algorithm. Most of the solutions studied used high accuracy noise levels without any 2-way range bias. Only a few selected solutions were studied with reduced accuracy noise levels and range biases.

Table 4: Measurement Related Errors Used for the Data Simulation

	1σ Value	
Errors	**High Accuracy**	**Reduced Accuracy**
Two-Way Range Noise (meters)	0.6	3
Two-Way Doppler noise	0.002529 Hz (0.36 mm/sec)	0.011241 Hz (1.6 mm/sec)
Three-Way Doppler noise	Same as two-way	Same as two-way
Two-Way Range Bias (meters)	2^{+}	11

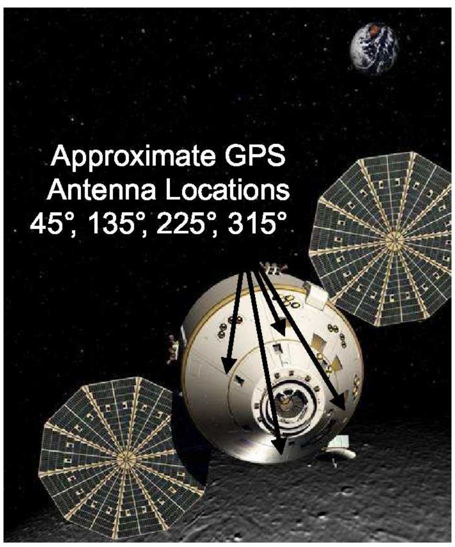
GPS Receiver and Antenna Assumptions

The availability of GPS pseudorange measurements to the Orion spacecraft in cis-lunar space depends on a variety of factors related to the design and sensitivity of the Orion GPS receiver, and the placement and design of the Orion GPS antennas. The DatSim software accurately models the broadcast power levels of GPS signals transmitted across the limb of the Earth, as a function of the GPS satellite look-angle to Orion. In most cases the available GPS signals will be weaker than those typically seen in terrestrial applications due to larger transmitter look angles and greater RF path losses.

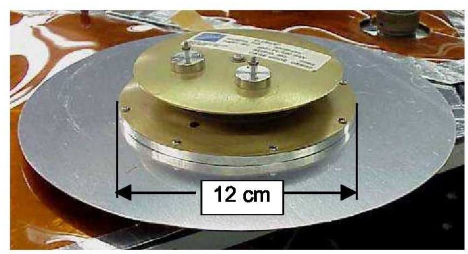
For this study, two GPS receiver sensitivities were considered: a "standard" GPS receiver, for which a tracking threshold of 35 dB-Hz was assumed, and a "weak signal tracking" GPS receiver, which was assumed to be 10 dB more sensitive. The 25 dB-Hz weak signal tracking capability has been demonstrated in the Goddard Space Flight Center developed Navigator GPS receiver [References 5, 6]. Similar technology is being considered for the Orion GPS receiver.

The Orion spacecraft will have four hemispherical patch antennas, installed at roughly 90 degree offset locations around the conical surface of the Orion Command module, as shown in Figure 5a. This configuration of antennas is expected to provide positive gain around most of the spherical coverage region around the spacecraft, with the exception in the region near the tail (engine bell) of the spacecraft. To simplify the modeling of the specific Orion antenna locations in our GPS measurement simulation, the Orion receiving antennas were modeled as a single, omni-directional antenna with zero dB gain in all directions. This should be a conservative assumption for the Orion GPS system, assuming the tail-region of the Orion spacecraft is generally not allowed to point in the direction of the GPS satellites (towards the Earth).

In one of the cases, an additional Earth-pointing antenna was added that would provide 10 dB additional gain in the peak gain direction. This implementation could be realized on Orion by installing an antenna of the type shown in Figure 5b to the Orion high-gain antenna assembly, which is generally pointed in the direction of the Earth. Although this is not currently part of the GPS design for Orion, it represents a possible upgrade that could be made to the spacecraft to significantly improve GPS availability. Table 5 summarizes the three GPS receiver/antenna configurations that are discussed in detail in this paper.



5a.)



5b.)

Figure 5a - Approximate Orion GPS antenna locations, and 5b – Example 10 dB hybrid patch antenna flown on the AMSAT OSCAR-40 GPS experiment

Table 5 GPS Receiver and Antenna Model Assumptions

Cases	Antenna type	Antenna Gain (dB-Hz)	Receiver Sensitivity (dB-Hz)	Improvement Relative to Case A (dB)
Case A	Omni-Directional Antenna	0	35 (Standard Receiver)	0
Case B	Omni-Directional Antenna	0	25 (Navigator GPS)	10
Case C	Hybrid case consisting of a 10 dB Earth-pointing antenna, and omni-directional (0 dB) gain elsewhere	10	25 (Navigator GPS)	20

The availability of GPS pseudorange signals for the three cases is shown in Figure 6. In Case A, GPS pseudorange measurements are only available within the last two hours prior to EI. For Case B, which assumes an additional 10 dB of receiver sensitivity, GPS measurements are available for approximately 16 hours prior to EI. In Case C, which assumes another 10 dB of gain through a directional antenna, GPS signals can be detected during the entire ~84 hour Earth return trip.

