Global Positioning System (GPS) Enhanced Orbit Determination Experiment (GEODE) on the Small Satellite Technology Initiative (SSTI) Lewis Spacecraft

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ABSTRACT

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center is currently developing the capability to use the Global Positioning System (GPS) to provide high-accuracy attitude, orbit, and time autonomously onboard NASA spacecraft. NASA's Small Satellite Technology Initiative Lewis spacecraft will host the GPS Attitude Determination Flyer (GADFLY) experiment. The primary objective of GADFLY is to demonstrate the use of GPS onboard for autonomous attitude and orbit determination and precise time distribution. GADFLY includes the GPS Enhanced Orbit Determination Experiment (GEODE) to flight qualify NASA-developed navigation algorithms for high-accuracy real-time onboard orbit determination.

The GEODE flight software is designed to be hosted either on the GPS receiver's digital receiver/processor unit or the primary spacecraft computer. GEODE executes a background Kalman filter and a foreground real-time state propagator, outputting position and velocity data every 1.0 second. Preflight processing of raw pseudorange measurements from existing spaceborne GPS receivers indicates that the GEODE navigation algorithms should provide a real-time total position accuracy of better than 10 meters (1σ) and velocity accuracy of better than 0.01 meter per second (1σ), with Selective Availability at typical levels. On-orbit performance will be assessed by comparing GEODE autonomous solutions with solutions obtained by differential postprocessing of GPS measurements.

INTRODUCTION

The Global Positioning System (GPS) is becoming a more attractive navigation option for National Aeronautics and Space Administration (NASA) spacecraft due to the recent declaration that the GPS is fully operational. The GPS Standard Positioning Service (SPS) can deliver real-time onboard spacecraft navigation accuracies in the 10- to 150-meter (1σ) range depending on the navigation process, improving to the submeter level in a postprocessing ground environment.

The basic GPS SPS commercial receiver computes the real-time three-dimensional spacecraft position and receiver time bias by solving a set of simultaneous equations constructed using pseudorange measurements to a minimum of four GPS space vehicles (SVs). The spacecraft velocity is either computed by solving a similar set of simultaneous equations constructed using "pseudorange rate" measurements or derived directly from the spacecraft position estimates. These products are often referred to as the "geometric," "point," or "unfiltered" solutions. The major source of error in the GPS SPS measurements arises from the Selective Availability (SA) corruption applied to the signals to limit geometric solutions to approximately 100 meters (two dimensional, 95 percent of the time) when SA is enabled. Typically, GPS receiver vendors advertise three-dimensional position accuracies on the order of 150 meters (1σ).

Since the geometric solutions are derived from measurements at a single time, they produce relatively poor velocity solutions, compared with typical filtered orbit determination solutions. In addition, the geometric solutions can undergo significant discontinuities when the set of four GPS SVs used in the solution changes. For example, References 1 and 2 indicate that the GPS receiver experiment that was hosted on the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) spacecraft produced real-time total position accuracies of about 60 meters (1σ) and velocity accuracies of 1.5 meters per second (1σ), during periods when SA was active, with occasional spikes of over 500 meters and 5 meters per second for the position and velocity, respectively.

Although the real-time position accuracy achievable using the basic geometric solution approach is adequate for some onboard applications, the position discontinuities are not acceptable for high-precision instrument pointing applications. In addition, the poor velocity accuracies are not adequate for navigation applications that require prediction of the real-time spacecraft state, such as view period prediction and maneuver planning.

The Small Satellite Technology Initiative Lewis (SSTI Lewis) spacecraft, currently scheduled for launch in the last quarter of 1996, is being developed for NASA Headquarters by TRW, Inc. SSTI Lewis, which is a demonstration spacecraft for several new Earth science and engineering technologies, will host the GPS Attitude Determination Flyer (GADFLY) experiment. The Goddard Space Flight Center (GSFC) Navigation, Guidance, and Control Branch is flying the GADFLY experiment to demonstrate and validate the ability to provide precise time and to determine spacecraft orbit and attitude using the GPS SPS. The primary GADFLY experiment objective is to provide on-orbit validation of the GPS attitude sensing in low Earth orbit using a space-qualified GPS receiver. Reference 3 discusses the GADFLY experiment in detail.

As a secondary experiment, GSFC proposed that the GADFLY GPS receiver host the GPS Enhanced Orbit Determination Experiment (GEODE). GEODE is a joint venture of the GSFC Navigation, Guidance, and Control Branch and the Flight Dynamics Division (FDD) to flight qualify NASA-developed navigation algorithms for high-accuracy real-time onboard orbit determination. This high accuracy will be achieved through the implementation of a sophisticated real-time Kalman filtering algorithm with high-fidelity state dynamics modeling. This paper discusses the GEODE objectives and operational configuration, the capabilities and architecture of the GEODE flight software, and the projected on-orbit performance.

