TDRSS Onboard Navigation System (TONS) Flight Qualification Experiment*

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Abstract

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) is currently developing an operational Tracking and Data Relay Satellite (TDRS) System (TDRSS) Onboard Navigation System (TONS) to provide realtime, autonomous, high-accuracy navigation products to users of TDRSS. A TONS experiment was implemented on the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) spacecraft, launched June 7, 1992, to flight qualify the TONS operational system using TDRSS forward-link communications services. This paper provides a detailed evaluation of the flight hardware, an ultrastable oscillator (USO) and Doppler extractor (DE) card in one of the TDRSS user transponders, and the ground-based prototype flight software performance, based on the 1 year of TONS experiment operation. The TONS experiment results are used to project the expected performance of the TONS I operational system. TONS I processes Doppler data derived from scheduled forward-link S-band services using a sequential estimation algorithm enhanced by a sophisticated process noise model to provide onboard orbit and frequency determination and time maintenance. TONS I will be the prime navigation system on the Earth Observing System (EOS)-AM1 spacecraft, currently scheduled for launch in 1998.

Inflight evaluation of the USO and DE short-term and long-term stability indicates that the performance is excellent. Analysis of the TONS prototype flight software performance indicates that realtime onboard position accuracies of better than 25 meters root-mean-square are achievable with one tracking contact every one to two orbits for the EP/EUVE 525-kilometer altitude, 28.5-degree inclination orbit. The success of the TONS experiment demonstrates the flight readiness of TONS to support the EOS-AM1 mission.

Introduction

The Tracking and Data Relay Satellite (TDRS) System (TDRSS) provides National Aeronautics and Space Administration (NASA) low Earth-orbiting spacecraft with telemetry, command, and tracking services. These user spacecraft require position, time, and frequency knowledge to maintain precise attitude control, antenna pointing to each TDRS, and operational health and safety and to annotate their science data. Currently, TDRSS supports user orbit, frequency, and time determination through ground-based extraction and processing of range and either two-way or one-way return-link Doppler tracking data. Future TDRSS user mission profiles forecast the need for onboard, realtime, high-accuracy position knowledge to 10 meters (1σ), time determination to 1 microsecond (1σ), and frequency determination to 1 part in 10^{12} (1σ). These missions also require systems that can be easily integrated into a user's onboard environment, with minimal power, weight, and volume penalty to the spacecraft subsystems and low budgetary impact. The TDRSS Onboard Navigation System (TONS), developed by NASA, can meet these objectives via the onboard extraction of high-fidelity tracking measurements from a forward-link signal using components already available on a TDRSS user spacecraft.

The ultimate objective is to develop an autonomous user navigation system that (1) supports accurate onboard orbit, time, and frequency determination, based on observation of a continuously available, unscheduled navigation beacon signal; (2) decreases the user's reliance on TDRSS ground operations and scheduled TDRSS resources; and (3) provides

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sufficient failure recovery modes to maintain or extend the user lifetime to accomplish science objectives. TONS is being developed in stages: the one-way return-link Doppler navigation experiment hosted on the Cosmic Background Explorer (COBE) spacecraft; the TONS experiment successfully flown on Explorer Platform (EP)/Extreme Ultraviolet Explorer (EUVE); and the TONS I, TONS II-A, and TONS II operational systems. This paper discusses the TONS experiment implementation and provides an assessment of the performance of the TONS hardware and software components as the predecessor to an operational TONS I implementation.

TONS Development

Future NASA mission navigation requirements, such as those for the Earth Observing System (EOS)-AM1 mission, point to the need for autonomous onboard navigation. By offering various levels of upgrades to TDRSS user spacecraft and TDRSS capabilities, TONS allows corresponding increases in the degree of user navigation autonomy, navigation services, and failure recovery modes. In addition, TDRSS onboard navigation options will provide graceful degradation modes to maintain user autonomy and/or extend spacecraft mission lifetime, with little impact on the user spacecraft itself. The operations concept for each of the TONS stages is explained in Reference 1 and is summarized below.

The first stage was the navigation experiment on the COBE spacecraft, in which an external ultrastable oscillator (USO) provided a reference frequency to a second-generation TDRSS user transponder to supply accurate one-way return-link Doppler measurements for ground-based orbit and frequency determination. This experiment demonstrated that one-way return-link noncoherent Doppler tracking provides equivalent accuracy to two-way coherent Doppler tracking. This tracking method became operational on COBE and later on the Ocean Topography Experiment (TOPEX)/Poseidon spacecraft. Processing accurate one-way and two-way Doppler tracking of TOPEX provided orbit determination accuracies of better than 10 meters (3σ).

Components for the TONS experiment were integrated into the EP, launched with the EUVE on June 7, 1992. The TONS experiment provided an opportunity to flight qualify TONS by processing Doppler measurements extracted on-orbit in a ground-based flight-emulation environment. The TONS experiment required an S-band multiple-access (MA) or S-band single-access (SA) forward-link scheduled reference signal from TDRSS, a Doppler extractor (DE) card in the second-generation TDRSS user transponder, a USO, and a ground-based navigation processor to process the Doppler measurements downlinked in the user spacecraft telemetry. In addition, software onboard the user spacecraft demonstrated onboard control of user signal acquisition. TDRS ephemerides, computed separately on the ground, are provided as input to the navigation processor. The TONS experiment provided a ground-based version of user spacecraft orbit and frequency determination and onboard control of user signal acquisition, necessary for an operational TONS system.

TONS I uses Doppler measurements derived from an S-band forward-link scheduled TDRSS service to provide onboard orbit and frequency determination and uses the frequency bias estimate for onboard time maintenance. The timetag of the pseudorandom noise (PN) code epoch received by the transponder is used in the User Spacecraft Clock Calibration System (USCCS) to perform time determination on the ground. Figure 1 illustrates the TONS I navigation scenario. TONS I requires the user to have a stable frequency reference, a Doppler measurement capability and PN code epoch receipt timetagging in the user transponder, and onboard navigation processing and signal acquisition software. TONS I is compatible with the current TDRSS configuration and currently available user spacecraft components.

TONS II-A is an augmented version of TONS I that provides the user spacecraft with additional Doppler measurements derived from a forward-link S-band beacon signal, when the TDRSS service is not scheduled for a user, to provide nearly continuous, realtime orbit and frequency determination. This signal can be provided by the current TDRSS using the interservice radiated multiple-access signal available between scheduled user services. The interservice signal is available about 80 percent of the time. Figure 1 also illustrates the TONS II-A navigation scenario with the beacon signal.

