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Autonomous Navigation With Ground Station One-Way Forward-Link Doppler Data*

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Abstract

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) has spent several years developing operational Onboard Navigation Systems (ONSs) to provide realtime autonomous, high-accuracy navigation products for spacecraft using NASA's space and ground communication systems. The highly successful Tracking and Data Relay Satellite System (TDRSS) ONS (TONS) experiment on the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) spacecraft, launched June 7, 1992, flight demonstrated the ONS for high-accuracy navigation using TDRSS forward-link communications services. In late 1994, a similar ONS experiment was performed using EP/EUVE flight hardware (the ultrastable oscillator (USO) and Doppler extractor (DE) card in one of the TDRSS transponders) and ground system software to demonstrate the feasibility of using an ONS with ground station forward-link communication services. This paper provides a detailed evaluation of ground-station-based ONS performance over the 20-day period of data collected.

The Ground-station ONS (GONS) experiment results are used to project the expected performance of an operational system. The GONS processes Doppler data derived from scheduled ground station forward-link services using a sequential estimation algorithm enhanced by a sophisticated process noise model to provide onboard orbit and frequency determination. Analysis of the GONS experiment performance indicates that realtime onboard position accuracies of better than 125 meters (1σ) are achievable with two or more 5-minute contacts per day for the EP/EUVE 525-kilometer altitude, 28.5-degree inclination orbit. GONS accuracy is shown to be a function of the fidelity of the onboard propagation model, the frequency/geometry of the tracking contacts, and the quality of the tracking measurements. GONS provides a viable option for using autonomous navigation to reduce operational costs for upcoming spacecraft missions with moderate position accuracy requirements.

1.0 Introduction

Due to recent advances in space-qualified components such as high-capacity solid state recorders and the trend toward smaller spacecraft that cannot support Tracking and Data Relay Satellite System (TDRSS) services, either from cost or power perspectives, many future spacecraft missions are returning to ground stations (GSs) for their communication support. Traditionally, GSs provide command, telemetry, and tracking services for user spacecraft, which can be costly and operationally intensive. New ground terminals are being designed that provide increased autonomy to reduce operations costs. However, these new ground terminals will provide only command and telemetry services, requiring users to acquire spacecraft navigation data from alternate sources, such as an autonomous navigation system.

Autonomous navigation using an onboard system has distinct advantages. Autonomous navigation products can be included directly in the science telemetry and forwarded to the scientific investigators located worldwide, with remote communication links to the mission operations centers. Autonomous navigation solutions can be used onboard as input to other subsystems, such as attitude control, ground track generation, maneuver definition and

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control, and communication signal acquisition. Autonomous navigation systems also can provide a time maintenance or determination function for the spacecraft, increasing spacecraft self-sufficiency and reducing ground operations.

The Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) has spent several years developing high-accuracy onboard navigation systems for spacecraft using National Aeronautics and Space Administration (NASA) space and ground communications systems. The highly successful TDRSS Onboard Navigation System (TONS) experiment on the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) spacecraft flight qualified high-accuracy algorithms for autonomous navigation using TDRSS carrier signals (Reference 1). As a result, the Earth Observing System-AM1 (EOS-AM1) is implementing TONS as its prime operational navigation system.

To address increases in the planned use of ground stations as the sole communication medium for future low-Earth orbiting spacecraft, the FDD performed an experiment to investigate the potential of onboard navigation using Doppler measurements of the S-band communication signals transmitted from ground stations. After this Ground-station Onboard Navigation System (GONS) experiment, several parametric studies were performed to investigate the sensitivity of GONS navigation accuracy. These studies included decreasing the accuracy of the initialization/ a priori state, reducing the gravity model size used for state propagation, and increasing the measurement sampling interval used in state estimation. Reference 2 contains details of the GONS experiment not presented in this paper; Reference 3 discusses GSFC FDD's initiative to integrate the GONS capability with a spacecraft communications receiver to provide an "off-the-shelf" navigation package.

Section 2.0 of this paper discusses the GONS flight qualification experiment, and Section 3.0 describes the flight hardware performance. GONS navigation performance and GONS parametric studies are described in Sections 4.0 and 5.0, respectively. Section 6.0 gives the conclusions of the study, followed by acknowledgments and a list of the references cited in the paper.

2.0 GONS Flight Qualification Experiment

The EP/EUVE spacecraft houses hardware previously used for TONS to accurately measure the Doppler shift of a one-way forward signal from TDRSS to a user spacecraft. This hardware consists of a second generation TDRSS user transponder with the optional Doppler Extractor (DE) card and an Ultrastable Oscillator (USO). Using this same equipment, the GONS experiment was conducted for 20 days, beginning in September 1994. The objectives of the GONS experiment were to demonstrate the transponder's capability to extract accurate Doppler measurements of a GS carrier signal when referenced to an USO, to determine the achievable navigation accuracy from this data, and to analyze the potential of a single-station orbit determination solution.

For the TONS experiment, the DE card was added to transponder-B on EP/EUVE, and the USO provided the external frequency reference to this DE. In April 1994, a failure occurred in transponder-B's transmitter, without causing harm to the receiver. At that time, the omni-directional antenna was switched to transponder-B's receiver. For the GONS experiment, acquisition of a GS carrier could still occur through the transponder-B receiver. However, due to the failure of the associated transmitter, the return-link data could not be telemetered to the ground in realtime.

Given the circumstances onboard EP/EUVE, each contact was handled via a blind acquisition of the spacecraft. The blind acquisition used a single frequency sweep at a rate of 20 kilohertz per second over a range of 200 kilohertz around the receive center frequency, 2106.406300 megahertz, anticipating that the second generation transponder receiver would acquire the forward-link signal during the sweep. The Doppler measurements were then telemetered to the ground during a subsequent TDRSS contact to dump playback data and retrieved from processed telemetry tapes. The GONS experiment configuration is illustrated in Figure 1.