GEODE OBJECTIVES

The primary objective of GEODE is to flight qualify a GPS/SPS receiver with NASA-developed navigation algorithms to provide high-accuracy real-time spacecraft position and velocity adequate to meet both the high-precision instrument pointing and state prediction requirements. The following GEODE accuracy goals have been defined for the 520-kilometer-altitude, 97-degree-inclination, circular SSTI Lewis orbit, with SA at typical levels:

- Real-time total position accuracy of better than 20 meters (1σ)
- Real-time total velocity accuracy of better than 0.03 meter per second (1σ)

GEODE's navigation performance must not require continuous visibility of a minimum of four GPS SVs and must be able to withstand loss of contact with the GPS SVs for several hours without undergoing a significant degradation in accuracy. In addition, the navigation algorithms must be implemented within the processing resources available on the host processor.

GEODE CONFIGURATION

SSTI Lewis hosts a separate payload and technology demonstration module that includes the GADFLY components, as shown in Figure 1. The GADFLY components include a space-qualified nine-channel GPS L1 frequency, Coarse Acquisition (C/A) code receiver interfaced with the primary spacecraft components via the Goddard Electronics Module (GEM). The GPS Attitude and Orbit Determination System (GPSAODS) receiver, developed by Space Systems/LORAL, is a redundant unit consisting of one GPS Tensor™ dual receiver, one four-channel preamplifier assembly, and four L1 receiving antennas. Reference 3 provides a detailed discussion of the SSTI Lewis GADFLY configuration.

The GPSAODS receiver measures the signal transmission time from the GPS SV to the user spacecraft in terms of the GPS C/A code phase delay averaged over

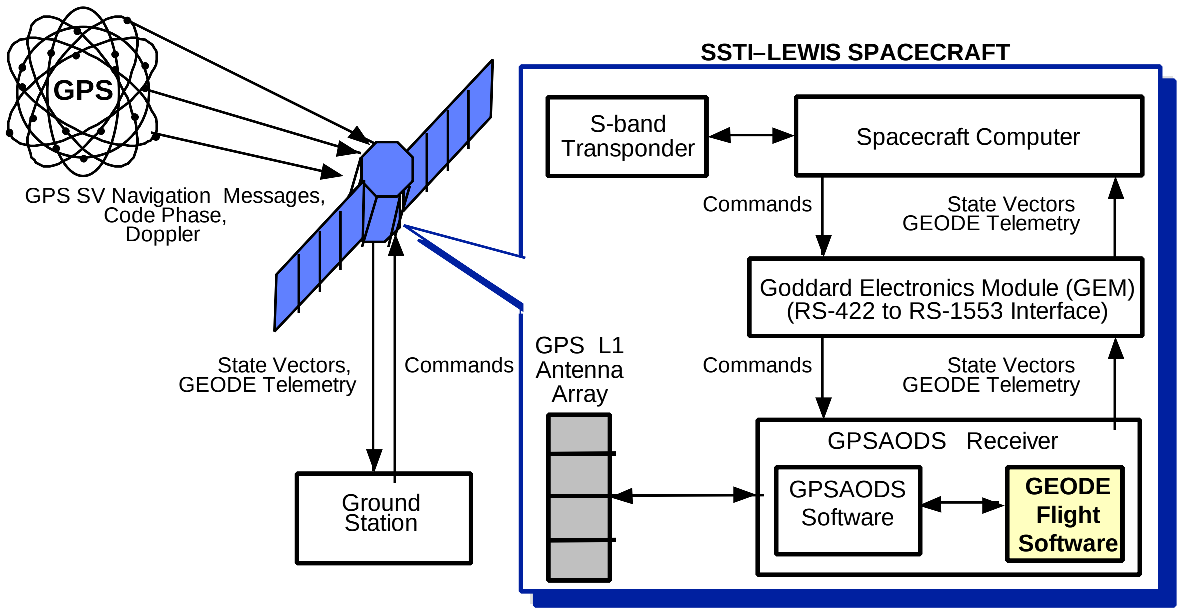

Figure 1. Planned GADFLY/GEODE Configuration on SSTI Lewis

500 milliseconds. The receiver measures the Doppler shift of the signal from the GPS SV to the user spacecraft in terms of the GPS C/A carrier phase delay averaged over 500 milliseconds. Each receiver channel can continuously track one GPS SV to provide a maximum of nine pseudorange, Doppler, and carrier phase measurements made essentially simultaneously (i.e., within 1 millisecond). With SA at typical levels, the GPSAODS receiver should provide either real-time unfiltered (50 percent probability that position error ≤ 100 meters) or Tensor-filtered (mean position error ≤ 50 meters) state vectors and precise time (less than 1 microsecond error with respect to GPS time) via a 1-pulse-per-second discrete output to the Lewis spacecraft, when GPS data are available. References 4 and 5 provide a detailed discussion of the GPSAODS receiver capabilities.