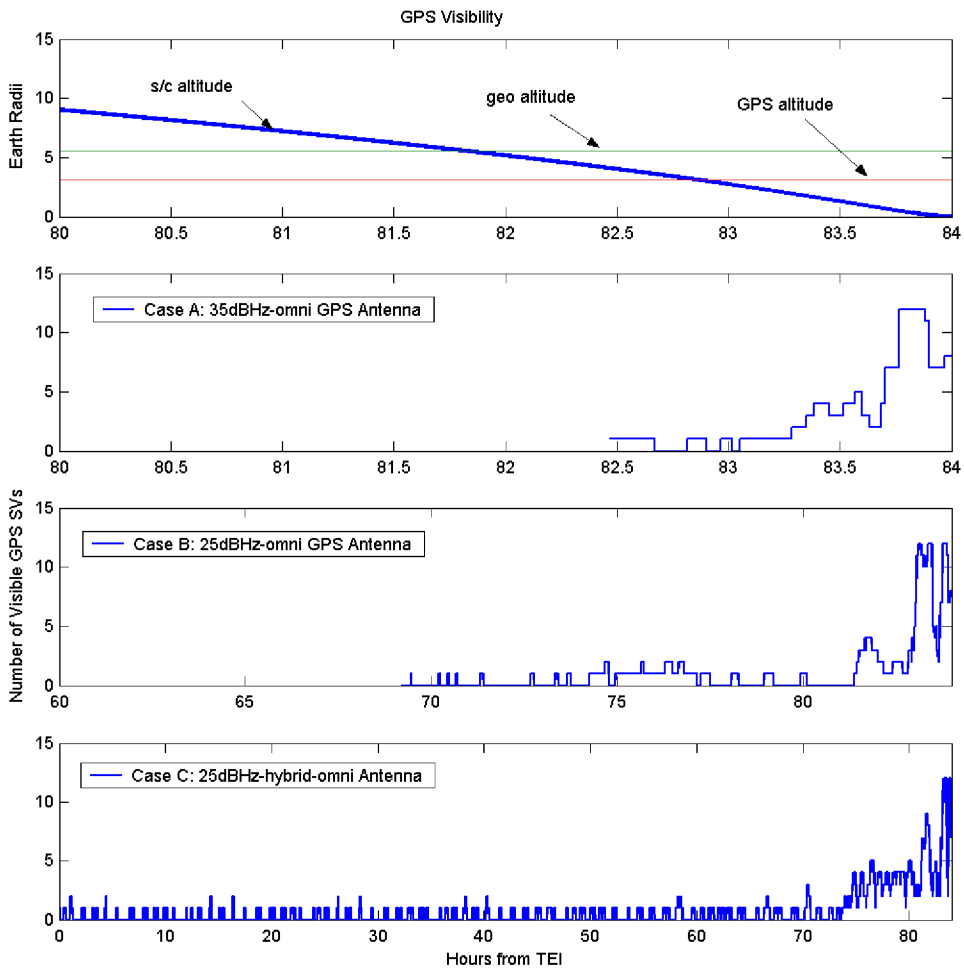


Figure 6 The top plot shows the altitude of the Orion spacecraft (in Earth-radii) during the final four hours before Earth entry interface. The bottom three plots show the GPS pseudorange availability of the three cases studied.

Noise and Clock Errors Assumed for GPS Pseudorange Measurement Simulations

One sigma measurement noise values assumed for the GPS Pseudorange (PR) measurement simulations were modeled as a function of received GPS signal to noise ratio, as specified in Table 6. These values are consistent with measured performance for the Navigator receiver.

Table 6 Simulated GPS PR Measurement Noise (1-σ)

Signal Acquisition Threshold	One-Sigma Value (meters)
> 38 dBHz	4.4
< 38 dBHz and > 30 dBHz	6.1
< 30 dBHz and > 25 dBHz	8.8

Two clock error models were studied. As seen in Figure 7, the clock error model 1 is based on a relatively stable oscillator that is close to a clock error model assumed previously for the Magnetospheric MultiScale Mission (MMS) navigation analysis (Reference 8). This clock error will be referred to as the MMS clock error model. The clock model 2 bias errors are approximately 25 times the clock model 1 bias errors and the clock model 2 drift errors are approximately 10 times the clock mode 1 drift errors. Most solutions presented in this paper were obtained using GPS PR measurements simulated assuming the MMS clock error model (model 1).

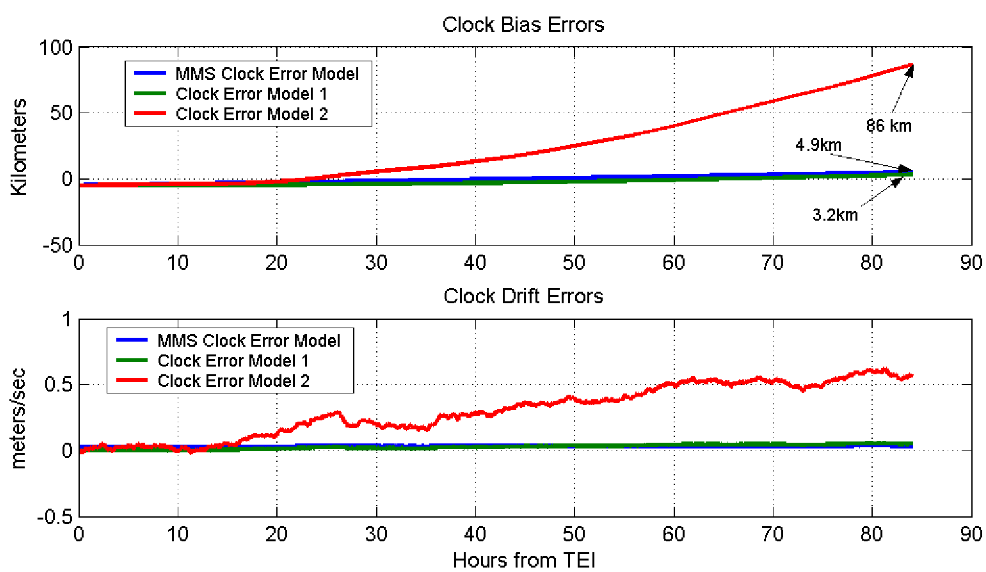


Figure 7 GPS Receiver Clock Error Models

Overview of Navigation Solutions Examined

Navigation solutions were obtained by processing different combinations of measurements, simulated with different error effects and magnitudes. The results presented in the next section are predominantly comparisons of results that combine GPS pseudorange measurements with different combinations of ground tracking stations and ground tracking measurement data types.