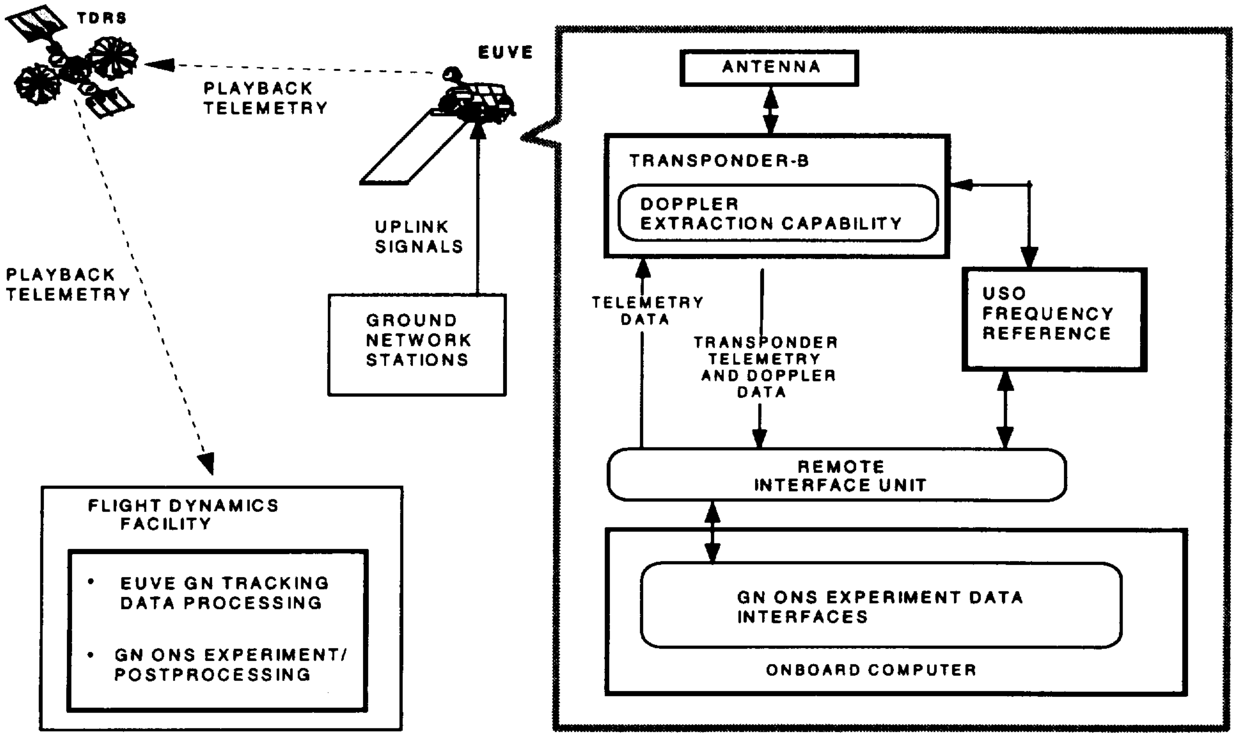

Figure 1. GONS Experiment Configuration

To support the GONS experiment, contacts were scheduled on a noninterference basis from Deep Space Network (DSN) GSs in Goldstone, California (GDS), Madrid, Spain (MAD), and Canberra, Australia (CAN), resulting in zero to five contacts per day, with lengths varying from 3 to 10 minutes. The experiment tracking data distribution, shown at the top of Figure 2, provided four significant analysis periods: two data gaps of 74 hours (days 4–7) and 47 hours (days 18–20), respectively, and two 4-day periods (days 0–4 and 11–15) with more than two contacts per day.

3.0 Flight Hardware Performance

The EP/EUVE flight transponder performs differently when configured in the GS service mode. The Doppler shift is measured in the DE by accumulating the difference between the received carrier frequency and the receiver's numerically controlled oscillator (NCO), which is referenced to the USO. The difference is rectified by a 24-bit internal frequency control word (FCW) sent simultaneously to the NCO and to an accumulator. In the TDRSS mode, the NCO updates every 500 microseconds (μs), thereby accumulating 20480 updates over the 10.24-second Doppler count interval in the DE. To track the higher dynamics between the user and the ground in the GS mode, the second-generation transponder NCO updates every 250 μs. Therefore, accumulation of 20480 updates occurs in 5.12 seconds in the GS mode, providing Doppler data at twice the TDRSS-mode rate.

To measure the performance of the hardware that provided the GONS Doppler measurement function, namely the DE and the USO, measurement residual statistics were computed and analyzed. To determine the USO frequency bias and drift, the measurement residuals (shown in Figure 2) were computed with respect to a TDRSS-only EUVE reference solution. The GONS experiment initial USO bias of 117 hertz and drift rate of –0.1 hertz per day are consistent with earlier TONS experiment results. Prefit residuals from the GONS navigation solution were analyzed to determine GONS measurement noise characteristics, as shown in Figure 3. Analysis of the prefit residuals from the entire 20-day period indicates a low systematic error of less than 0.006 hertz, with a standard deviation of 0.023 hertz.