The GEODE flight software was designed to be hosted on one of the receiver's digital Receiver Processor Units (RPUs), a RAD6000 RISC microprocessor operating at 20 megahertz, and integrated with the GPSAODS flight software components. However, because the accelerated development schedule for SSTI Lewis will not provide sufficient time to integrate and validate the GEODE flight software after delivery of the GPSAODS receiver, implementation of the GEODE flight software on the primary spacecraft computer is now being pursued. If the launch schedule does not allow sufficient time for this implementation, downlinked GPS measurements will be processed using the GEODE flight software hosted on a surrogate flight computer.

The primary scientific instrument on SSTI Lewis is the Hyperspectral Imager (HSI), which drives the mission and spacecraft requirements. The HSI absolute ground-sample along-track/cross-track position knowledge requirement is allocated as ≤ 150/150/230 meters (3σ) in along-track/cross-track/radial position, ≤ 10/30/50 arc-seconds (3σ) in roll/pitch/yaw, and ≤ 2 milliseconds (3σ) in data timetag error. The GPSAODS Tensor receiver will provide a filtered solution that should satisfy the onboard position and time requirements. However, the HSI has set a 70-meter (3σ) total position accuracy goal to meet its enhanced science objectives and would therefore benefit from the improved orbit determination accuracy provided by GEODE.

In addition to providing enhanced position accuracy for the HSI instrument, GEODE provides highly accurate velocity solutions, which are particularly important when the state vectors are used for orbit prediction. The enhanced GEODE spacecraft states can be propagated accurately for science planning and scheduling, eliminating the cost of any additional ground-based orbit determination postprocessing.

GEODE NAVIGATION ALGORITHMS

The GEODE flight software builds on proven technology to achieve a significant accuracy improvement compared with geometric GPS solutions. The GSFC FDD defined the GEODE navigation algorithms based on mature onboard navigation systems developed for spacecraft using NASA's space and ground communications systems. The highly successful experiment on the EP/EUVE spacecraft flight qualified high-accuracy algorithms for autonomous navigation using the Tracking and Data Relay Satellite System (TDRSS) and/or ground station carrier signals (Reference 6). The Earth Observing System-AM1 (EOS-AM1) is implementing a TDRSS Onboard Navigation System (TONS) as the prime operational navigation system (Reference 7), with a total position accuracy goal of 25 meters (1σ).

The FDD onboard navigation algorithms consist of the following core components:

- An extended Kalman filter augmented with physically representative models for the gravity, atmospheric drag, and time bias and drift state process noise to provide a realistic state error covariance
- A high-fidelity state dynamics model to reduce sensitivity to measurement errors and provide high-accuracy velocity estimates, permitting accurate state prediction during signal outages or degraded coverage

For GEODE, these core onboard navigation algorithms were augmented with the following new capabilities:

- GPS pseudorange and Doppler measurement models
- Initialization and enhanced fault detection capabilities using instantaneous geometric GPS solutions
- Sampling of available measurements to reduce the impact of SA, such that measurements from a single GPS SV are processed no more frequently than a specified minimum interval

Reference 8 indicates that the impact of SA clock dithering on the pseudorange measurement is approximately 30 meters (1σ), with a correlation time of approximately 5 minutes. The impact on the Doppler measurement is approximately 0.15 meter per second. For GEODE, measurements from a specific SV are sampled nominally at a 5-minute rate to reduce the correlation between the SA-induced measurement errors, and SA clock dithering is treated as white noise without the addition of filter states or colored noise models. Table 1 summarizes the set of algorithms selected to meet the GEODE navigation performance goals. Detailed mathematical specifications are defined in Reference 9.