All TONS-related upgrades to TDRSS are being designed to be transparent to the standard TDRSS user. The TONS I system is discussed in more detail in Reference 2.
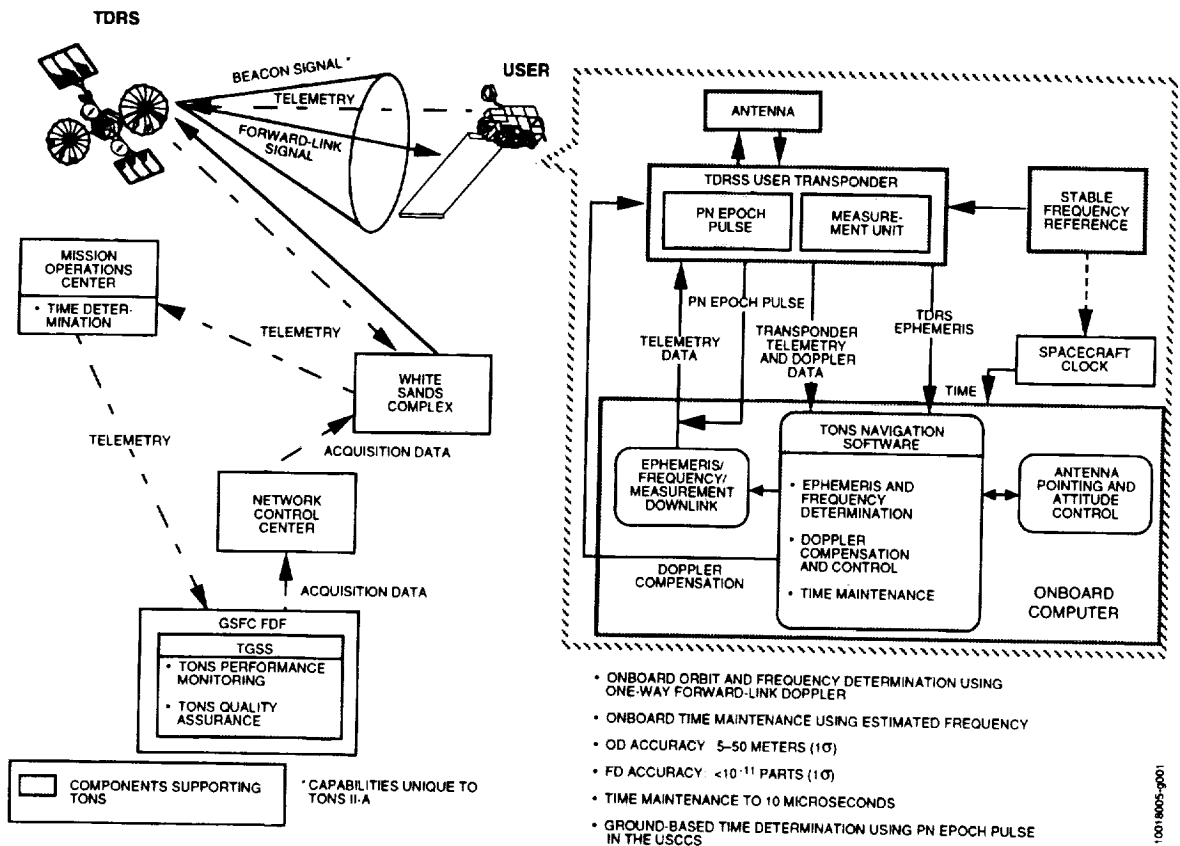
Figure 1. TONS Navigation Scenarios

TONS Experiment Description

The TONS experiment involves flight systems onboard EP/EUVE and ground systems for experiment data processing and performance analysis. Figure 2 provides an overview of the TONS experiment configuration. During the 1 year of the TONS experiment, all major experiment objectives were accomplished:

- The TONS flight hardware components, the USO and DE card, were successfully activated and provided excellent performance well within specifications.

- The onboard Doppler compensation (OBDC) application resident in the EP/EUVE 1750A coprocessor was successfully activated and demonstrated onboard signal acquisition for more than 90 TDRSS contacts with a 100-percent success rate.

- The accuracy and processing efficiency of the TONS prototype flight software was demonstrated using the Doppler measurements extracted onboard.

- Modifications to the baseline TONS navigation algorithms were evaluated with respect to improved accuracy and processing efficiency.

- The accuracy of the TONS prototype flight software was verified by comparison with independent high-accuracy EP/EUVE ephemerides determined by Jet Propulsion Laboratory (JPL) personnel by processing Global-Positioning-System (GPS)-derived measurements.

This paper discusses these accomplishments and presents the conclusions and recommendations. Detailed discussions are provided in References 3 and 4.

The EP, TDRSS, and ground segments for the experiment are described in the following paragraphs. The space and ground segments of this configuration are described in detail in References 5 through 8.
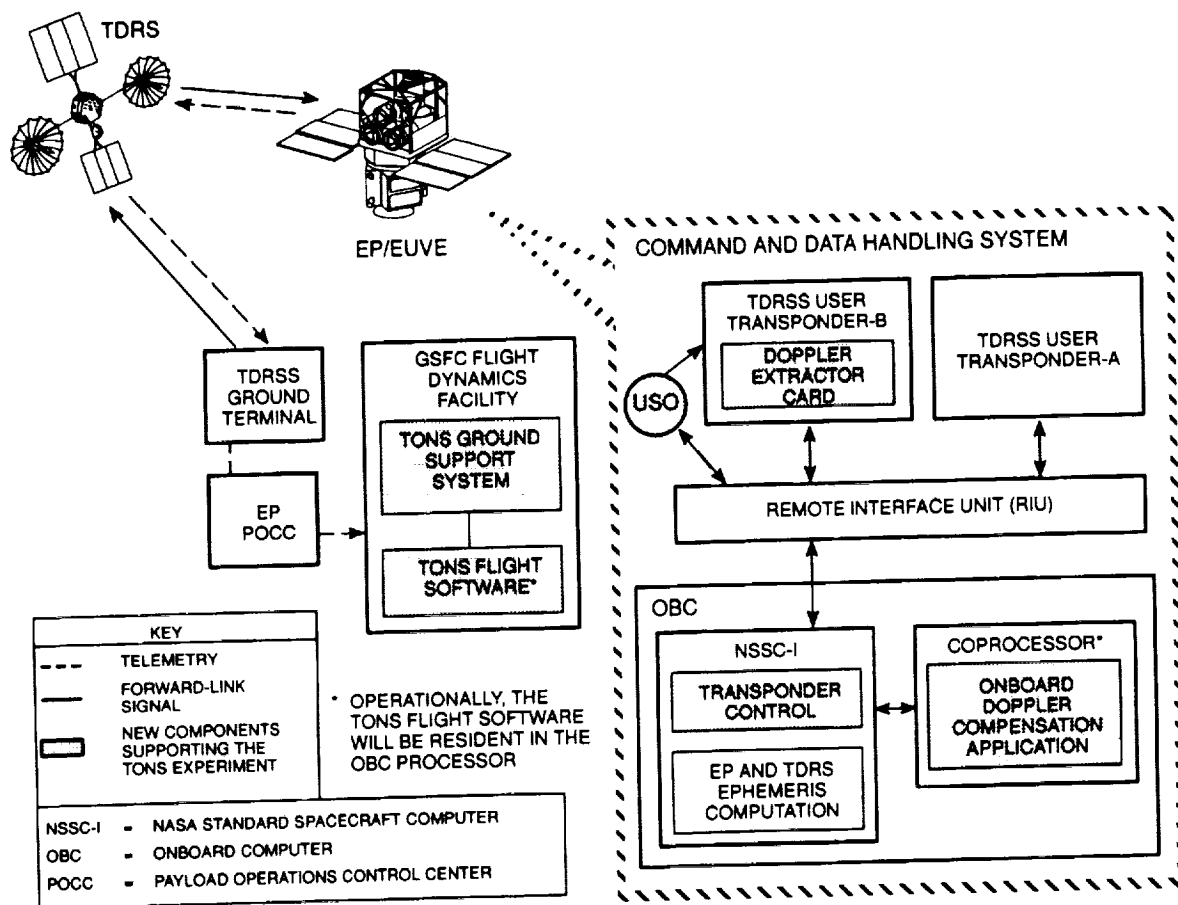
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Figure 2. TONS Experiment Overview

EP and TDRSS Segments

Two second-generation TDRSS user transponders are onboard EP/EUVE, one of which, Transponder-B, is augmented with a DE card. An external USO supplies a stable frequency reference to Transponder-B for Doppler measurement. Both the transponder and the USO are controlled via a Remote Interface Unit (RIU) on EP. The transponder/DE/RIU configuration implemented for the TONS/EUVE experiment is not optimal. Three different oscillators provide the timing and frequency references supporting the Doppler measurement, Doppler count accumulation, and telemetry data collection operations via the RIU. This configuration produces unnecessary timing ambiguities.