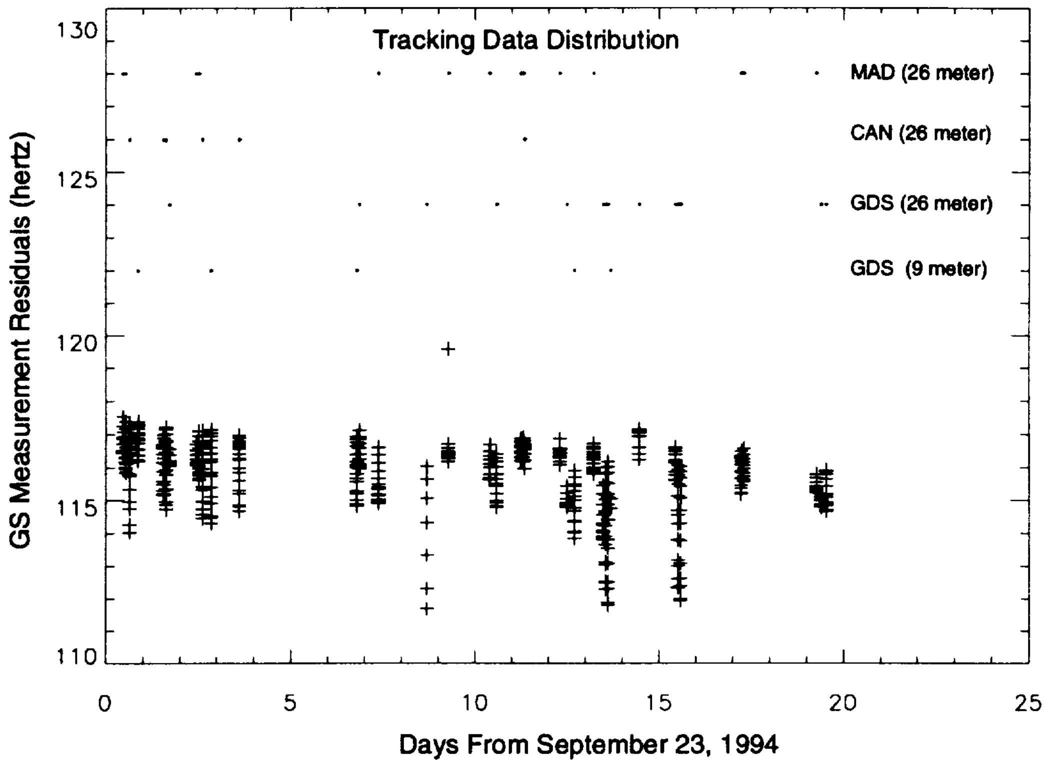

Figure 2. EUVE Ground Tracking Data Distribution and Measurement Residuals

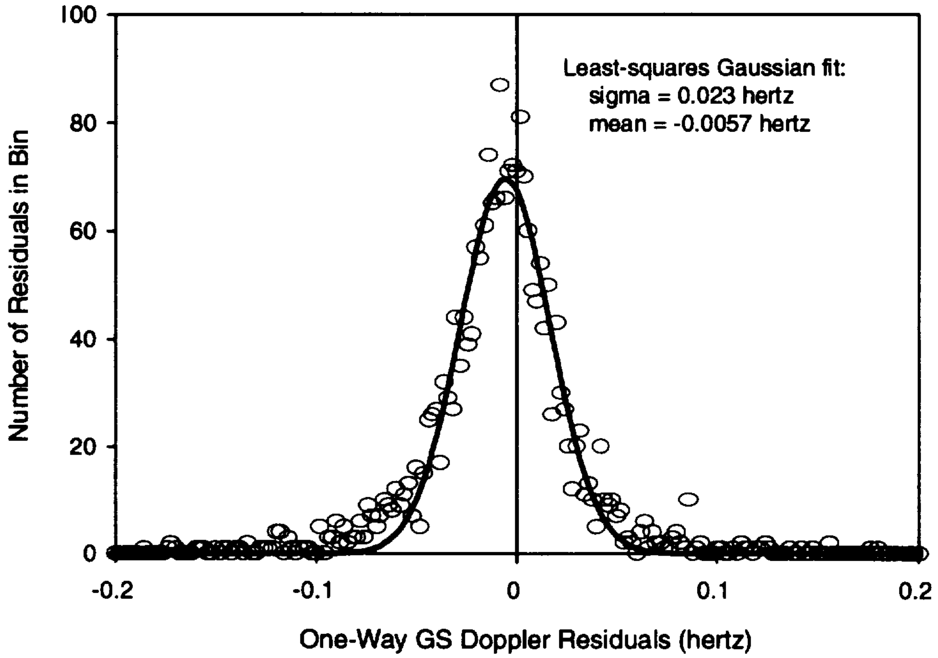

Figure 3. Histogram of Prefit Measurement Residuals

4.0 GONS Navigation Performance

To assess the accuracy of the navigation solution obtained using GONS experiment measurements, a reference solution was computed using an extended Kalman filter to process TDRSS range and two-way Doppler measurements for EUVE and Bilateration Ranging Transponder System (BRTS) range data for the TDRSS spacecraft. The filtered TDRSS reference solution state consisted of the EUVE position, velocity, and atmospheric drag coefficient; the position, velocity, and solar radiation pressure coefficient for each of the two TDRS spacecraft; and the measurement biases. The filtered TDRSS reference solution used a full 70 × 70 Joint Gravity Model-2 (JGM-2) gravity model and accurate atmospheric data to provide a very-high-accuracy state propagation model.

To simulate an onboard computing environment, the GONS experiment one-way forward Doppler measurements were also processed using an extended Kalman filter. The solution state consisted of the EUVE position, velocity, atmospheric drag coefficient, and USO frequency bias. This GONS solution used the JGM-2 gravity model truncated to 30 × 30 and averaged atmospheric density tables to simulate the limitations imposed by an onboard environment. Although hosted on a ground processor, these navigation algorithms used in the GONS experiment meet the strict throughput and memory budgets associated with onboard environments. A summary of the GONS algorithms is provided in Table 1.

The EUVE position estimation, atmospheric drag coefficient estimation, and USO frequency bias estimation are described in the following subsections, followed by a discussion of the GONS navigation performance with northern hemisphere GS tracking.