III. RESULTS

GEONS uses an EKF to estimate the spacecraft position and velocity and associated covariance. GEONS filter solutions were obtained using the simulated measurements discussed in the previous section. An algorithm similar to the vector measurement update algorithm (Reference 7) was used when simultaneously processing multiple measurements from different tracking stations at a given measurement time. In this scheme, the state is updated once at each measurement time using all available measurements. The filter was initialized using an initial state that includes a priori state errors, and the state propagation was performed using a simpler force model than that used for the truth trajectory generation. Initial conditions and propagation force models for the GEONS filter are summarized in Table 7. The velocity process noise variance rate and measurement standard deviations specified for the filter vary from solution to solution.

Table 7: Filter Initial Conditions and Force Models Used for State Propagation

Items	Values
Initial Position Errors	5 kilometers in each direction
Initial Velocity Errors	5 m/sec in each direction
A Priori Position Variance	10^8 m^2 in each direction
A Priori Velocity Variance	10^2 $(m/sec)^2$ in each direction
Propagation Force Models	Point Mass Gravity: Sun and Moon Earth Gravity Model: JGM2 8x8 Earth GM: $GM_{Earth}(1 + 3x10^{-8})$ [3-sigma perturbed] Lunar GM: $GM_{Moon}(1 - 10^{-5})$ [3-sigma perturbed] Solar Radiation Pressure (CR=1.4) Atmospheric Drag (CD = 2.2) S/C Area = 100 m^2 No non-gravitational acceleration errors
Integration Stepsize	30 seconds

Several GEONS solutions were generated using combinations of ground tracking and GPS measurements. All these solutions were obtained in the presence of FLAK effects. Solutions were analyzed in terms of the sensitivity to the relative weighting of the ground tracking and GPS measurements specified in the filter.

The navigation results can be grouped into three different segments based on the types and number of measurements that were used to generate the solutions, as illustrated in Figure 8. The three segments are defined as follows:

s1 Periods when both GPS and ground tracking measurements are present
s2 Periods when only GPS measurements are present, with < 4 GPS signals
s3 Periods when only GPS measurements are present, with 4 or more GPS signals

Ground tracking measurements are available from TEI until approximately two hours before entry interface. The s2 and s3 segments correspond to this two-hour period when there is no coverage of the Orion trajectory from an Earth-based ground station. Because the different GPS receiver cases result in different periods of time when GPS measurements are available, the duration of the segments varies for each of the cases.

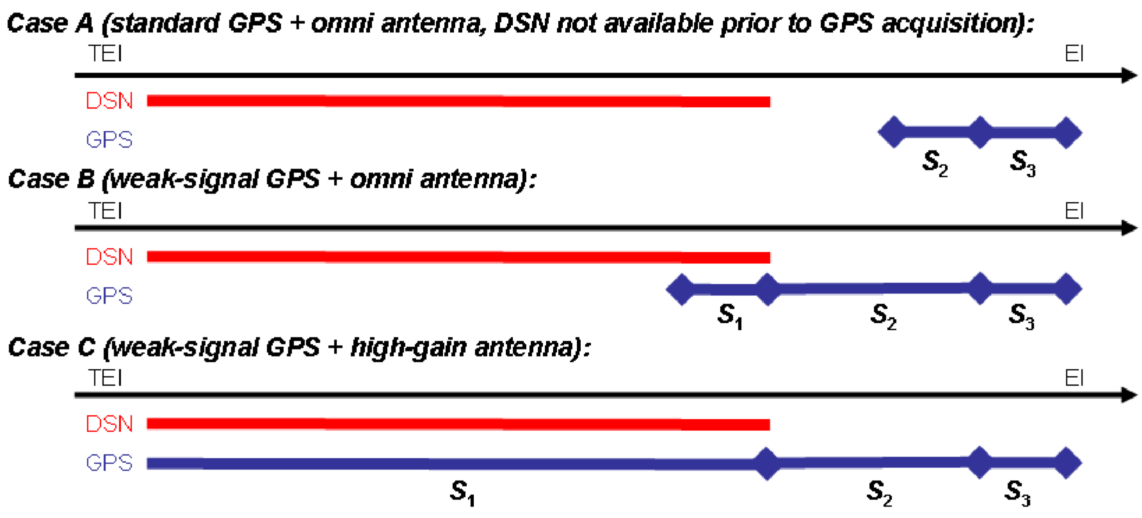


Figure 8 Definition of tracking segments discussed in analysis results

Case A Results – Standard GPS Receiver (35 dB-Hz)

With the Case A receiver, there are no "s1" periods when both GPS and ground tracking measurements are present because GPS measurements are only available immediately before entry interface, after contacts with the two-way Earth-based tracking station have ended. As a result, the GPS measurements allow measurement updates to be performed during the final hours before entry interface. A typical Case A solution is shown in Figure 9. Between 82-84 hours elapsed time, the navigation solution is a simple propagation of the last measurement update made from the 6-station ground tracking station solution. The presence of measurements from even a single GPS satellite produces an immediate improvement in the position errors.