The transponder's microprocessor sends 24-bit frequency control words (FCWs) to the receiver's numerically controlled oscillator (NCO) every 500 microseconds to maintain lock with the received TDRSS forward-link signal. The DE card accumulates 20480 of these internal FCWs to a resolution of 0.01 hertz at S-band in a 40-bit accumulator. The aggregate count is latched at 10.24-second intervals.

The nondestruct 40-bit Doppler count measurement, along with additional transponder status telemetry bits, is placed in the EP/EUVE downlink engineering telemetry stream and transmitted to the Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) via the POCC. The average Doppler frequency over 10.24 seconds is computed from the nondestruct Doppler counts and processed using the TONS prototype flight software to estimate the EP/EUVE orbit and onboard reference (USO) frequency offset.

In addition, EP/EUVE has the capability for onboard Doppler compensation and control of TDRSS forward-link signal acquisition to within the transponder's ± 1500-hertz bandwidth using an OBDC application resident in the EP/EUVE coprocessor (a MIL STD 1750A microprocessor) and stored commands. The OBDC application computes the predicted instantaneous Doppler shift of the forward-link signal based on TDRS and user spacecraft vectors and converts the

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predicted shift to an external transponder FCW. This 16-bit FCW is input as a serial command to the transponder and is updated every 8.192 seconds on EP/EUVE throughout the contact. At EP/EUVE's maximum Doppler rate of 55 hertz per second, an 8.192-second update rate changes the FCW to offset the receiver by approximately 450 hertz. After the transponder achieves signal acquisition, new FCWs are processed only if the receiver loses lock. The OBDC process replaces the current method of signal acquisition, in which the ground terminal must dynamically compensate the forward-link signal to eliminate the apparent Doppler shift at the spacecraft. The POCC then requests that this frequency variation be inhibited when acquisition is verified so that a valid tracking service can be initiated.

EP/EUVE also hosts a Motorola GPS Demonstration Standard Positioning System (SPS)/L1 receiver/processor (GPSDR) assembly unit as a secondary experiment in the Payload Equipment Deck (PED). The downlink telemetry includes the GPS tracking measurements, which were used by JPL experimenters to determine a high-accuracy EP/EUVE solution in a sophisticated ground-based system.

Experiment Ground Segment

To support the ground-based flight demonstration, the GSFC/Flight Dynamics Division (FDD) developed the TONS Ground Support System (TGSS) and TONS prototype flight software. The TGSS processes the EP/EUVE telemetry data, analyzes tracking data quality, and provides tools for assessing performance of the onboard hardware and software experiment components. The TONS prototype flight software performs the navigation processing in an emulated flight environment created by the TGSS. The TONS flight software schedules and executes the navigation processing tasks, including the processing of TDRSS one-way forward-link Doppler measurements and other data required by the navigation algorithm (e.g., TDRS ephemerides, tracking schedule), state vector propagation and estimation, Doppler compensation prediction, and output of navigation-related data. The design for the TGSS and prototype flight software is presented in Reference 6.

The flight software environment approximates the flight processing environment on EP/EUVE to achieve a major objective of the TONS experiment, i.e., developing and demonstrating the prototype TONS I flight software. The prototype flight software was developed in Ada on a Digital Equipment Corporation (DEC) MicroVAX 3100. The software was crosscompiled using the Tartan Ada crosscompiler for execution in the onboard coprocessor, a MIL STD 1750A architecture microprocessor that runs at 15 megahertz and executes at a peak rate of approximately 2 million instructions per second (MIPS). In the TONS operational systems, the TONS flight software will reside in the user spacecraft's onboard processor.

The accuracy of the navigation process depends on the quantity and quality of the Doppler measurements extracted onboard, the accuracy of the TDRS ephemerides, and the algorithms and models used for processing. The TONS flight software algorithms were selected (1) to provide a realtime ephemeris accuracy of 10 meters (1σ), with continuous tracking of low Earth-orbiting spacecraft; (2) to require a maximum of 256K bytes for the navigation processing; (3) to consume no more than 20 percent of the available central processing unit (CPU) of a 2-MIPS MIL STD 1750A microprocessor; and (4) to provide operational simplicity and ease of adaptability to a beacon tracking environment. To meet these goals, a sequential estimation algorithm was selected and provided with a sophisticated process noise model to improve performance and robustness. These algorithms are defined in Reference 9.

TONS Experiment Flight Hardware Performance

To support the experiment, EP/EUVE includes the hardware components necessary to perform onboard extraction of accurate one-way forward-link TDRSS Doppler measurements. These components consist of a USO to provide a precision frequency reference for onboard Doppler extraction and a DE card in one of the TDRSS second-generation transponders. Table 1 lists the associated hardware performance specifications and summarizes the measured performance statistics.

The USO performance was monitored and evaluated starting with its power-on on June 9, 1992, 2 days after the EP/EUVE launch. After the stability warm-up period was complete, the USO was selected as the frequency reference for Transponder-B on June 18, 1992. Figure 3 shows the USO's receive frequency offset relative to the nominal S-band receive frequency of 2106.40625 megahertz, estimated based on one-way forward-link Doppler measurements. Note that the increase of approximately 0.6 hertz on December 16 is due to the inclusion of general and special relativistic

Table 1. TONS Flight Hardware Performance

Performance Measure	Specification	On-Orbit Performance
USO long-term drift (parts/day fractional frequency)	1.0×10^{-10}	0.98×10^{-10}[*] 0.81×10^{-10}[**] 0.62×10^{-10}[***]
Allan variance (fractional frequency)	2.0×10^{-12} (USO only, 10-second interval)	2.5×10^{-12} (combined USO and DE, 10.24-second interval)
Doppler noise (hertz-RMS over 10.24-second interval)	0.0033	0.0026

[*] Value on June 18, 1992　　　　[**] Value on November 30, 1992　　　　[***] Value on May 31, 1993
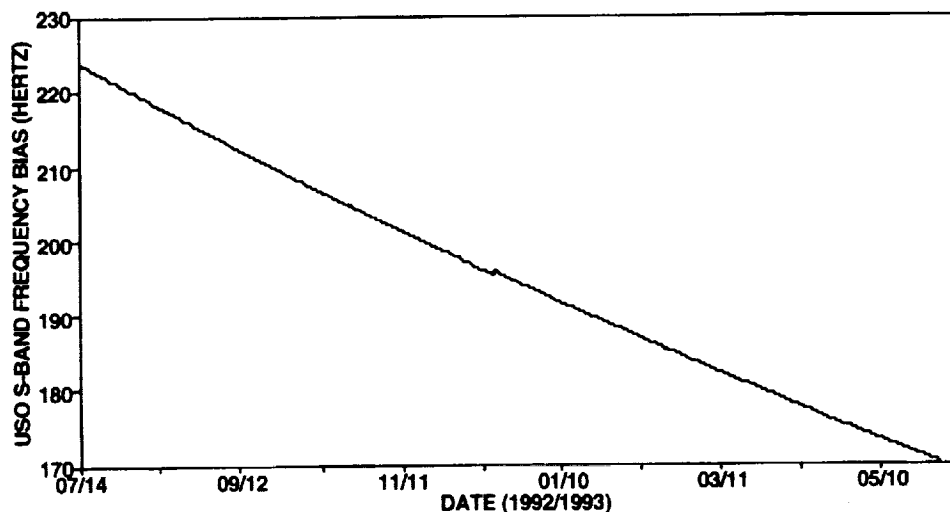
Figure 3. USO S-Band Receive Frequency Offset Estimated From One-Way Forward-Link Doppler Measurements

corrections starting at that time. The systematic characteristic change in the offset is equivalent to a near-linear long-term drift of approximately -0.98×10^{-10} parts per day (or equivalently -0.21 hertz per day) when the USO was selected as the reference frequency, decreasing to -0.62×10^{-10} parts per day (or equivalently -0.14 hertz per day) by May 31, 1993.