Table 1. Summary of GONS Experiment Algorithms

Algorithm Type	Algorithm
Primary Coordinate System	Mean equator and equinox of J2000.0 with analytic coordinate transformations, UT1 offset from coordinated universal time (UTC) updated daily
Primary Time system	UTC
Filter Spacecraft Acceleration Model	• 30 x 30 Joint Gravity Model-2 (JGM)-2 nonspherical geopotential • Earth, solar, and lunar point masses with analytic ephemeris • CIRA72 atmosphere density model with average atmospheric density tables
Spacecraft State Transition Matrix	Semianalytic formulation including J_2 and Earth point-mass acceleration partial derivatives
Frequency Reference Bias Propagation	Linear model with frequency drift input by user
Estimator	Extended Kalman filter with physically connected process noise models
Estimation State	• User position and velocity vectors • Atmospheric drag coefficient • Spacecraft frequency reference bias
State Process Noise Model	• Radial/in-track/cross-track (RIC) formulation of Earth gravity model errors • Gauss-Markov model for atmospheric drag coefficient and frequency reference bias
Measurement Model	• GS one-way forward-link Doppler with iterated light-time solution • Tropospheric measurement corrections • Relativistic corrections
Measurement Editing	• Doppler data validity checks • Measurement residual n-sigma test

4.1 EUVE Position Estimation

Figure 4 shows the root-sum-square (RSS) spacecraft position differences between the GONS and filtered TDRSS reference solutions for the entire experiment period. The GONS solution converges to below the 100-meter level after the first three contacts, which occur on consecutive orbits, and maintains a smooth, well-behaved signature except during large data gaps. During the first data gap of 74 hours (ending on day 6), the GONS solution propagates well, with a peak RSS position difference of 550 meters when compared with the filtered TDRSS reference solution, which includes TDRSS tracking during that interval. The predicted position standard deviation increases to 1 kilometer by the end of the 74-hour data gap, indicating a very realistic covariance propagation. The GONS solution recovers immediately following the start of the next tracking contact to the 100-meter level.

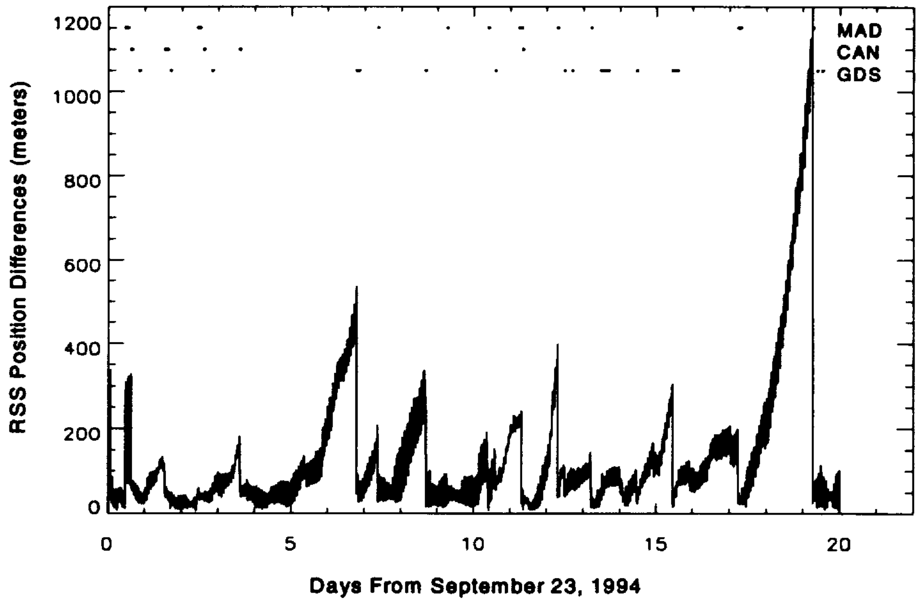

Figure 4. EUVE Total Position Differences Between the GONS and Filtered TDRSS Reference Solutions

During the second data gap interval of 47 hours (ending on day 19), the RSS position differences increase to 1.2 kilometers. The larger RSS differences seen during the second propagation period can be attributed to less accurate atmospheric density modeling during the propagation, as well as to a TDRSS spacecraft maneuver during the propagation period that adversely affected the TDRSS filter reference solution. The GONS solution differences show an immediate recovery to the 100-meter level upon processing data from the next contact, an important attribute for an autonomous navigation system.

During the two 4-day periods when there were three to four GS contacts per day, data from the filtered TDRSS reference solution was processed in a Rauch-Tung-Striebel smoother to provide a more accurate reference solution. As shown in Figure 5, the RSS position differences between the GONS solution and the smoothed TDRSS reference solution for the first 4-day period of interest are below 100 meters following processing of the first three GS contacts, except during an 18-hour propagation. The large differences seen in the first day of processing are during the first 3 contacts and are due to initializing GONS with a large initial covariance. Figure 6 shows similar results during the second 4-day period. The root mean square (RMS) of the position differences over the two 4-day periods are 81 meters and 124 meters, respectively. These results indicate that a highly stable autonomous navigation solution of better than 125 meters (1σ) can be achieved with a moderate GS tracking schedule, with highly reliable propagation during data gaps and immediate recovery during processing of the next contact.

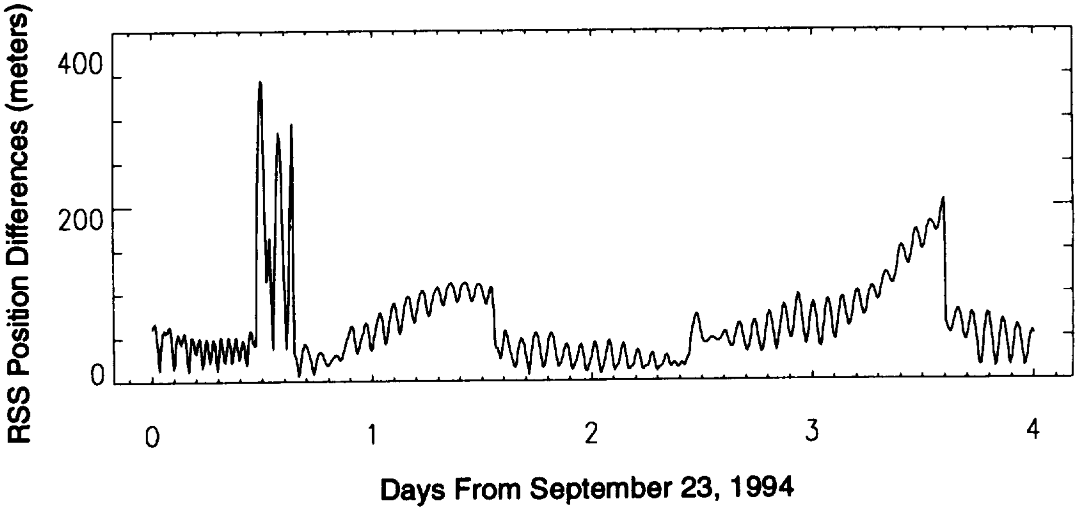

Figure 5. EUVE Total Position Differences Between GONS and First Smoothed TDRSS Reference Solutions