To significantly reduce peak central processing unit (CPU) usage, GEODE navigation processing is segmented into the following two tasks:

- Real-time state prediction to the next whole coordinated univeral time (UTC) second, which is executed in the foreground every second to produce the real-time state data output packets
- State vector estimation, which is executed in the background nominally every 30 seconds to propagate the current state estimate and to correct the current state using the sampled GPS tracking measurements

Algorithm Type	Algorithm
Primary coordinate system	· Mean equator and equinox of J2000.0 with analytic coordinate transformations
Primary time system	· Coordinated universal time (UTC)
Numerical integrator	· Runge-Kutta 4th-order
Filter spacecraft acceleration model	· Joint Gravity Model-2 (JGM-2) nonspherical geopotential up to degree 30 and order 30 · Earth, solar, and lunar point masses with analytic ephemeris · Analytic representation of Harris-Priester atmospheric density
Spacecraft state transition matrix	· Semianalytic formulation including J_2 and Earth point mass acceleration partial derivatives
Estimator	· Extended Kalman filter with physically realistic process noise and factored covariance matrix
Estimation state	· User position and velocity vectors · Atmospheric drag coefficient correction · GPS receiver time bias and time bias drift corrections
State process noise model	· Earth gravity model errors · Random walk model for atmospheric drag correction and time reference bias and drift · Maneuver position and velocity variances uplinked prior to maneuver
Measurement model	· GPS pseudorange and Doppler with GPS receiver time and time bias and drift corrections · Geometrical editing of measurements with high ionospheric errors
Real-time space-craft acceleration model	· Earth point mass and J_2

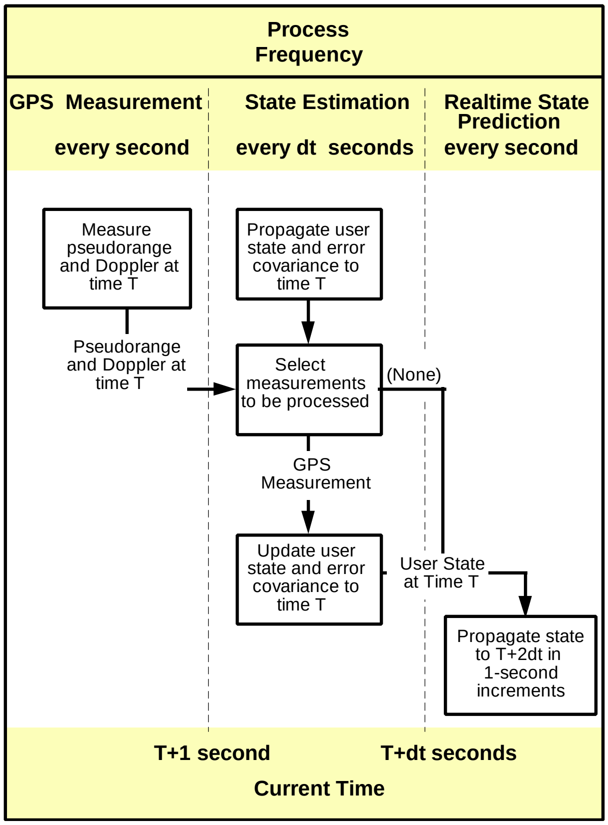

Figure 2. GEODE Navigation Processing Scenario

Figure 2 provides an overview of this processing scenario. In this figure, dt is the time interval between state vector propagations by the GEODE estimator, nominally equal to 30 seconds. GPS measurement, state estimation, and real-time prediction processing are performed in parallel for different time periods. The GPS measurement process and real-time prediction occur once per second. GEODE state estimation is performed at regular intervals, e.g., measurements are processed every 30 seconds, with intermediate propagation of the filter state vector at smaller intervals if needed to maintain prediction accuracy.

FLIGHT SOFTWARE DEVELOPMENT

The GEODE flight software is being developed to be portable and modular to facilitate reuse on other missions and incorporation in other GPS receivers or spacecraft processors. The primary development platform is a Sun Sparcstation 10 using the Solaris 2.3 operating system. Ada83 was selected as the programming language to maximize reuse from the TONS flight software, which was implemented in Ada83.

The following resource goals for the GEODE flight software were defined based on the resources available on candidate spacecraft processors:

- Maximum memory utilization limited to 100 kilobytes (KB) of random-access memory (RAM) and 300 KB of read-only memory (ROM)
- Peak CPU utilization limited to 0.5 million instructions per second (MIPS)

The guiding principle behind the GEODE flight software design was to use an object-oriented approach to partition the software in a manner to insulate the core navigation modules by allocating the host-specific functions to the GEODE interface packages. This modular design promotes high reuse of GEODE software in different spacecraft computer configurations, because only the interface modules will require adaptation to the new host hardware/software configuration.