DE performance was monitored and evaluated starting with the initial measurements extracted during the first TDRSS contact after launch prior to enabling of the USO. The DE demonstrated excellent performance, producing Doppler measurements of comparable quality to the standard TDRSS two-way and one-way return-link Doppler measurements. Evaluation of the combined USO and DE short-term stability after launch indicates that the Allan variance is on the order of 2.5 parts in 10^{12}. The one-way forward-link Doppler noise is approximately 2.6 millihertz-root-mean-square (RMS) at S-band (2106.40625 megahertz), which is equivalent to 0.35 millimeter per second. The corresponding noise for the one-way return-link Doppler measurements via the Tracking Subsystem at the TDRSS White Sands Ground Terminal (WSGT) is 2.3 millihertz-RMS at S-band. Analysis of TDRSS two-way Doppler measurements for EP/EUVE provided a Doppler noise of 5.2 millihertz-RMS at S-band.

TONS Experiment OBDC Performance

On March 30, 1993, an OBDC acquisition test was performed, in which the application was enabled by a stored command prior to the scheduled TDRSS contact and acquisition was monitored on the ground. In this test, the FCWs computed in the OBDC application were used to shift the transponder center frequency to acquire a fixed-frequency (i.e., 2106.40625 megahertz) forward-link signal transmitted from the TDRSS ground terminal. OBDC proved successful in offsetting the Transponder-B receiver by approximately 38,000 hertz to acquire the signal within the nominal 15 seconds. Comparison of the telemetered FCWs with the measured Doppler shift indicates that OBDC-computed frequency offsets follow the

Doppler measurements to provide an accurate acquisition aid throughout the orbit. During April and May 1993, more than 90 TDRSS contacts were scheduled using OBDC with a 100-percent success rate. Figure 4 illustrates the OBDC application performance during the OBDC acquisition test, in terms of the predicted and measured Doppler shift. The predicted Doppler shift based on the computed FCWs is within ± 150 hertz of the actual frequency compared with the acquisition requirement of ± 1500 hertz.

TONS Experiment Navigation Software Performance

An indepth evaluation of the prototype flight software performance was a primary objective of the TONS experiment. This section presents the performance results using the baseline flight software algorithms, as well as an evaluation of modifications to improve accuracy and efficiency.

TDRS Ephemeris Accuracy

To process the one-way forward-link Doppler measurements, the TONS flight software uses routine TDRS state vectors uplinked daily and postmaneuver state vectors uplinked approximately 2 hours following a TDRS maneuver. During the July 14 through August 31, 1992, time period, the routine TDRS vectors were uplinked at 0:00 coordinated universal time (UTC), 10 hours before the end of the routine operational definitive solution. Starting on September 1, a more operationally realistic procedure was followed in which the routine TDRS vectors were uplinked at 12:00 UTC, 2 hours after the end of the routine operational definitive solution and were then used by the TONS flight software to predict the TDRS positions for the next 24 hours.

Comparison of the 26-hour TDRS-4 (TDRS-East) predictions with the corresponding definitive ephemerides over the January 1 through March 31, 1993, time period, yielded daily maximum differences varying from 10 to 130 meters, excluding predictions through periods with north/south stationkeeping maneuvers. A similar comparison of the 26-hour TDRS-5 (TDRS-West) ephemeris predictions yielded daily maximum differences varying from 10 to 60 meters. A covariance analysis of the routine operational TDRS definitive solutions indicates that ground-to-space ionospheric errors from the Bilateration Ranging Transponder System (BRTS) at the White Sands Complex, measurement noise, and range bias are the dominant error sources in the routine operational TDRS definitive solutions.

EP/EUVE Definitive Ephemeris Accuracy

The accuracy of the TONS flight software is assessed by comparing the flight software solutions with EP/EUVE definitive orbit determination solutions computed daily using a batch-least-squares estimator with high-fidelity modeling. The definitive estimator processed 34-hour spans of standard TDRSS tracking data and used definitive TDRS
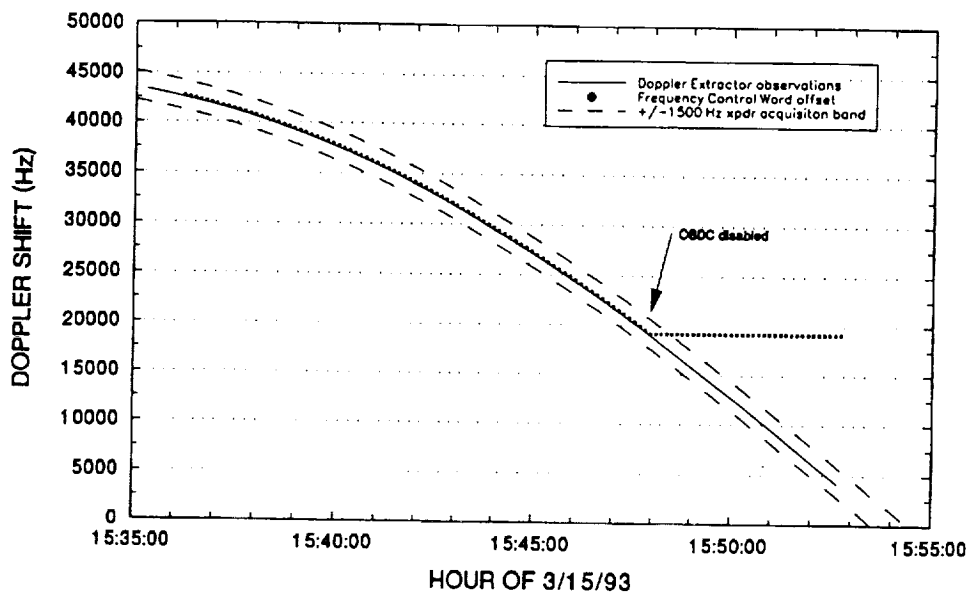

Figure 4. OBDC Performance Results

ephemerides. More accurate orbit propagation models were used in the definitive orbit determination than in the TONS flight software. The definitive solution uses a larger geopotential model [the Goddard Earth Model (GEM)-T3 50 × 50], a Jacchia atmospheric density model with historical solar activity data, solar and lunar ephemerides derived from the Jet Propulsion Laboratory's Development Ephemeris (DE)-200, Earth tides, and polar motion corrections.