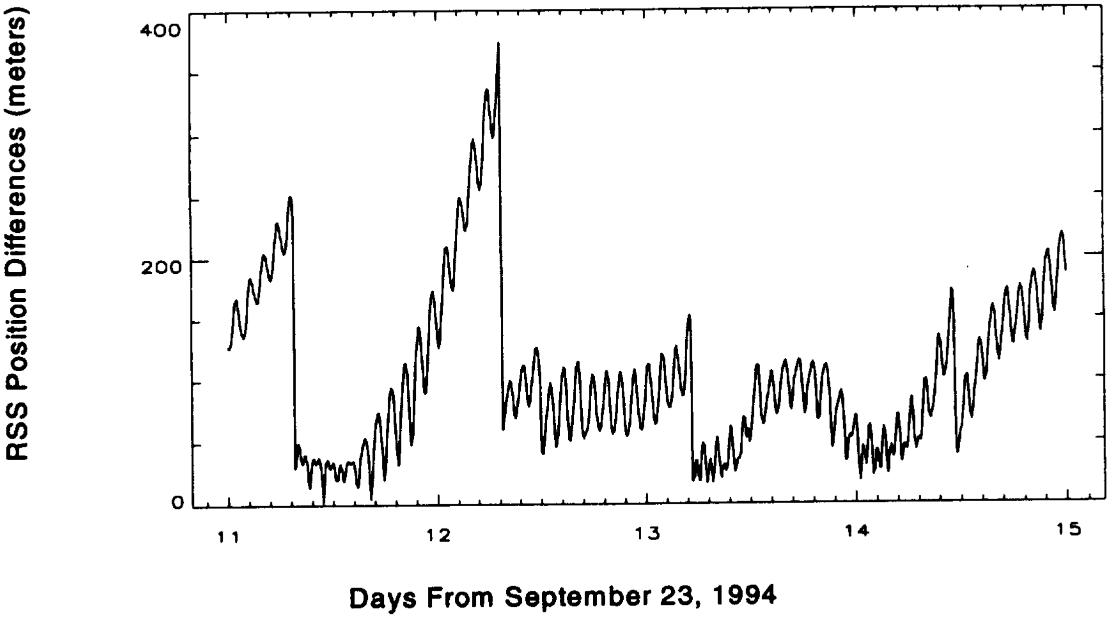

Figure 6. EUVE Total Position Differences Between GONS and Second Smoothed TDRSS Reference Solutions

4.2 EUVE Atmospheric Drag Coefficient Estimation

The GONS solution used different values for the Gauss-Markov coefficient of drag (C_D) sigma and C_D half-life than the TDRSS solution because of the tracking data frequency and larger uncertainty in atmospheric density. The filtered TDRSS reference solution used a nominal a priori drag coefficient value of 2.0, with a C_D sigma of 0.4 and a C_D half-life of 20 days. The GONS solution used a C_D sigma of 1.0 and a C_D half-life of 10 days. These values were chosen to allow the drag model to accommodate larger periods of propagation, because GS tracking was only available, on average, two to three times per day. The propagation of the drag coefficient is such that the correction will decay to zero exponentially, leaving an a priori drag coefficient of 2.0. Figure 7 compares the drag coefficient estimation for the two solutions. Early in the GONS solution, the drag estimate corrects to roughly 1.25. At the same time, the filtered TDRSS reference solution drag estimate is between 1.0 and 1.5. The subsequent corrections to the drag estimate in the GONS solution leave the drag coefficient oscillating around 1.0, until day 11; after day 11, the drag estimate is adjusted to between 2.0 and 2.5 for the rest of the solution. It is interesting to note that the filtered TDRSS reference solution drag estimate remains near 1.0 until day 15 and that the RSS position differences between the two solutions are not adversely affected

The definitive atmosphere model used in the TDRSS solutions shows nominal solar activity during the filter time period. The 3-hourly A_p geomagnetic index values increase more than 50 points near the middle of the 20-day solution. The $F_{10.7}$ solar flux is near 80 (× 10^{-22} watts per meter^2 per hertz) (nominal to low value) with a slight upward trend. The change in A_p, which is not modeled in the GONS solution, may drive the adjustments in the drag coefficient estimate around day 10 of the GONS solution.

