ANALYSIS OF NAVIGATION PERFORMANCE FOR THE EARTH OBSERVING SYSTEM (EOS) USING THE TDRSS ONBOARD NAVIGATION SYSTEM (TONS)*

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ABSTRACT

Use of the Tracking and Data Relay Satellite System (TDRSS) Onboard Navigation System (TONS) has been proposed as an alternative to the Global Positioning System (GPS) for supporting the Earth Observing System (EOS) mission. This paper presents the results of EOS navigation performance evaluations with respect to TONS-based orbit, time, and frequency determination (OD/TD/FD). Two TONS modes are considered: one uses scheduled TDRSS forward link service to derive one-way Doppler tracking data for OD/FD support (TONS-I); the other employs an unscheduled navigation beacon service (proposed for Advanced TDRSS (ATDRSS)) to obtain pseudorange and Doppler data for OD/TD/FD support (TONS-II). Key objectives of the analysis were to evaluate nominal performance and potential sensitivities, such as suboptimal tracking geometry, tracking contact scheduling, and modeling parameter selection. OD/TD/FD performance predictions are presented based on covariance and simulation analyses. EOS navigation scenarios and the contributions of principal error sources impacting performance are also described. The results indicate that a TONS mode can be configured to meet current and proposed EOS position accuracy requirements of 100 and 50 meters (3σ), respectively, as well as support onboard time maintenance to an accuracy of 1-2 μsec or better.
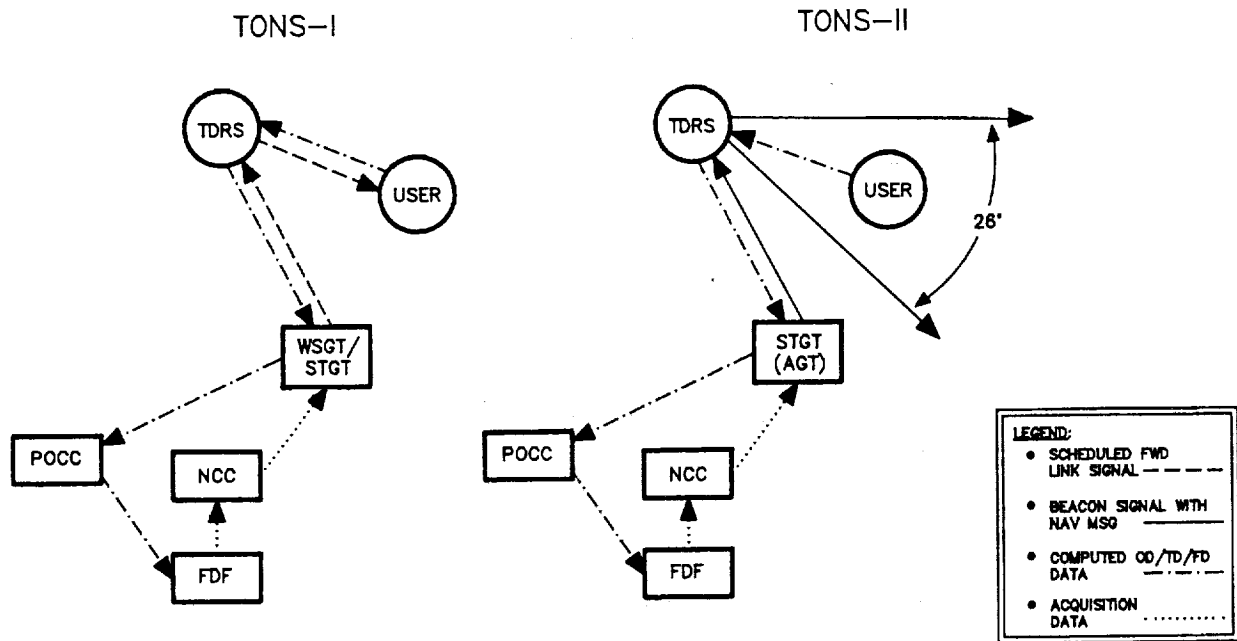

1.0 INTRODUCTION

The Earth Observing System (EOS) mission will support a multitude of science instruments on polar orbiting platforms over a 15-year period. In the current baseline program the approved set of EOS instruments will be distributed between two large platforms, each planned for a nominal 5-year design life. To achieve the required 15-year mission lifetime a total of six spacecraft would be launched into Sun-synchronous, high inclination orbits at 30-month intervals via expendable launch vehicles (TITAN-IV class).[1]

To support EOS navigation, science data annotation and other requirements the platforms are specified to have the capability for onboard estimation of orbit data and to provide an accurate time reference. The most stringent orbit determination accuracy requirement for operational phase mission support is 100m (3σ) with a goal of 50m (3σ).[2] This is a derived requirement for support of navigation base attitude determination (36 $\overset{\frown}{sec}$ per axis).[2] The EOS platform time reference is specified to be accurate within 10 μsec relative to UTC.[2] Use of the Global Positioning System (GPS) signals for orbit and time determination (OD/TD) is the current baseline for providing primary EOS navigation support.[3]

As a backup to GPS navigation, the EOS platform is also specified to have the capability to accept ground-derived orbit data based on TDRSS coherent tracking (2-way range and Doppler-based solutions) or noncoherent tracking (1-way return link Doppler-based solutions). A TDRSS Onboard Navigation System (TONS) under development by the Goddard Space Flight Center (GSFC) has also been proposed as an alternative to GPS for primary EOS navigation support in either of two configurations, TONS-I or TONS-II.