The core navigation modules (Ada packages) that perform the orbit propagation and estimation processing were reused verbatim from the TONS flight software. New modules were designed to provide the GPS SV and tracking data models (Doppler and pseudorange), GPS SV selection, and fault detection functions and to provide an interface compatible with the flight executive of GEODE's host processor.

For integration with the GPSAODS receiver, a Tensor-compatible interface is needed that includes a common memory access package. The proposed integrated GPSAODS/GEODE flight software architecture is shown in Figure 3. In this architecture, the GEODE flight software receives command data via uplink packets that are processed by the GPSAODS executive and loaded into a shared RAM segment. GPS pseudorange and Doppler measured by the Tensor, GPS SV ephemeris and clock parameters, and the Tensor orbital solutions are made available to the GEODE flight software via the shared RAM segment. The GEODE-computed user spacecraft orbit solution is output to the shared RAM segment and could replace the Tensor solution that is nominally output by the Tensor unit to the SSTI Lewis spacecraft computer.

If the GEODE flight software is hosted on the primary spacecraft computer, an interface compatible with the spacecraft's flight executive would be needed to initiate the GEODE processing tasks; to input GEODE commands and GPSAODS packets containing measurements, GPS SV ephemeris and clock data, and orbit solutions; and to output GEODE telemetry packets. The choice of using the GPSAODS or GEODE-computed user spacecraft solution would be determined by ground command.

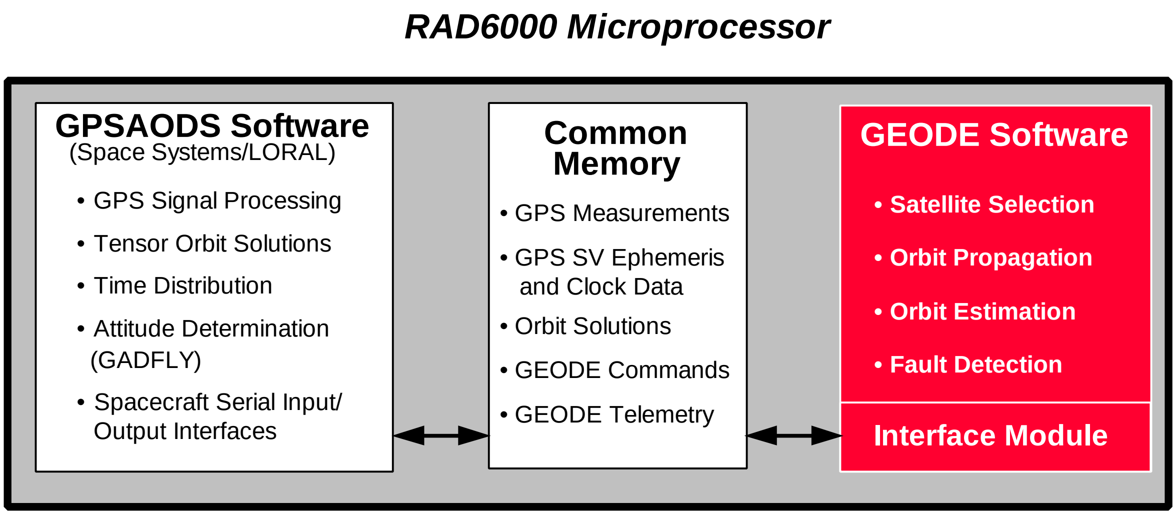

Figure 3. Integrated GPSAODS/GEODE Flight Software Architecture

PREFLIGHT PERFORMANCE ASSESSMENT

To project the expected performance of the GEODE flight software for SSTI Lewis, the GEODE flight software was used to process GPS pseudorange measurements obtained from experimental receivers flown on the EP/ EUVE and TOPEX/POSEIDON (T/P) spacecraft. In addition, experiments were performed using simulated GPS code phase and Doppler measurements to investigate GEODE flight software performance in the presence of impulsive maneuvers and for receivers with poor constellation visibility. The results from these investigations are provided in this section.

EUVE Measurement Processing

A prototype GPS Demonstration Receiver (GPSDR), provided by Motorola Corporation, is being flown as a navigation experiment on the EP/EUVE spacecraft, which has a 525-kilometer-altitude, 28-degree-inclination, circular mission orbit. This GPSDR is a 12-channel single-frequency (L1) receiver tracking carrier and P-code, with six channels dedicated to each of two antennas separated by about 2 meters. The receiver has no multipath protection and has a low-stability time reference with a clock drift rate on the order of 1×10^{-6} seconds per second.