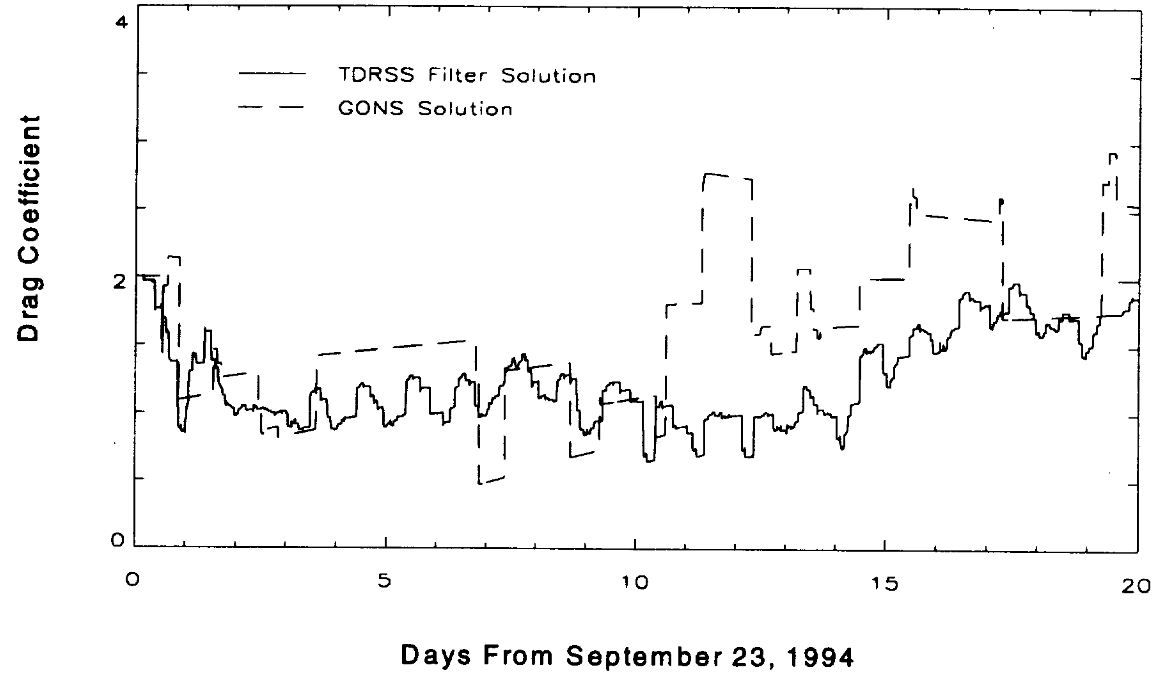

Figure 7. EUVE Drag Coefficient Estimation for GONS and Filtered TDRSS Reference Solutions

4.3 USO Frequency Bias Estimation

USO frequency bias estimation is required for accurate processing of the one-way forward GS tracking data in this solution. The a priori USO frequency bias was set to 118 hertz and the drift constant was set to 0.1 hertz per day. The bias was modeled as a Gauss-Markov parameter with a sigma of 10 hertz and a half-life of 100 days. The long half-life of the bias correction causes it to propagate at almost a constant value.

Figure 8 shows the total USO frequency estimation (frequency bias plus integrated drift) for the GONS solution. From the initial values, the frequency bias initially reduces to 117.5 hertz and the total USO frequency estimation drifts to approximately 115.8 hertz. This estimate is very close to that shown by the residuals in Figure 2. The frequency bias estimate is on track during the entire 20 day period

4.4 GONS Navigation Performance With Northern Hemisphere GS Tracking

The GONS experiment data were analyzed to simulate autonomous navigation solutions using a single GS by deleting the Southern Hemisphere station from the GONS solution. Both Northern Hemisphere stations were used, because too many data gaps exist to establish realistic results using a strictly single-station solution. Figure 9 shows that initial convergence of the GONS Northern Hemisphere solution (30 x 30) to the 200-meter level occurs after the first contact, with convergence to the 100-meter level occurring after two additional contacts. During the first data gap, now lasting 94 hours, the RSS position differences of the GONS Northern Hemisphere solution versus the TDRSS reference solution increase to 1.9 kilometers, with an immediate recovery to the 100-meter level upon processing of the data from the next contact. After this period, the RSS position differences of the GONS Northern Hemisphere solution versus the TDRSS reference solution are virtually identical to those from the GONS solution using data from all stations. Therefore, after filter convergence, a single-station autonomous navigation solution with a moderate tracking scenario (i.e., one to two contacts per day) can provide onboard real-time position accuracies of better than 125 meters.