Case A solutions are sensitive to the GPS PR measurement standard deviations specified in the filter. GEONS filter solutions were obtained using two different GPS PR standard deviations, 40 and 100 meters, with 40 meters providing better results for Case A. The solution shown in Figure 9 was obtained with a GPS PR standard deviation of 40 meters (1-sigma). These solutions were obtained using MMS GPS receiver clock error model. Error statistics for Case A are provided in Table 8.

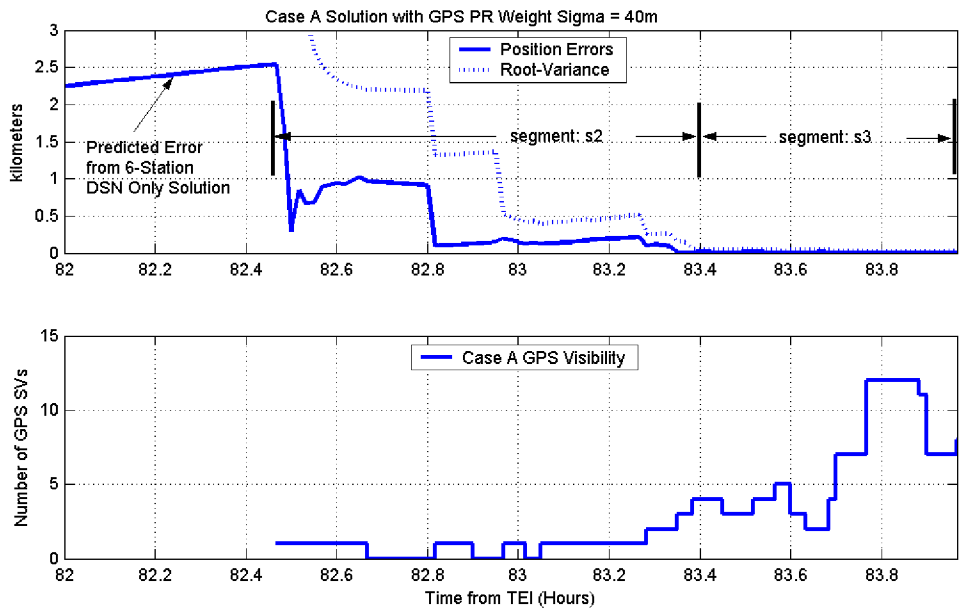


Figure 9 Number of GPS Satellites and Position Errors for Case A Solution With GPS PR Standard Deviation = 40 Meters

Table 8 Case A Position Error Summary

	s2 (m)	s3 (m)	GPS PR σ (m)
RMS MAX	824 2539	20 38	100
RMS MAX	818 2539	9 16	40

Case B Results – Weak Signal Tracking GPS (25 dB-Hz)

With a Case B GPS receiver, four solutions were obtained using ground tracking plus GPS measurements, two of them with ground tracking from 6 ground stations and the other two with ground tracking measurements from only the 3 two-way ground stations.

B1: 2-way ground station range and Doppler from 3 two-way stations and Doppler from 3 three-way stations plus all available GPS PR measurements from a Case B GPS receiver

B2: Same as B1, except with no 2-way ground station range measurements during segment s1 in which both ground tracking and GPS tracking are available.

B4: 2-way ground station range and Doppler from 3 two-way stations plus all available GPS PR measurements from a Case B GPS receiver

B5: Same as B4, except with no 2-way ground station range measurements during segment s1 in which both ground tracking and GPS tracking are available.

Figure 10 shows the variations of position and velocity errors over time for segments s2 and s3 using Case B GPS receiver and a GPS PR standard deviation of 100 meters. A GPS PR standard deviation of 40 meters was also evaluated, and the results were different for segments s2 and s3. In segment s3, smaller GPS PR standard deviation gives smaller errors, while, in segment s2, smaller GPS standard deviation gives larger errors. The better overall solution may be the one obtained using GPS PR standard deviation of 100 meters (Figure 10); however, this solution may be further improved using a segment-dependent GPS PR standard deviations, for example, using 100 meters for segments s1 and s2, and 40 meters for segment s3 where ≥4 GPS SVs are visible.

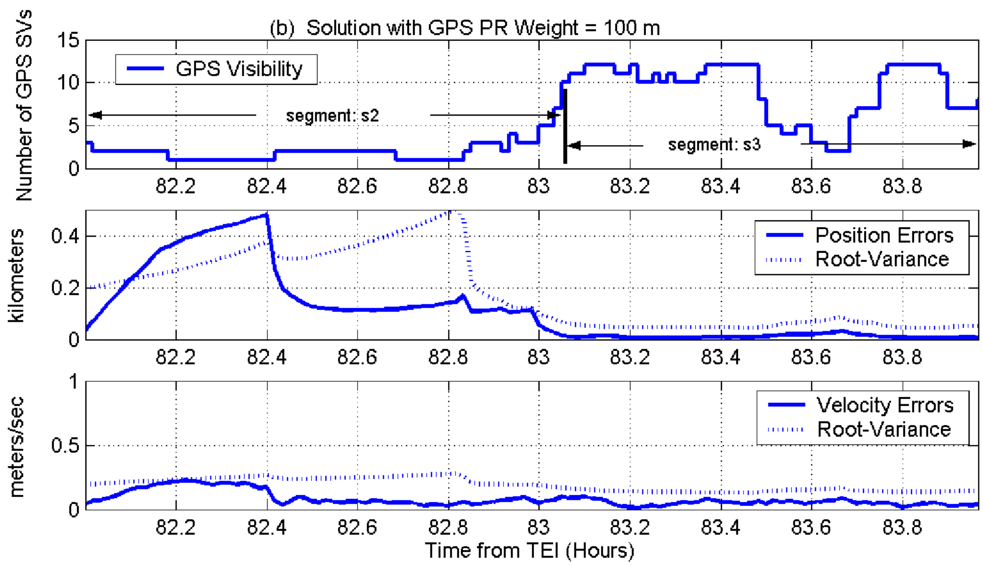


Figure 10 Position and Velocity Errors of Case B Solutions With GPS PR Standard Deviation = 100 Meters In Segment S2 and S3