The GEODE flight software was used to process raw GPS pseudorange measurements extracted onboard EUVE for the September 22–24, 1992 timeframe, during which SA was active. Ground station point solutions during this time period show a dispersion on the order of 100 meters (1σ), confirming that SA was significant. To emulate the onboard real-time processing environment, GPS broadcast ephemeris and clock data were used and no external data smoothing or editing were performed. The total root-mean-square (RMS) position errors in the GPS broadcast ephemerides ranged from 4 to 14 meters. One pseudorange measurement was processed every 30 seconds, with measurements selected such that measurements from a specific GPS SV were processed no more frequently than every 300 seconds.

The resulting GEODE solutions were compared with reference solutions provided by the Jet Propulsion Laboratory (JPL), based on their ground-based postprocessing of the GPS measurements using differential GPS techniques. These 30-hour GPS-derived solutions had 6-hour overlap RMS differences of approximately 5 meters for the time period processed (Reference 10).

The GEODE filter was initialized using a state vector obtained from GPSDR's geometric solution. During the 4-hour period required to reach steady-state performance, the total position differences did not exceed 50 meters. After the filter convergence period, the total root-sum-square (RSS) position and velocity differences between the GEODE and reference solutions were 9.7 meters (RMS) and 11.1 millimeters per second (RMS), respectively. Figure 4 shows the RSS position differences for this 2-day period. This performance is comparable to the 14.4-meter RMS position differences for the same time period reported in Reference 11 for the best real-time solutions, which used both pseudorange and carrier phase measurements with a 50×50 JGM-2 gravity field.

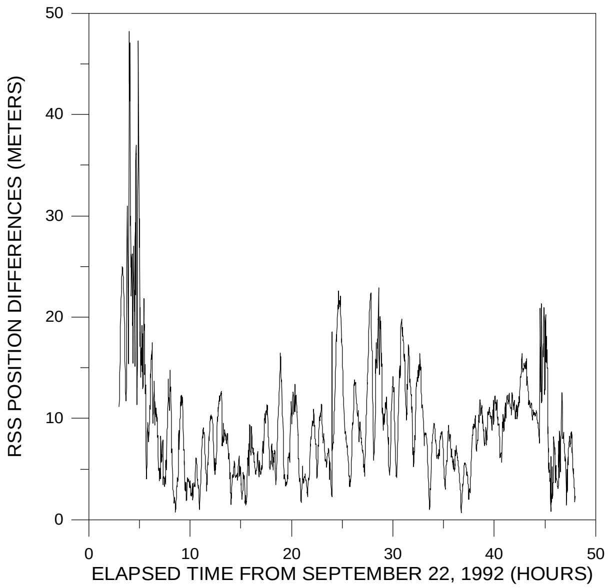

Figure 4. GEODE Versus GPS-Differential Position Differences for EUVE

TOPEX/POSEIDON Measurement Processing

A dual frequency Motorola GPS receiver is also being flown as a navigation experiment on the T/P spacecraft, which has a 1336-kilometer-altitude, 66-degree-inclination, circular mission orbit. This GPS receiver is a six-channel dual frequency receiver, tracking carrier and C/A-code. The receiver has a moderate stability time reference with a clock drift rate on the order of 5×10^{-8} seconds per second. The GEODE flight software was used to process raw pseudorange measurements for the November 17–20, 1993, timeframe, during which SA was active on only six GPS SVs. One pseudorange measurement was processed every 30 seconds, with measurements selected such that measurements from a specific GPS SV were processed no more frequently than every 210 seconds. Broadcast GPS SV ephemeris and clock data were used, and external measurement smoothing or editing was not performed.

The resulting GEODE solutions were compared with the T/P Precise Orbit Ephemerides (POEs) developed by JPL personnel using differential GPS measurements. The T/P POEs have an estimated accuracy of better than 0.5 meter in total position. The GEODE filter was initialized using a state vector obtained from GPSDR's geometric solution. During the 4-hour period required to reach steady-state performance, the total position differences did not exceed 50 meters. After the filter convergence period, the total RSS position and velocity differences between the GEODE and reference solutions were 7.8 meters (RMS) and 5.9 millimeters per second (RMS), respectively.

Maneuver Tests

The capability of the GEODE flight software to handle spacecraft stationkeeping maneuvers was also verified. GPS pseudorange and Doppler measurements were simulated for the 517-kilometer-altitude, 97-degree-inclination, circular nominal Lewis orbit, using the postfacto definitive GPS SV ephemerides. Two impulsive maneuvers were modeled, each with a velocity change of 0.35 meter per second, separated by 47 minutes. A low stability time reference was modeled using a clock drift rate of 5×10^{-8} seconds per second and a large random walk error of 3×10^{-8} seconds (1σ). SA effects were included at a level of 23 meters (1σ).