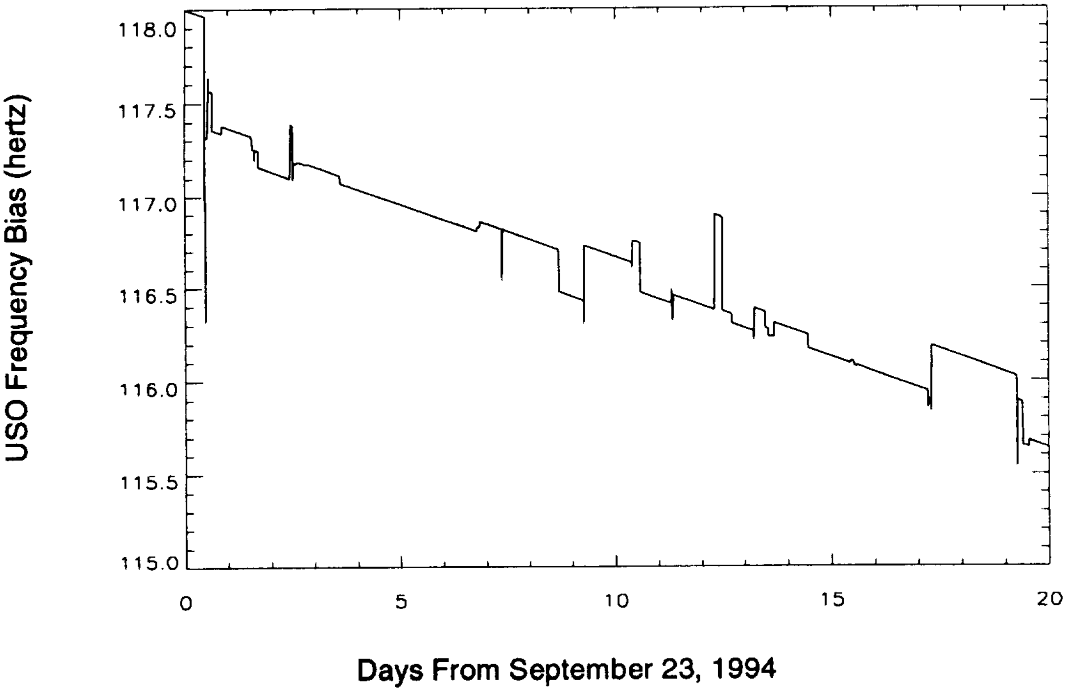

Figure 8. Total EUVE USO Frequency Bias Estimation From GONS Solutions

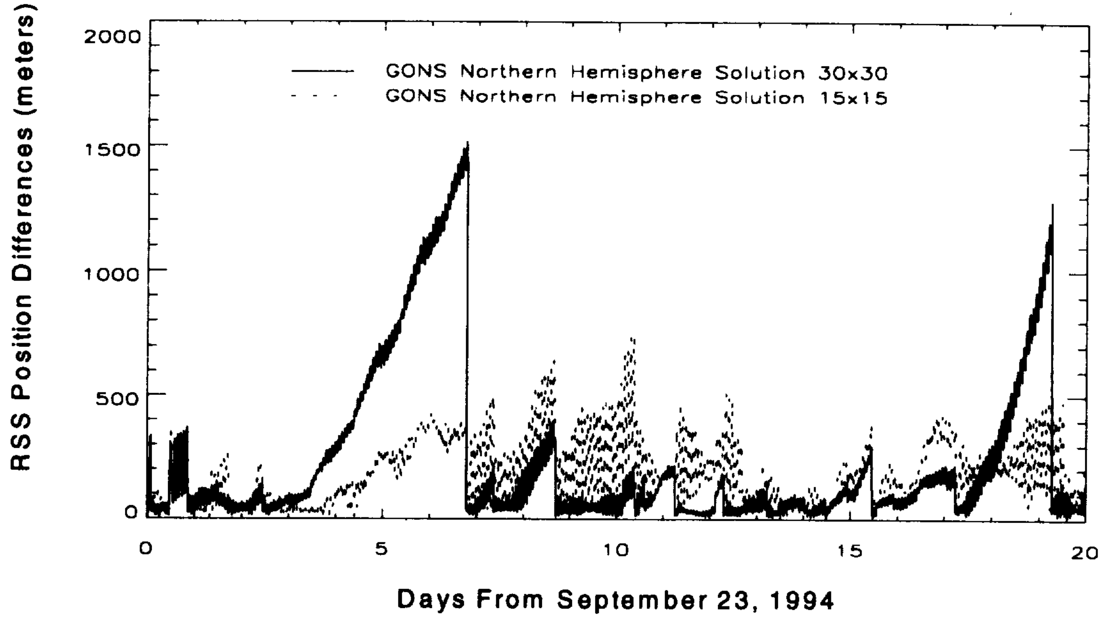

Figure 9. GONS Northern Hemisphere Solution Versus Filtered TDRSS Solution Differences

5.0 GONS Parametric Studies

The FDD's interest in navigation system requirements for spacecraft missions with moderate orbit determination accuracy led to the following studies of GONS performance. These studies included reducing the gravity model size used for ephemeris propagation, decreasing the accuracy of the initialization/a priori state, and increasing the measurement sampling interval used in state estimation. The intent of these analyses is to understand more about how GONS can be implemented to reduce spacecraft operations costs and still meet navigation requirements.

GONS performance with reduced gravity modeling, with offset initial state, and with increased sampling intervals are described in Sections 5.1, 5.2, and 5.3, respectively.

5.1 GONS Performance With Reduced Gravity Modeling

The 30 x 30 geopotential model used in the GONS experiment is the major contributor to the amount of onboard central processing unit (CPU) required for the navigation system. For this reason, a parametric study of the size of the geopotential model versus the system's navigation accuracy was performed. The GONS solution and the GONS Northern Hemisphere solution were run with the JGM-2 geopotential model reduced to 15 x 15 and 5 x 5. Table 2 shows the peak RSS differences from the filtered TDRSS reference solution for the first 17 days and the RMS of the RSS position differences from the second smoothed TDRSS solution (days 11–15) for the geopotential model sizes of 30 x 30, 15 x 15, and 5 x 5. Table 2 includes the difference in RMS values for days 11–15 that the new solutions have from the GONS solution. Figure 9 shows the RSS position differences between the GONS Northern Hemisphere solution with 15 x 15 geopotential model and the filtered TDRSS reference solution for the entire 20-day experiment period.

These and other GONS solutions indicate that the most significant change in performance with respect to gravity model size occurs when the order of the geopotential model is smaller than the orbital revolutions per day. For the EP/EUVE orbit, this resonance occurs below the 15 x 15 geopotential model. The 15 x 15 gravity model solutions in Table 2 show that a 75-percent reduction in CPU results in only a moderate accuracy penalty of roughly 100 meters RMS after the GONS solution has converged and two or more GS contacts per day are available.

Table 2. Reduced Geopotential Size Results

Gravity Model Sizes	RSS Position Differences From TDRSS Solutions (meters)		Degradation From GONS Solution (meters)
	Peak During Day 0–17	RMS for Day 11–15	RMS for Day 11–15
GONS Solution			
30 × 30	525 (day 6)	124	N/A
15 × 15	730 (day 10)	191	67
5 × 5	3800 (day 6)	687	563
Northern Hemisphere GONS Solution			
30 × 30	1900 (day 6)	90	–34
15 × 15	740 (day 10)	192	68
5 × 5	4500 (day 6)	802	678

5.2 GONS Performance With Offset Initial State

All of the solutions presented thus far have started from a definitive user state (position and velocity) accurate to approximately 100 meters. Operationally, GONS would have to be initialized with a predicted state. To see how this would affect GONS performance, the GONS Northern Hemisphere 15 × 15 solution was run with initial in-track offsets of 1 kilometer and 10 kilometers. Figure 10 illustrates the additional convergence time these offset solutions require. The RSS differences between the GONS and TDRSS solutions have been orbit-averaged to take out the orbital variation that would make these solution differences difficult to compare. The 1-kilometer offset solution settles after 1 full day and three GS contacts, and the 10-kilometer run takes a full 7 days and eight GS contacts. The 4-day tracking data gap after day 4 adversely affects the convergence time of the 10-kilometer offset solution. For each offset solution, the position and velocity components of the initial state covariance matrix were adequately enlarged to accommodate the initial state errors.