The Case B GPS configuration also results in a 12 hour s1 segment, or overlapping availability of GPS and ground tracking measurements. Figure 11 shows a solution (B1) that combines 2-way ground station range and Doppler from 3 two-way stations and 2-Way Doppler from 3 three-way stations plus all available GPS PR measurements. Also plotted in red is a solution obtained from the ground tracking-only solution (no GPS measurements included). It is seen from Figure 11 that errors were substantially reduced when GPS PR measurements were also processed in addition to ground station measurements during the segment s1.

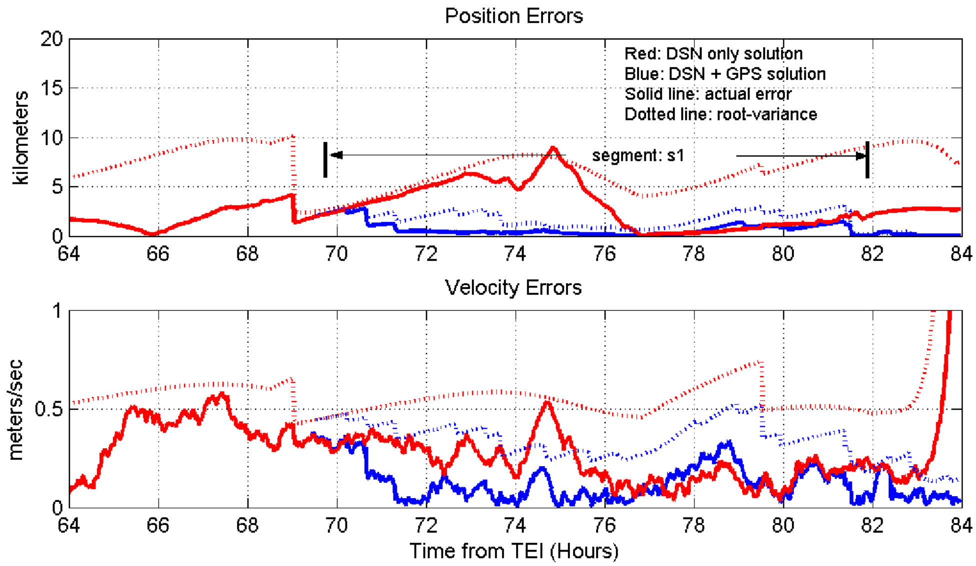


Figure 11 Position and Velocity Errors of Case B Solution [Solution B1 With GPS PR Standard Deviation = 100 Meters]

Another solution (B2) which used only ground station Doppler measurements and GPS measurement (no ground station two-way range measurements), showed similar error behaviors to B1. Error statistics collected for the segment s1 are given in Table 9. The results suggest that acceptable solutions may be obtained without ground station range measurements when GPS PR measurements are available even when the number of visible GPS SVs is fewer than 4 (typically 1 or 2 in this case).

Additional solutions were computed by using tracking data from only three ground tracking sites. Solution B4 includes two-way ground station range and Doppler from 3 two-way stations plus all available GPS PR measurements from a Case B GPS receiver. Solution B5 is the same as B4, except that no two-way ground station range measurements are processed during segment s1 in which both ground tracking and GPS tracking are available. The reference solution obtained using only ground tracking measurements from 3 two-way stations (with no GPS measurements) is highly unstable throughout the entire return trip from the Moon. Table 9 also shows error characteristics for the three-station solutions. At least for the last 15 hours of solution B5, the navigation solution can be substantially improved by processing GPS PR measurements together with the 3-station ground tracking measurements. Figure 12 compares solution B4 with the 3 ground-station-only reference solution. Solutions B4 and B5 over s1 are substantially better than the reference 3-station ground tracking only solution. Adding Case B GPS to 3-station ground tracking produces solutions somewhat better than 6-station ground-tracking-only (but not as good as 6-station ground tracking plus Case B GPS).