A covariance analysis of the EP/EUVE definitive solution accuracy indicates that geopotential modeling error is the dominant error source, followed by TDRS-ephemeris-related errors and TDRS-to-EUVE ionospheric delay. The covariance analysis did not model TDRS-maneuver-induced errors and geomagnetic activity effects. The covariance analysis also indicates that the RMS position differences measured over the overlapping time periods are comparable to the RMS solution errors, indicating that the measurement of overlapping differences provides an approximate estimate of the definitive solution accuracy.

Figure 5 shows the measured daily maximum and RMS overlap position differences of the definitive solutions, for July 14, 1992, through May 31, 1993. In general, the daily maximum overlap differences are below 60 meters, and the daily RMS difference is approximately 20 meters. Large TDRS ephemeris errors arising from TDRS north/south stationkeeping maneuvers and/or large fluctuations in geomagnetic activity occurred on the days for which the maximum and RMS differences were larger than nominal.

To provide an independent check on the accuracy of the EP/EUVE definitive batch-least-squares solutions, these definitive solutions for September 15, 16, 22, 23, and 24, 1992, were compared with JPL-provided high-accuracy solutions computed by processing the GPS measurements from EP/EUVE in a sophisticated ground-based system (Reference 10). The mean differences were about 15 meters RMS and 30 meters maximum, very similar to the corresponding TDRSS definitive overlap differences for the same timeframe. Therefore, based on measured overlap differences, covariance analysis, and comparisons with GPS-derived ephemerides, the accuracy of the definitive batch-least-squares solutions is estimated to be 65 meters (3σ) over the entire experiment timespan, with daily maximum differences always below 130 meters.

Baseline Flight Software Accuracy

Starting on July 14, 1992, the EP/EUVE POCC began to inhibit Doppler compensation during all TDRSS contacts via the high-gain antenna (HGA) when OBDC was not used. The resulting daily TDRSS contact schedule provided six to seven 30-minute coherent passes and six to seven 20-minute noncoherent passes via the HGA. Typically, 10 to 12 of these passes were usable in the TONS flight software; however, on several days there were eight or fewer usable passes, producing data gaps as long as 24 hours. Due to HGA visibility constraints associated with the slowly spinning EP attitude configuration, there was a gap of about 4 to 6 hours each day in the Doppler data that were processed by the TONS flight software prior to January 24, 1993, when the spacecraft attitude was changed to a three-axis stabilized attitude configuration. In the three-axis stabilized attitude configuration, the HGA has TDRSS visibility periods, but not necessarily tracking contacts, every EP orbit.
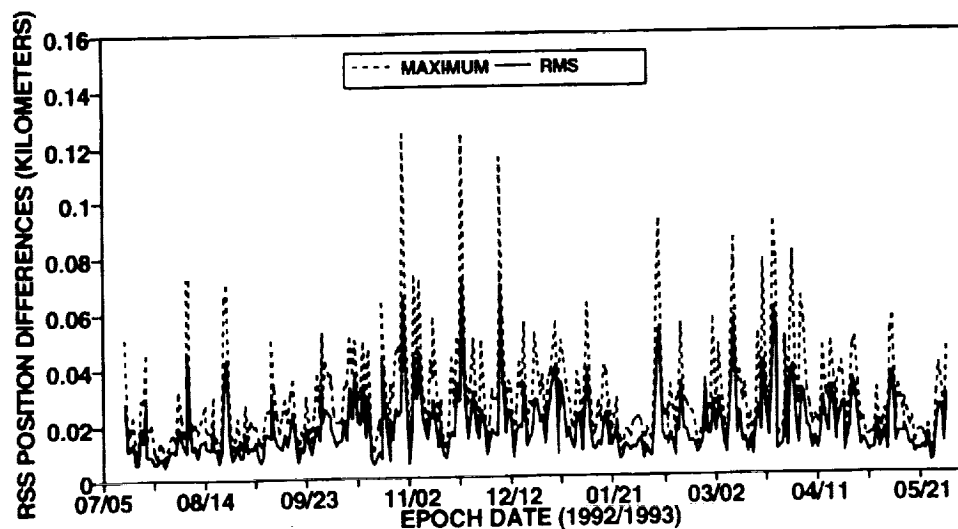

Figure 5. EP/EUVE Definitive Overlap Comparisons

On July 14, 1992, the TONS flight software was initialized using the batch-least-squares-derived EP/EUVE position, velocity, and USO bias estimates and a USO drift rate based on the rate of change of the USO bias through July 13. Table 2 lists the baseline estimation and propagation parameters used in the TONS flight software processing. A more detailed description is provided in References 3 and 4. The robustness of the filter processing was excellent. The filter stabilized within 12 hours of initialization and recovered immediately after data gaps of up to 24 hours. Filter processing was run continuously for 155 days without reinitialization or any parameter changes, except for an increase in the measurement editing multiplier. On December 16, 1992, the flight software's filter was reinitialized to accommodate a software upgrade to model special and general relativistic effects in the computation of the USO frequency bias. The filter converged to a steady-state solution after processing four tracking passes without exceeding a difference of 200 meters versus the definitive solution and was then run continuously for 165 additional days.

Sequential covariance analysis to assess the accuracy of the TONS flight software solutions indicates that the flight software solution accuracy should be comparable to the definitive solution accuracy excluding the effects of measurement timetagging errors, geomagnetic fluctuations, and TDRS maneuver-induced errors, which were not modeled. The dominant error source is the geopotential modeling error, with significant contributions from TDRS ephemeris prediction errors and small contributions from TDRS-to-user ionospheric refraction effects and atmospheric density modeling errors.

In the TONS/EUVE experiment implementation, measurement timetag ambiguities result from the sum of the RIU clock offset from UTC, the DE accumulation delay, the DE/RIU synchronization delay at the start of the accumulation interval, and the instability of the transponder's A1 module oscillator, which provides the DE accumulation interval. The expected magnitude and characteristics of these timetagging errors is discussed in References 11 and 12. For example, the addition of onboard measurement timetagging errors of 3 milliseconds increases the along-track error component by 20 meters and the total RMS error by approximately 10 meters.

Figure 6 shows the daily maximum and RMS position differences between the flight software and definitive estimates during periods with tracking every one to two orbits. Figure 7 shows the monthly mean values of the daily RMS differences between the TONS flight software and definitive estimates in the case of tracking every one to two orbits. These values are 5 to 15 meters larger than the definitive solution overlap RMS differences. As shown in Figure 8, the monthly mean values of the daily maximum differences between the TONS flight software and definitive estimates in the case of tracking every one to two orbits are about 10 to 30 meters larger than the definitive solution overlap maximum differences. These larger differences are expected because the measured difference between the TONS flight software and the definitive ground-based estimates reflects the errors in both the flight software and definitive batch-least-squares estimates. Measurement timetagging uncertainties also contribute to the difference between the two estimates.