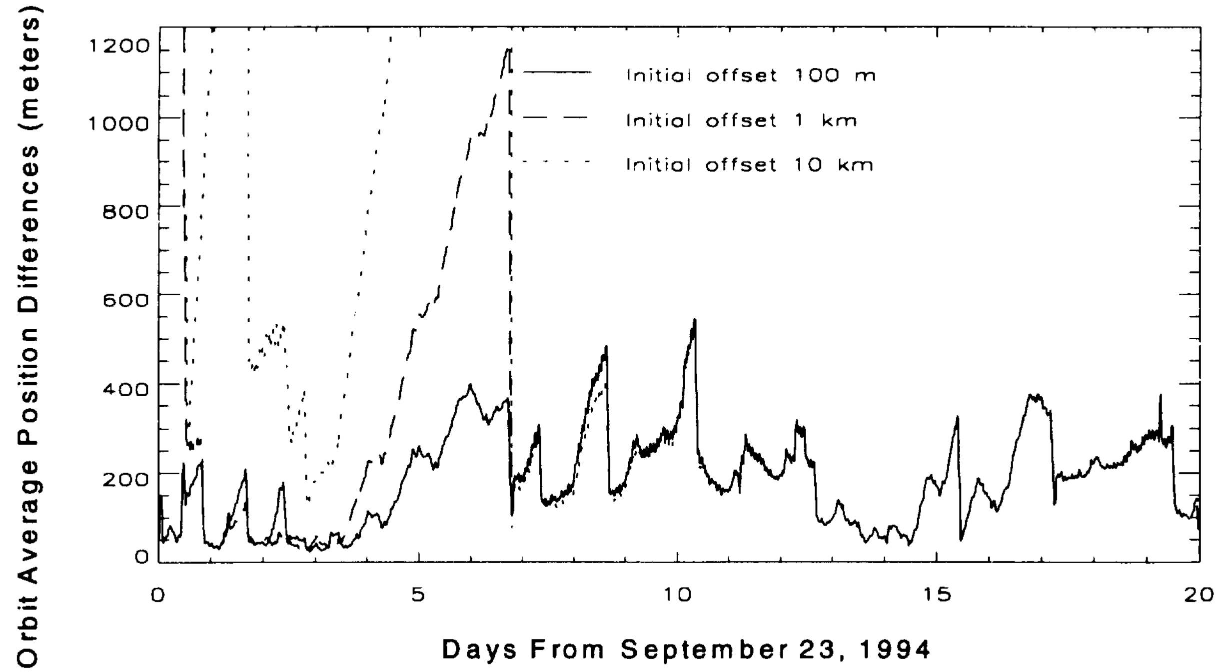

Figure 10. GONS Northern Hemisphere 15 × 15 Solution With Varying Initial State

5.3 GONS Performance With Increased Sampling Intervals

Another factor that influences the amount of onboard CPU required for GONS is the measurement sampling interval. In the GONS solutions so far, each have processed all available tracking data from all or the Northern Hemisphere stations. To see how the sampling interval affects GONS, new GONS Northern Hemisphere solutions were made at data rates of every other (10.24-second) and every sixth (30.72-second) tracking measurement. Table 3 shows the peak RSS differences from the filtered TDRSS reference solution for the first 17 days and the RMS of the RSS position differences from the second smoothed TDRSS solution for each tracking measurement data rate. Table 3 includes the difference in RMS values for days 11–15 that the new solutions have from the GONS solution. The values in this table show moderate accuracy improvements for an increased tracking measurement rate. This result is consistent and may be due to measurement standard deviation used during estimation. This analysis shows that measurement sampling, which produces significant CPU savings in measurement processing, has little effect on overall navigation performance.

Table 3. GONS Northern Hemisphere 15 × 15 Solution

Measurement Rate (seconds)	RSS Position Differences From TDRSS Solution (meters)		Degradation From GONS Solution (meters)
	Peak During Day 0–17	RMS for Day 11–15	RMS for Day 11–15
5.12	740 (day 10)	192	68
10.24	700 (day 10)	180	56
30.72	600 (day 10)	156	32

6.0 Conclusions

The GONS experiment using the EUVE spacecraft was successful, despite the use of blind signal acquisitions, a sparse tracking schedule, and extensive data processing requirements. The three objectives of the experiment were all met: to demonstrate the transponder's capability to obtain accurate Doppler observations of the GS carrier signal when referenced to a USO, to determine the achievable navigation accuracy from the data, and to analyze the potential of a single station orbit determination solution. The navigation accuracy of the GONS solution was found to be better than 250 meters (1σ) with tracking data gaps of up to 3 days. When the tracking frequency is greater than two contacts per day, a navigation solution on the order of 125 meters (1σ) is possible onboard the user spacecraft. The GONS solution RSS position differences demonstrated an immediate recovery from the 1900-meter level to the 100-meter level following a 3-day data gap. The selective use of tracking data from the Northern Hemisphere GSs created a solution with accuracies comparable to the GONS solution (using all one-way forward GS tracking data) after the filter had fully converged. However, tracking from Southern Hemisphere stations reduces the length of time required for the filter to converge.

The parametric studies of the GONS performance indicate that gravity model size and measurement sampling interval can be adjusted to suit individual CPU and navigation requirements. A GONS solution using a 15 × 15 gravity model and with measurement data processing once every 30 seconds can still meet many future spacecraft processing requirements. Comparable accuracy can also be achieved using an uplinked initial state with errors of up to 10 kilometers after filter convergence is achieved.

This experiment demonstrates the GONS navigation concept. GONS passively uses the user spacecraft communication system and has no extra power/weight/volume requirements. The accuracies found in this experiment support most of the existing navigation requirements of future NASA spacecraft. The system uses high-fidelity models, including a propagator that could provide backup navigation data. The Northern Hemisphere solution analysis indicates that GONS support of a user spacecraft with a single ground tracking station is feasible. Future directions for GONS analysis and development include investigating GONS performance with Doppler measurements referenced to a temperature-compensated crystal oscillator (TCXO) and design/ implementation of GONS in a spacecraft transponder (Reference 3).

Acknowledgment

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