The GEODE flight software was used to process measurement pairs selected such that measurements from a specific GPS SV were processed no more frequently than every 300 seconds. Broadcast GPS SV ephemeris and clock data were used to emulate a real-time processing environment. The impulsive maneuvers were not modeled in the state propagation; however, the maneuver process noise was included in the propagation of the state covariance matrix. Note that without the addition of the maneuver process noise, the filter would rapidly diverge.

The resulting GEODE solutions were compared with the truth ephemeris used in the data simulation. The GEODE filter maintained an total position accuracy of better than 200 meters throughout the maneuver sequence and returned to the premaneuver accuracy of better than 10 meters (1σ) within 2.5 hours. It is expected that more accurate solutions could be obtained during the maneuver timespan if the maneuver is explicitly modeled in the state propagation using either thruster measurements or the commanded thruster on/off times and magnitudes.

Poor Visibility Tracking Tests

GEODE flight software performance was also investigated for the case of a proposed mission that is to use one antenna with a 60-degree field of view about the zenith, limiting GPS SV visibility to no more than three in view at any time. GPS pseudorange and Doppler measurements were simulated for a 400-kilometer-altitude, 28.5-degree-inclination, circular spacecraft orbit, using the postfacto definitive GPS SV ephemerides. A low stability time reference was modeled using a clock drift rate of 5×10^{-8} seconds per second and a large random walk error of 3×10^{-8} seconds (1σ). SA effects were included at a level of 23 meters (1σ).

The GEODE flight software was used to process measurement pairs selected such that measurements from a specific GPS SV were processed no more frequently than every 300 seconds. This produced an average

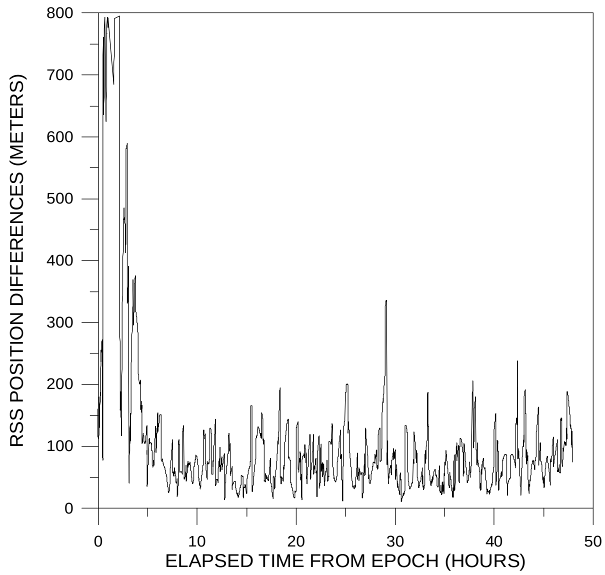

Figure 5. GEODE Versus Truth Position Differences for Poor Visibility Tracking Case

measurement processing rate of one pair every 320 seconds. Typically, only one or two GPS SVs were visible, with intervals of up to 25 minutes when no SVs were visible. Broadcast GPS SV ephemeris and clock data were used to emulate a real-time processing environment. The resulting GEODE solutions were compared with the truth ephemeris used in the data simulation. After the filter convergence period (approximately 5 hours in which the measurement gaps total to 1 hour), the RSS position difference between the GEODE and reference solutions was 85 meters (RMS). Figure 5 shows the RSS position differences for this 2-day period.

Performance Summary

The EUVE and T/P comparisons verify that the GEODE filter, with its high-fidelity dynamic model, provides a highly reliable onboard navigation capability. The GEODE filter automatically edited erroneous measurements and measurements from GPS SVs with out-of-range broadcast GPS ephemerides or clock corrections and significantly reduced the effects of SA corruption and ionospheric errors. In addition, these comparisons indicate that the GEODE flight software algorithms can provide 10-meter (1σ) position and 10-millimeter per second (1σ) velocity accuracy using only pseudorange measurements from an SPS receiver, which is significantly better than the performance goal for GEODE for SSTI Lewis. Some accuracy improvement is expected with the addition of Doppler measurements.

The maneuver test verifies that the GEODE algorithms can maintain accurate performance following a maneuver sequence if the approximate maneuver times and magnitudes are used to model the associated state process noise covariance. The poor visibility test demonstrates that the GEODE algorithms can provide a highly reliable onboard navigation capability even in the case of a tracking scenario for which the standard geometric point solution processing would not be possible.