Table 2. Baseline TONS Flight Software Parameters

Parameter or Option	EP/EUVE Values	TDRS Values
Estimated Parameters	User position and velocity Drag coefficient correction USO frequency bias correction	N/A
Tracking data	One-way forward-link Doppler	N/A
Data rate	One per 10.24 seconds	N/A
Sigma editing multiplier	3 (through November 4, 1992) 6 (after November 4, 1992)	N/A
Doppler measurement weight	0.1 hertz	N/A
Integrator type (step size)	Runge-Kutta 3(4+) (10.24 seconds)	Runge-Kutta 3(4+) (102.4 seconds)
Integration coordinate system	Mean of J2000.0	Mean of J2000.0
Geopotential model	GEM-T3 (30 × 30)	GEM-T3 (8 × 8)
Atmospheric density model ($F_{10.7}$ solar flux, power of cosine)	Analytic Harris-Priester (135, 2)	N/A
Solar and lunar ephemerides	Analytic	Analytic
Solar radiation pressure	No	Yes

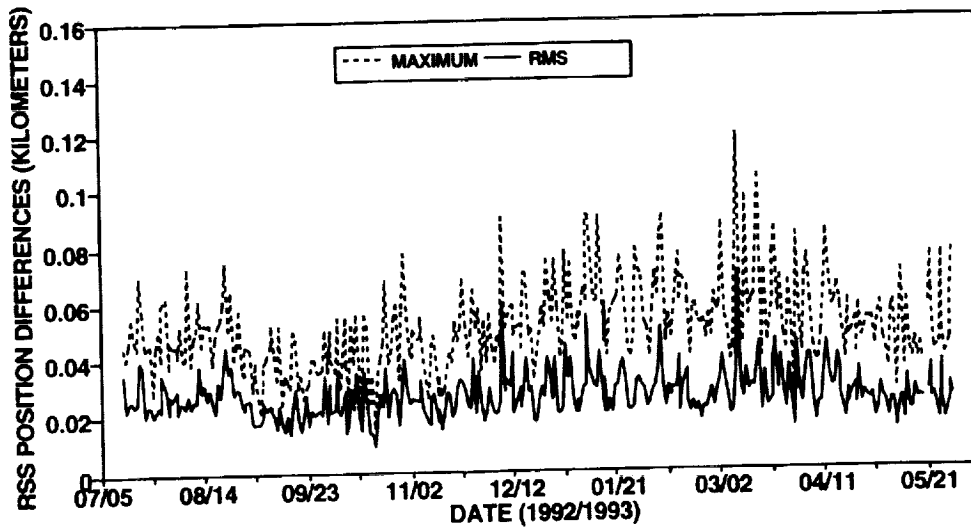NOTE: GEM = Goddard Earth Model   N/A = not applicable

Figure 6. TONS Flight Software Versus Definitive EP/EUVE Position Differences During Periods With Tracking Every One to Two Orbits
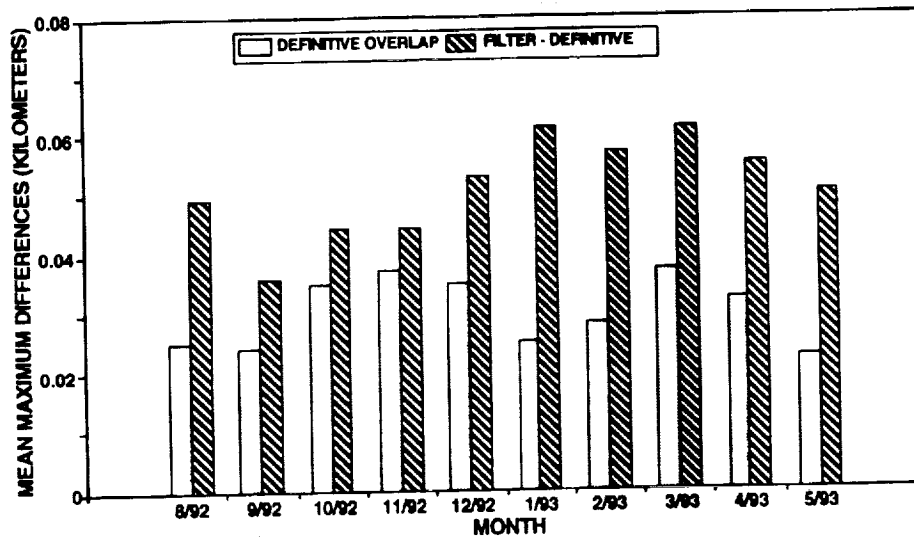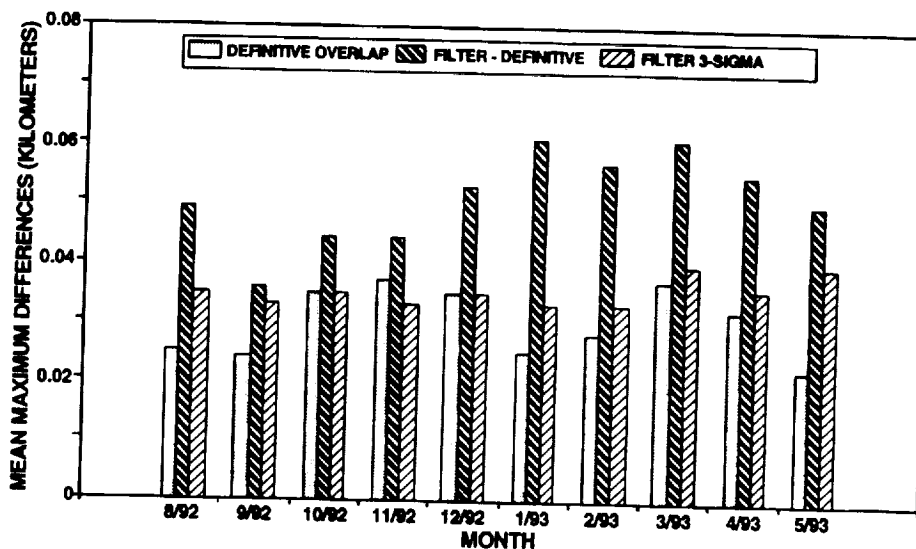

Figure 7. Mean Monthly RMS Values for TONS Flight Software Versus Definitive EP/EUVE Position Comparisons and Definitive Overlap Comparisons During Periods With Tracking Every One to Two Orbits

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Figure 8. Mean Monthly Maximum Values for TONS Flight Software Versus Definitive EP/EUVE Position Comparisons and Definitive Overlap Comparisons During Periods with Tracking Every One to Two Orbits

To provide an independent check on the accuracy of the EP/EUVE filter solutions, TONS experiment filter solutions for September 15, 16, 22, 23, and 24, 1992, were compared with GPS-derived solutions. The GPS-derived solutions were provided by JPL, based on their ground-based postprocessing of the GPS measurements extracted onboard EP/EUVE, using differential GPS techniques. Reference 10 states that these GPS-derived solutions had overlap RMS differences of approximately 5 meters for the 5-day period processed. Figure 9 shows the total position differences between the TONS flight software and the GPS-derived estimate for the September 22–24, 1992, timespan. The mean differences were about 17 meters RMS and 35 meters maximum for periods with tracking every one to two orbits, 4 meters RMS and 7 meters maximum less than the measured difference from the definitive solution for the same timeframe. In general, these differences are consistent with the following relationship:

$$ |\, \vec{r}_{FSW} - \vec{r}_{DEF} \,| = \left(|\, \vec{r}_{FSW} - \vec{r}_{GPS} \,|^2 + |\, \vec{r}_{DEF} - \vec{r}_{GPS} \,|^2\right)^{\frac{1}{2}} $$

where $\vec{r}_{FSW}$ = TONS flight software position estimate

$\vec{r}_{DEF}$ = definitive position estimate

$\vec{r}_{GPS}$ = GPS-derived position estimate

Based on this relationship and the data presented in Figure 8, the mean monthly values of the daily maximum flight software solution errors would be expected to be approximately 40 meters. Figure 8 shows the mean monthly values of the flight software's 3σ daily position maximum error estimates, which are approximately 35 meters. This optimistic error estimate is probably due to the fact that the flight software error estimates do not include timetag errors, TDRS-ephemeris-related errors, and errors in the coefficients used in the gravitational model (also referred to as errors of commission).