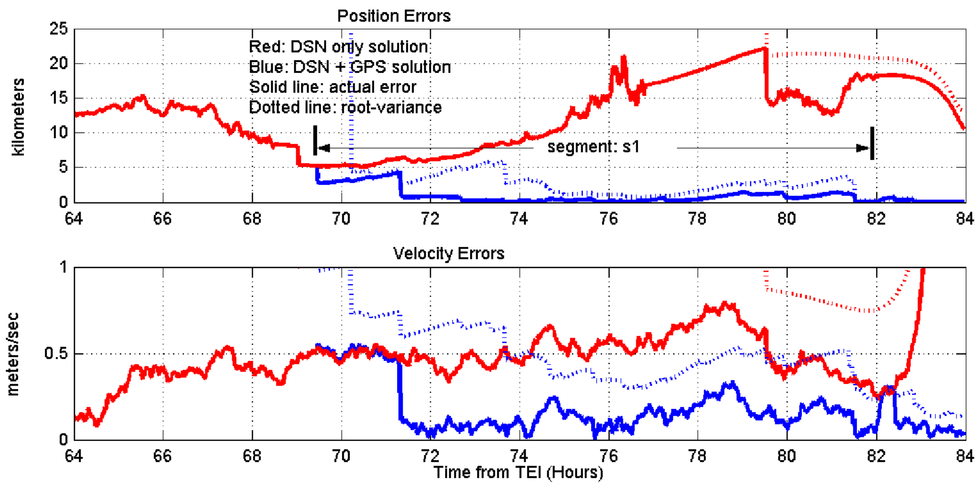


Figure 12 Case B Solution B4 with PR Noise Standard Deviation = 100 Meters

Table 9 Position and Velocity Error Statistics Over the Segment S1

Solution	Position Error (meters) RMS	Position Error (meters) MAX	Velocity Error (m/sec) RMS	Velocity Error (m/sec) MAX
6-Ground station reference solution (no GPS)	3876.6230	8911.6267	0.2451	0.5336
B1: Ground station range and Doppler (2-way and 3-way) plus GPS PR measurements during s1 (6 station)	892.3620	2765.0150	0.1497	0.3664
B2: Ground station Doppler (2-way and 3-way) plus GPS PR measurements during s1 (6 station)	863.8046	2769.3990	0.1483	0.3666
3-Ground station reference solution (no GPS)	13584.3602	22125.9514	0.5259	0.7994
B4: Ground station 2-way range and Doppler plus GPS PR measurements during s1 (3 station)	1347.8658	4291.9846	0.2164	0.5545
B5: Ground station 2-way Doppler plus GPS PR measurements during s1 (3 station)	1322.5879	4290.5572	0.2145	0.5546

Case C Results – Weak Signal Tracking GPS (25 dB-Hz) plus 10 dB Directional Antenna

With a Case C GPS receiver, four solutions were obtained using ground tracking plus GPS measurements, two of them with ground tracking from 6 ground stations and the other two with ground tracking measurements from 3 two-way ground stations. GPS only solutions in this case are not stable, because there are not a sufficient number of GPS PR measurements available to estimate the spacecraft position, velocity and GPS receiver clock parameters. Only one or two GPS SVs are visible at a given time over most of the return trip time span of 84 hours. The four solutions studied in this section are:

C1: 2-way ground station range and Doppler from 3 two-way stations and Doppler from 3 three-way stations plus all available GPS PR measurements from a Case C GPS receiver

C2: Same as C1, except with no 2-way ground station range measurements during segment s1 in which both ground tracking and GPS tracking are available.

C3: 2-way ground station range and Doppler from 3 two-way stations plus all available GPS PR measurements from a Case C GPS receiver

C4: Same as C3, except with no 2-way ground station range measurements during segment s1 in which both ground tracking and GPS tracking are available.

Position and velocity errors of solution C1 are shown in Figure 13. The corresponding errors associated with the reference solution obtained using 6-station ground tracking measurements only are also shown in Figure 13. In this case, the segment s1 covers 82 hours starting from TEI, almost the entire Earth-return trip. The ground tracking plus GPS solution is substantially better than the ground-tracking only solution, especially in terms of position errors. Velocity errors have not shown much improvement. Estimated clock bias errors are shown in Figure 14. Including ground station range and Doppler data improves estimation of the GPS clock bias and drift.

Position and velocity error statistics of solution C1 and C2 over the segment s1 are summarized in Table 10 together with the other Case C solutions. As can be seen from Table 10, solution C2 is very similar to C1, again indicating that DSN range measurements may not be needed in this case for the entire Earth return trip navigation. The only noticeable difference between C1 and C2 are in the estimated clock bias errors, the clock errors associated with C2 being slightly worse than those of C1. It appears that the presence of DSN range improves the GPS clock estimation (see Section IV.4). Both solutions C1 and C2 are substantially better than the reference solution obtained using 6-ground-station DSN measurements only.

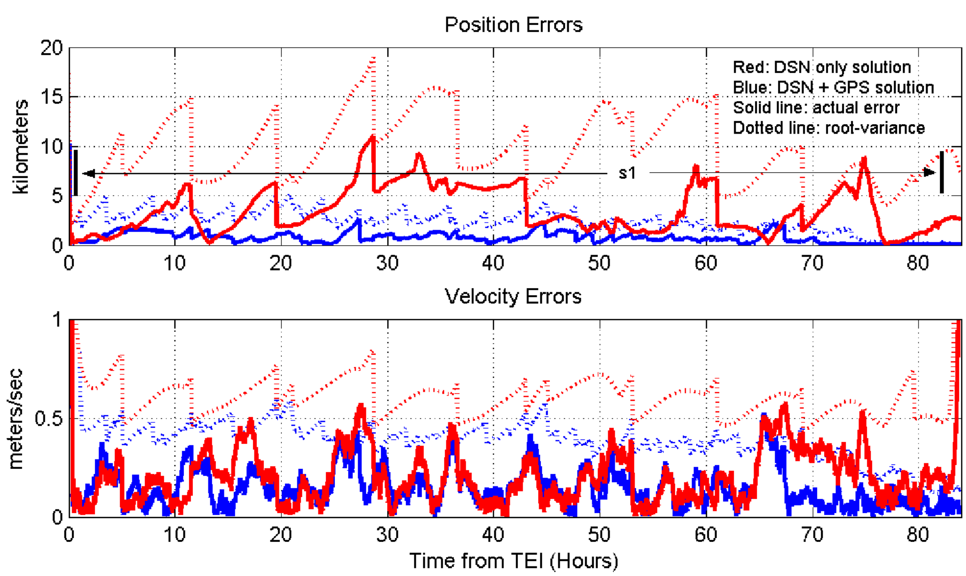


Figure 13 Position and Velocity Errors of Case C Solution (C1) With GPS PR Standard Deviation = 100 Meters