In all these investigations, the GEODE navigation performance was found to be insensitive to moderate adjustments in the filter process noise model parameters. Filter tuning consisted primarily of adjusting the measurement standard deviation to reflect the presence/absence of SA and adjusting the time bias and drift process noise spectral density to reflect the quality of the receiver's time reference.

ON-ORBIT PERFORMANCE ASSESSMENT

After launch of SSTI Lewis, the GSFC FDD will assess the on-orbit performance of the GADFLY/GEODE orbit solutions. An initial accuracy assessment will be performed by comparing the GPSAODS and GEODE solutions with moderately accurate definitive solutions obtained using S-band ground network tracking data. These S-band tracking solutions are expected to provide total position accuracies in the 25- to 50-meter (1σ) range. Subsequently, an in-depth accuracy assessment will be performed by comparing the GPSAODS and GEODE solutions with high-accuracy (i.e., submeter) solutions obtained by differential postprocessing of the Tensor GPS measurements together with GPS measurements obtained through the International GPS Service (IGS). In addition, the noise and bias characteristics of the GPSAODS pseudorange and Doppler measurements will be analyzed. Figure 6 illustrates the ground processing associated with this assessment.

FUTURE DIRECTIONS

Currently, roadblocks to the use of GPS on NASA spacecraft include lack of standardization in the products available from commercial GPS receivers and lack of reusable GPS navigation flight software and ground support software. To promote rapid, cost-effective deployment of GPS technology, the GSFC FDD and Mission Operations Division jointly investigated the feasibility of developing modular navigation software to support both flight and ground support applications. Development of reusable autonomous navigation system components is in progress (References 12 and 13).

Future directions for GSFC FDD's GPS autonomous navigation initiatives are (1) to investigate algorithm

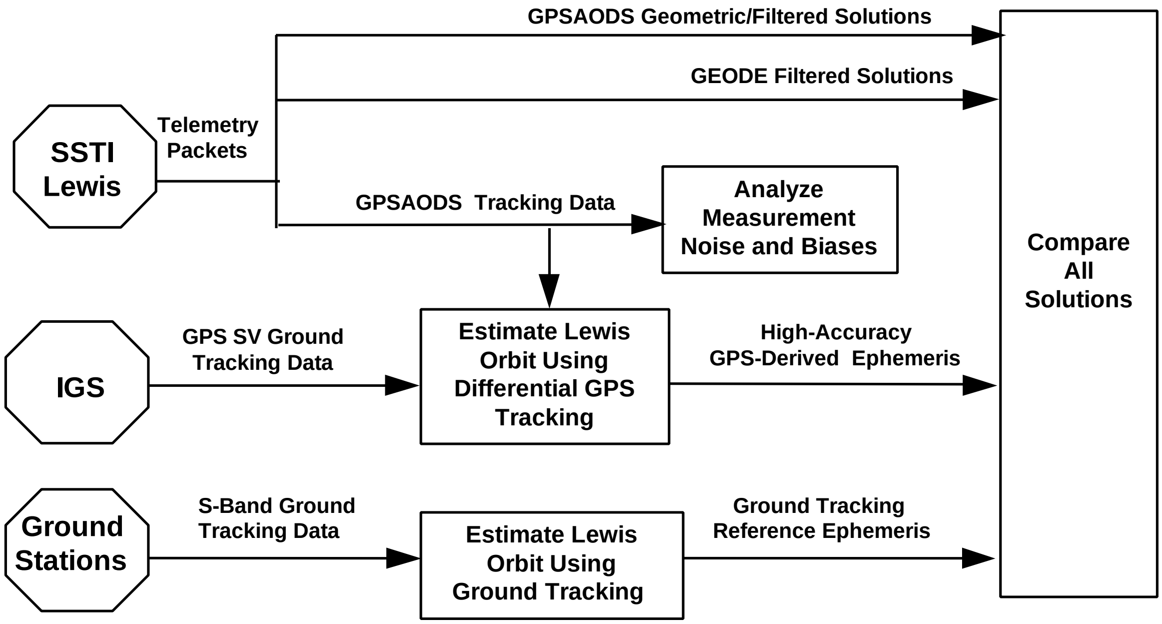

Figure 6. GADFLY/GEODE Orbit Performance Assessment Plan

enhancements to improve onboard accuracy using GPS, (2) to participate in a cooperative effort to build a NASA miniaturized GPS receiver, and (3) to extend the autonomous navigation applications to other flight applications such as high-eccentricity orbits and relative navigation using GPS. The GSFC FDD is also investigating the benefits of using the Federal Aviation Agency's Wide Area Augmentation System (WAAS) to further improve GPS real-time navigation accuracy and integrity.

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