Therefore, based on measured differences versus definitive solutions, covariance analysis, and comparisons with GPS-derived ephemerides, the baseline TONS filter solution accuracy is approximately 75 meters (3σ) during periods with tracking every one to two orbits. The largest errors occur in conjunction with large TDRS postmaneuver ephemeris errors and/or significant fluctuations in geomagnetic activity (when the definitive solution errors are also larger).

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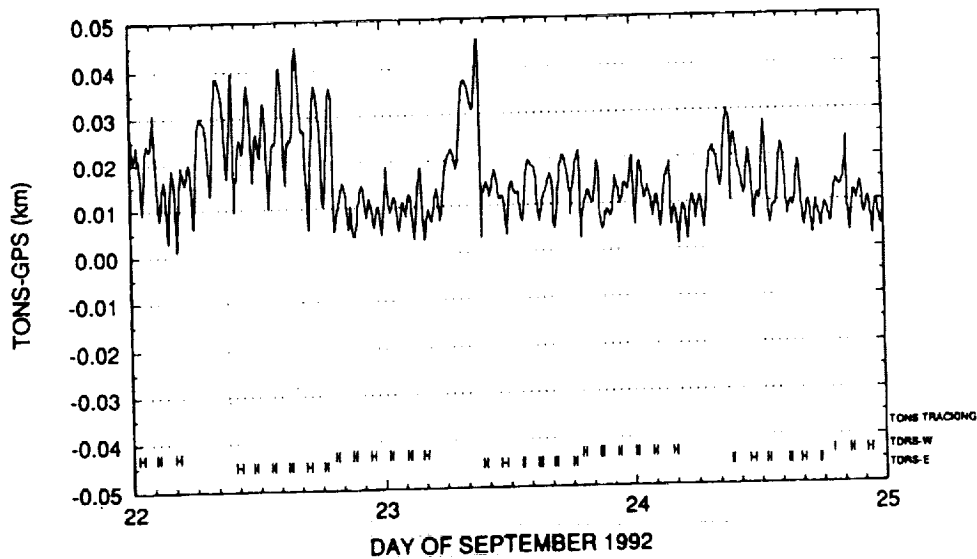
Figure 9. TONS Flight Software Versus GPS-Derived EP/EUVE Position Differences for September 22-24, 1992

Because the impact of TDRS ephemeris errors following north/south (N/S) maneuvers can be significant, the recommended operational concept for handling these maneuvers onboard is to use tracking from the nonmaneuvered TDRSs until an accurate postmaneuver TDRS vector can be uplinked. It is expected that the differences between the TONS flight software and definitive solutions would be further reduced if timetag errors were not present.

Figure 3 (given earlier) shows the TONS flight software estimate for the USO S-band receive frequency offset for July 14, 1992, through May 1, 1993. Note that the increase of approximately 0.6 hertz on December 16 is due to the inclusion of general and special relativistic corrections starting at that time. The USO drift rate was not estimated but applied using the initial value of -0.211 hertz per day, which was adjusted in February and April 1993. The corresponding estimate for the standard deviation of the offset is 1 part in 10^{11} (or equivalently 0.02 hertz). The USO S-band receive frequency offset estimate is consistent with the USO S-band receive frequency offset computed based on one-way return-link Doppler measurement residuals to within 0.1 hertz, the precision of the estimate computed using the one-way return-link Doppler measurement residuals.

Baseline Flight Software Processing Efficiency

The measured memory usage and peak CPU usage of the 1750A-hosted flight software are 233K bytes and 12 percent of the available CPU of a 2-MIPS processor, respectively. Algorithm optimization enhancements associated with the frequency of computation of coordinate rotation matrices and solar and lunar ephemeris and streamlining the geopotential computations have reduced peak CPU utilization from that reported in Reference 1 by approximately 40 percent without compromising accuracy. EP/EUVE ephemeris propagation, TDRS propagation, and measurement processing now require 6 percent, 1.75 percent per TDRS, and 2.5 percent of the peak CPU, respectively. The 48-bit 1750A software was used to process actual EP/EUVE TONS tracking data and the results compared with results obtained using the 64-bit VAX-based version of the flight software. The mean RSS position difference observed over the 31-day period processed was 0.22 meter, with a maximum of 1.6 meter. The largest differences occurred (1) when processing was continued using the results from the previous day, due to timing roundoff errors introduced in initiating the continuation of processing, which would not occur in the onboard environment; and (2) after propagation of more than 7 hours. Based on these results, there is no indication that there is a significant accuracy impact from the reduced precision of the 1750A processor.

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Performance With Algorithm Improvements

Modifications to the baseline TONS navigation algorithms were investigated with the following objectives:

- Improved accuracy of the state estimate and the state covariance estimate
- Simplification of the onboard algorithms without accuracy degradation
- Reduction in the peak processing CPU requirements

The results from this investigation are discussed in this section.

Table 3 summarizes the algorithm modifications that were studied to improve navigation accuracy. Significant accuracy improvements of up to 20 meters were achieved by either estimating or applying an accurate value for the USO frequency drift. However, estimating the USO frequency drift increased the time required for the estimator to converge to an accurate state estimate, while applying a calibrated drift value would require a monthly uplink of this value to the onboard software. The addition of gravity errors of commission to the state process noise model increased the filter's error estimate to a more realistic level.

Table 4 summarizes the algorithm modifications that have been studied to improve processing efficiency and their projected performance based on the baseline CPU utilization measurements. Based on this analysis, the following modifications can be used to reduce peak CPU usage to less than 5 percent:

- Peak CPU utilization can be decreased by 20 percent by replacing the baseline integrator with a fourth-order Runge-Kutta (RK4) algorithm
- Peak CPU utilization can be decreased by 50 percent by doubling the maximum EP integration stepsize and doubling the Doppler averaging interval

Summary

Stage two of NASA's stepwise approach to providing high-accuracy, autonomous navigation to TDRSS users is complete. With the successful implementation of the TONS experiment on EP/EUVE, the flight demonstration of onboard Doppler extraction, onboard signal acquisition, and the qualification of the TONS flight software have been accomplished. The TONS experiment has provided the following major conclusions:

- The USO performance is excellent, demonstrating a predictable near-linear decrease in frequency and a reliable reference frequency for one-way navigation.