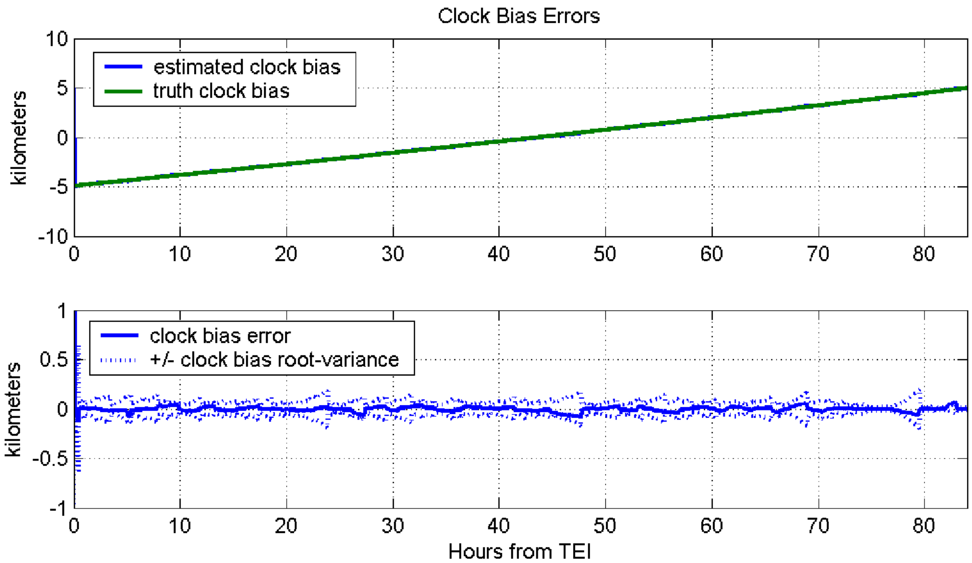


Figure 14 Clock Bias Errors of Case C Solution (C1) With GPS PR Standard Deviation = 100 Meters

Position and velocity errors of solution C3 using only 3 ground tracking stations are shown in Figure 15. The corresponding errors associated with the reference solution obtained using only 3-station ground tracking measurements are also shown in Figure 15. As can be seen from Table 10 and Figure 15, the solution obtained using ground tracking measurements from 3 ground stations plus GPS measurements from a Case C receiver is substantially better than the corresponding ground station only solution and is also seen to be better than the 6-station ground station only reference solution in terms of position errors. Clock bias errors of solution C3 are shown in Figure 16. The GEONS filter was able to estimate the GPS receiver clock bias using only one or two GPS PR measurements with the help of ground station range and Doppler measurements. Solutions C3 and C4 give similar results indicating that, even in the case of using only 3 ground stations, ground station range measurements may not be needed when GPS PR measurements are available.

The Case C results indicate that there may be a benefit in both navigation performance, and reduced reliance on ground based communications and tracking infrastructure, if the Orion spacecraft were to add a directional GPS antenna that could be pointed towards the Earth.

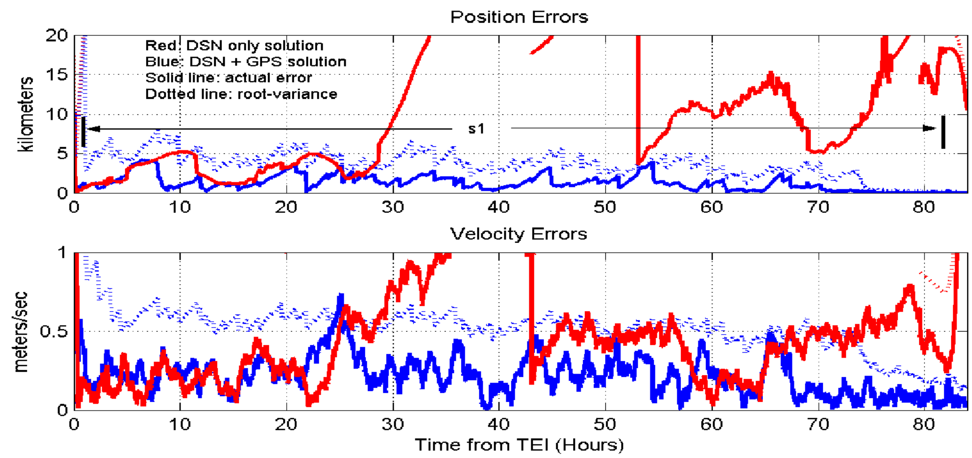


Figure 15 Position and Velocity Errors of Case C Solution (C3) With GPS PR Standard Deviation = 100 Meters

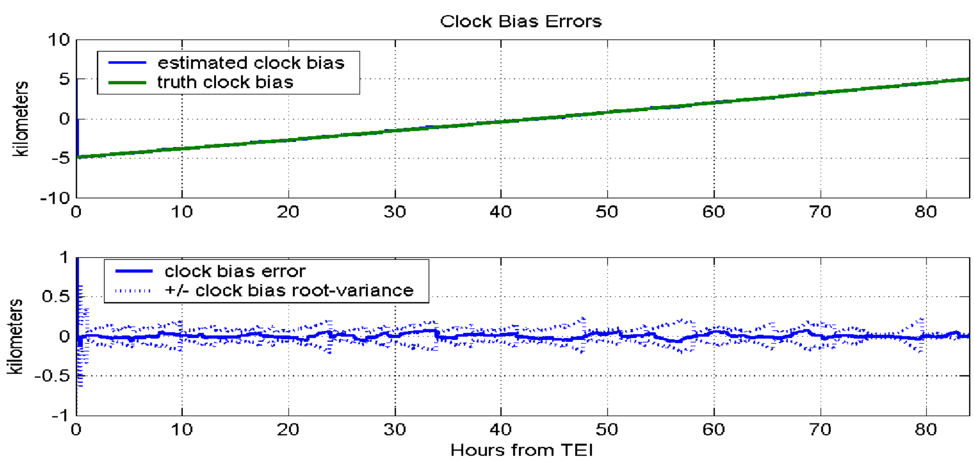


Figure 16 Clock Bias Errors of Case C Solution (C3) With GPS PR Standard Deviation = 100 Meters

Table 10 Position and Velocity Error Statistics Over Segment S1
(Statistics were taken from 6 to 82 hours from TEI)

Solution	Position Error (meters)		Velocity Error (m/sec)	
	RMS	MAX	RMS	MAX
6-Ground station reference solution (no GPS)	4339.8524	11025.5635	0.2395	0.5810
C1: Ground station range and Doppler (2-way and 3-way) plus GPS PR measurements during s1 (6 station)	871.7298	2655.1241	0.1720	0.5249
C1: Ground station Doppler (2-way and 3-way) plus GPS PR measurements during s1 (6 station)	886.2407	2560.6300	0.1712	0.5245
3-Ground station reference solution (no GPS)	19698.5695	63829.4302	0.5704	1.2530
C3: Ground station 2-way range and Doppler plus GPS PR measurements during s1 (3 station)	1551.7444	4271.7463	0.2482	0.7367
C4: Ground station 2-way Doppler plus GPS PR measurements during s1 (3 station)	1596.4651	4132.6932	0.2485	0.7276

IV. CONCLUSIONS

This analysis examined navigation performance for an Earth Return trajectory from a lunar sortie mission, compared navigation solutions with and without GPS pseudorange measurements, and with different combinations of Earth-based tracking sites, and ground tracking measurement types. Some conclusions from this analysis are as follows:

- FLAK error is the major error contributor to both the definitive and predictive position and velocity errors. Predicted state errors are dominated by FLAK effects in the predictive time span. Reduced definitive state errors do not necessarily lead to reduced predicted state errors.

- The typical receiver configuration provides only a very limited amount of GPS data during the final hour or so prior to Earth Entry Interface (EI). Using a "weak signal" GPS receiver without additional gain, GPS measurements were available for several hours prior to EI and could conceivably support navigation updates around the time of the final trajectory correction burn. Using a "weak signal" GPS receiver with 10 dB of additional gain, some GPS measurements were available throughout the entire 3-4 day Earth return cruise phase.

- In all cases that included GPS measurements, definitive position errors can be reduced substantially by including GPS PR measurements, but the corresponding velocity errors generally are not reduced as much.

- When GPS PR measurements are available, navigation solutions can be obtained without ground station range measurements and/or with a reduced set of ground stations, e.g., Solutions using 3-ground-station Doppler plus GPS are generally better than the solution using 6-ground-station range and Doppler.

The analysis indicates that with proper selection and configuration of the GPS receiver on the Orion spacecraft, GPS can potentially improve navigation performance during the critical final phases of flight prior to Earth atmospheric entry interface, and may reduce reliance on two-way range tracking from Earth-based ground stations. In some cases GPS could also reduce the need for three-way Doppler data. In order to realize these benefits, the Orion GPS Receiver should include requirements to perform weak signal tracking (to 25 dB-Hz), and consideration should be given to incorporating a directional GPS antenna that can be mounted on the steerable high gain antenna boom. Furthermore, the selection of the stability parameters for the reference oscillator for the Orion GPS receiver should consider the possible future use for weak signal tracking and trans-lunar GPS tracking.

V REFERENCES

1. Apollo Navigation Working Group Technical Report No. AN-1.3, *Apollo Missions and Navigation Characteristics*, Vonbun, Mayer, December 15, 1967.
2. C. D'Souza, J Getchius, G. Holt, M. Moreau, *Lunar Navigation Architecture Design Considerations*, 32nd Annual AAS Guidance, Navigation, and Control Conference, Jan 31-Feb 4, 2009.
3. Honeywell Technology Solutions, Inc., Mission Operations and Mission Services, FDF-59-012, *Global Positioning System (GPS) Enhanced Onboard Navigation System (GEONS) Mathematical Specifications* Version 2, Release 2.9, A. C. Long et al., prepared by a.i. solutions, Inc., September 2007.
4. a.i.-solutions, Inc., MOMS-FD-UG-0043, *User's Guide and Mathematical Specifications for the Measurements Data Simulation Program* Release 2.9,

   Anne Long, prepared for NASA/GSFC, September 17, 2007
5. L. Winternitz, M. Moreau, G. Boegner, S. Sirotzky, *Navigator GPS Receiver for Fast Acquisition and Weak Signal Space Applications*, Proceedings of the Insitute of Navigation GNSS 2004 Conference, September 2004.
6. B. Bamford, B. Naasz, M. Moreau, *Navigation Performance in High Earth Orbits Using the Navigator GPS Receiver*," 29th Annual AAS Guidance and Control Conference, Breckenridge, CO, February 4-8, 2005.
7. P. S. Maybeck, *Stochastic Models, Estimation, and Control*, Vol. 1, New York: Academic Press, Inc., 1979
8. CSC-5570-21, *Magnetospheric Multiscale Mission (MMS) Phase 1: Assessment of Expected Performance Using the Inter-Spacecraft Ranging and Alarm System (IRAS)*, Taesul Lee, David Kelbel and Anne Long, December 2003
9. FDF-59-013, *Magnetospheric Multiscale Mission (MMS) Maneuver Recovery Analysis,* Taesul Lee and Michael Volle, February, 2007