Table 3. Algorithm Modifications

Modification	Objective	Performance
Estimation of frequency drift	Improve accuracy	Reduces RMS differences by up to 20 meters but increases convergence time
Application of accurate USO frequency drift	Improve accuracy	Reduces RMS differences by up to 20 meters with monthly update of calibrated frequency drift
Addition of gravity errors of commission	Improve accuracy of state and covariance	Increases position covariance by 10 meters (3σ) but does not improve solution accuracy
Application of timetag bias	Improve state accuracy	Reduces along-track differences
Estimation of timetag bias	Improve accuracy of state and covariance	Timetag bias is not observable using only Doppler measurements
Estimation of TDRS measurement biases	Improve accuracy of state and covariance	Reduces filter stability; can reduce the impact of TDRS ephemeris errors larger than 75 meters but provides no significant improvement if TDRS ephemeris errors are below 75 meters (3σ)
Random-walk model for drag coefficient correction	Simplified algorithm	Provides accuracy comparable to more complex Gauss-Markov model
Random-walk model for USO bias correction	Simplified algorithm	Provides accuracy comparable to more complex Gauss-Markov model
Random-walk model for USO frequency drift correction	Simplified algorithm	Provides accuracy comparable to more complex Gauss-Markov model

Table 4. Projected Processing Reductions

Integration Stepsize (seconds)	Integrator*	Doppler Averaging Interval (seconds)	Peak EUVE Position Differences[†] (meters)	Peak CPU for 2 MIPS 1750A (%)
10.24	RK3(4+)	10.24	0.0	12 over 10.24 seconds
10.24	RK4	10.24	< 1	9.6 over 10.24 seconds
20.48	RK3(4+)	20.48	10	6.0 over 20.48 seconds
20.48	RK4	20.48	10**	4.8 over 20.48 seconds
30.72	RK3(4+)	30.72	15	4 over 30.72 seconds
61.44	RK3(4+)	61.44	20	2 over 61.44 seconds

* RK3(4+) = Runge-Kutta 3(4+); RK4 = Runge-Kutta 4   ** Estimated result
[†] Peak differences over 5 days versus baseline run

- The stability characteristics of the onboard system allow for time maintenance to the 10-microsecond level.

- The DE card in the second-generation TDRSS transponder produced Doppler measurements of comparable quality to the standard TDRSS two-way and one-way return-link Doppler measurements, with very low noise and no interference with user operations due to its passive activity.

- The capability to perform autonomous signal acquisition onboard EP/EUVE was demonstrated and used to aid signal acquisition in more than 90 TDRSS contacts with a 100-percent success rate.

- The TONS flight software performance was excellent. During periods with tracking of approximately one contact every one to two orbits, RMS position differences of 27 meters, RMS velocity differences of 0.03 meter per second, and frequency accuracies of better than 5 parts in 10^{11} (1σ) were achieved for EP/EUVE, compared to the corresponding definitive solutions with an estimated 65 meters (3σ) accuracy. Based on measured differences versus definitive solutions, covariance analysis, and comparisons with GPS-derived ephemerides, the baseline TONS filter solution accuracy is approximately 75 meters (3σ) during periods with tracking every one to two orbits.

- The robustness of the filter processing was remarkable. The filter stabilized within 24 hours of initialization and recovered immediately after data gaps of more than 24 hours. Starting on July 14, 1992, filter processing was performed continuously for 320 days with one reinitialization to accomplish a software upgrade and one parameter change, an increase in the sigma editing multiplier.

It is worthwhile to note that JPL's GPS-derived solutions, with RMS overlap differences of 5 meters for the 5 days processed, were computed in a ground-based postprocessing environment using differential GPS techniques. However, the TONS-derived solutions, with an estimated accuracy of 75 meters (3σ), are provided in realtime onboard the user spacecraft.

Synchronization of onboard time and frequency references in an operational implementation, improvements available in the third-generation TDRSS transponder, impending significant improvements in available geopotential modeling, and refinement of the navigation algorithms can be implemented to significantly improve navigation performance for TONS I and TONS II-A operational users. Based on the results of this experiment, the TONS I operational system will meet the EOS-AM1 navigation accuracy requirements of 50 meters (1σ) and allow EOS-AM1 to meet their navigation goal of 20 meters (1σ), especially if enhanced by the TONS II-A option.

In summary, TDRSS provides a means by which TDRSS users can obtain low-cost, realtime, high-accuracy onboard navigation to meet their requirements with little impact to user spacecraft weight, power, and volume, since TONS uses hardware components already available on the spacecraft. The capabilities are progressive with associated user enhancements and provide failure modes to maintain user autonomy or extend spacecraft lifetime.

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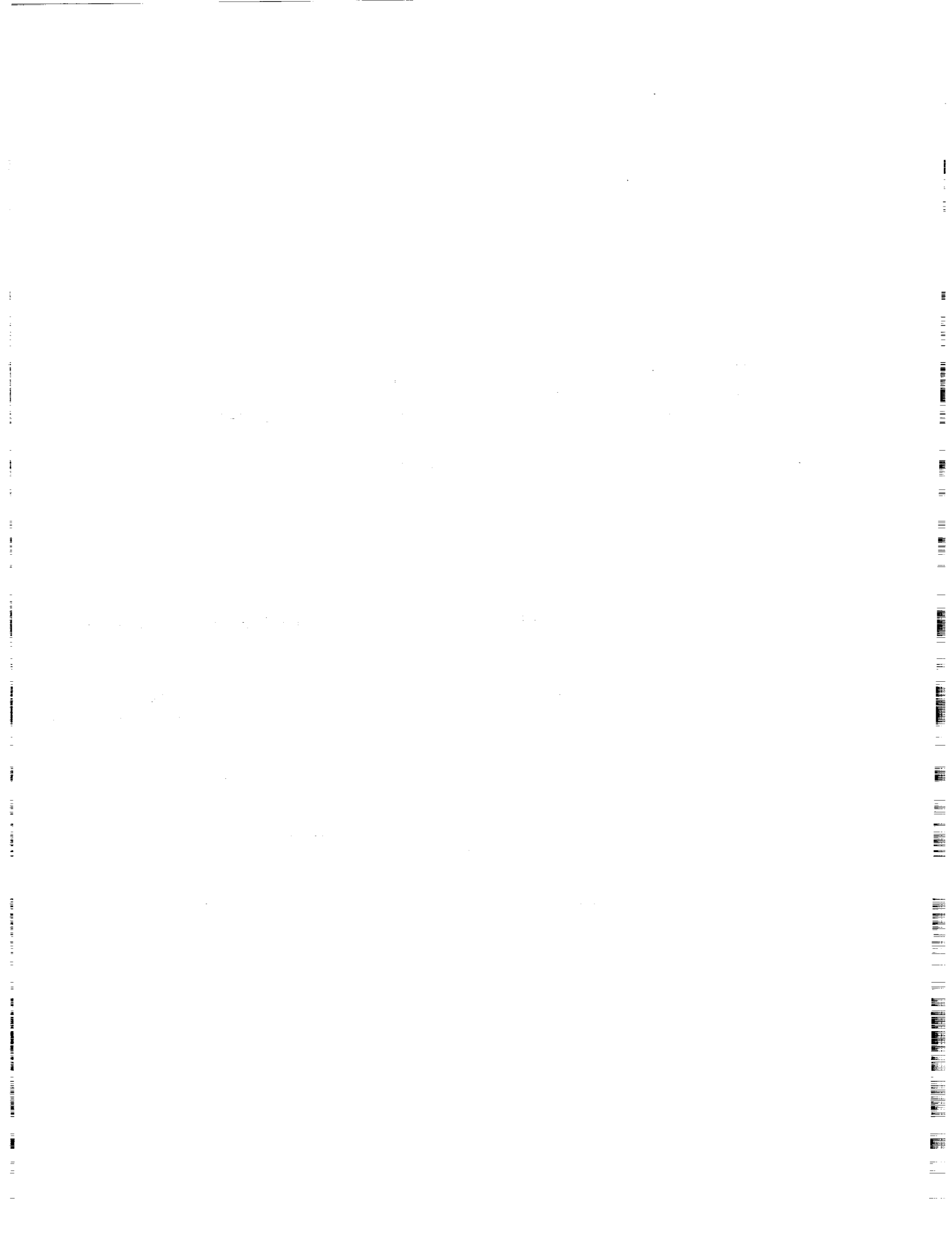
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