TONS-I can be implemented with the present TDRSS configuration by using one-way Doppler data derived from scheduled forward link S-band Single Access (SSA) or Multiple Access (MA) services to support onboard orbit and frequency determination (OD/FD). The Extreme Ultraviolet Explorer/Explorer Platform (EUVE/EP) mission (1991) will provide the initial TONS-I demonstration.[4,5] A TONS-I user requires a Doppler extractor in the second generation TDRSS user transponder, a stable reference frequency source, such as the Ultrastable Oscillator (USO) on EUVE/EP [4], and navigation processing software. Figure 1 describes the tracking configuration for supporting EOS platforms via TONS-I. Although TONS-I does not support user time determination (TD), the TDRSS-based User Spacecraft Clock Calibration System (USCCS) to be used for the Gamma Ray Observatory (GRO) mission can provide a time update capability of ~1 μsec.[6] In addition, precise FD available via TONS-I could support the estimation of clock drift corrections to preserve the time accuracy and significantly extend the interval between required USCCS operations.

TONS-II is a proposed future capability which would enable onboard orbit, time and frequency determination (OD/TD/FD) by processing one-way Doppler and pseudorange data derived from unscheduled forward link beacon signals transmitted continuously (see Figure 1). This requires some enhancements to TDRSS to generate the beacon signal and some user enhancements over TONS-I capability to process it (pseudonoise (PN) code agility and pseudorange extractor in the transponder and associated navigation software for pseudorange processing). A demonstration capability may be available with activation of the Second TDRSS Ground Terminal (STGT) [7], launch of additional TDRS satellites, and dedicated use of one or two MA forward links for the beacon signal. A TONS-II operational capability is being considered for implementation with the advent of Advanced TDRSS (ATDRSS) in the late 1990's.[8]

TONS-I   TONS-II

TDRS   USER   TDRS   USER   26°
WSGT/STGT   STGT(AGT)
POCC   NCC   POCC   NCC
FDF   FDF

LEGEND:
● SCHEDULED FWD LINK SIGNAL – – –
● BEACON SIGNAL WITH NAV MSG ———
● COMPUTED OD/TD/FD DATA –·—·—
● ACQUISITION DATA ··········

TONS Modes	Key Functions
TONS-I	A. GROUND SEGMENT (WSGT/STGT/POCC/FDF): 1. Support Scheduled FWD Link Service (MA, SSA or KSA) to Enable Onboard Doppler Data Acquisition 2. Supply TDRS Ephemeris Data on CMD Channel 3. Receive EOS NAV Data in RTN Link TLM For QC Processing, ACQ/Orbit Support & Ancillary Functions B. USER SEGMENT: 1. Acquire FWD Link Signal (Using OBDC) and Extract Doppler Observations 2. Perform OB NAV Processing for OD/FD 3. Supply Computed NAV Data to Onboard Functions and Ground in Standard TLM Format
TONS-II	C. GROUND SEGMENT (STGT(AGT*)/POCC/FDF): 1. Generate Continuous (Unscheduled) NAV Beacon Signals For Relay VIA Two TDRSs (ATDRSs)* 2. Supply Beacon NAV Message Data (TDRS Ephem, Timing etc.) 3. Same as A3 D. USER SEGMENT: 1. Acquire Beacon Signal (Using OBDC) and Extract Both Doppler and Pseudorange Observations 2. Perform Onboard NAV Processing For OD/TD/FD. 3. Same as B3

* ATDRSS Elements

Figure 1:   Overview of User Navigation Via TONS

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Previous predictions of navigation performance for future TDRSS/ATDRSS users (e.g., space station and polar platform) indicate that OD/TD accuracies in the range of 20-55 m (3σ) and a 0.3-0.5 μsec (3σ) may be achieved.[9] Because of this potential navigation performance capability and the weight/cost benefits of a TONS implementation, the EOS Project initiated a GPS/TONS Trade Study to support a possible recommendation relative to EOS onboard navigation alternatives. This paper presents the results of EOS navigation performance evaluations based on TONS which were developed as inputs to the Trade Study.[10] The analysis of TONS-I and TONS-II capabilities to support EOS navigation requirements also addresses potential performance sensitivities such as: suboptimal tracking geometry, contact scheduling/selection, drag solution capability, and selected modeling/navigation algorithm parameters. The following sections present the performance evaluation approach OD accuracy results, TD/FD performance using TONS and the analysis conclusions.

2.0 EOS NAVIGATION PERFORMANCE EVALUATION

The EOS navigation task is to estimate optimal values of the spacecraft trajectory parameters and other selected parameters used in modeling the spacecraft dynamics (e.g., drag) and TDRSS/ATDRSS tracking measurements (e.g., USO bias). With TONS-I, the navigation subsystem would estimate a minimum of seven parameters: three position, three velocity and reference oscillator (USO) bias. With TONS-II at least one additional parameter, user clock bias, would be estimated. Due to inherent inaccuracies in the dynamic and measurement models employed, uncertainties in assumed parameters, and measurement noise, errors will arise in the estimated set of parameters.

To evaluate EOS navigation performance in both TONS modes, covariance analysis techniques were used, and additionally, simulation runs were made for particular cases. Covariance analysis provides a statistical measure (1σ estimate) of the accuracy in orbit, time, and/or frequency determination computed as a function of assumed error contributor statistics, the tracking geometry and contact distribution, and time from a given epoch. Simulation analysis provides a time profile of EOS navigation errors computed by differencing parameters calculated from appropriate truth models with corresponding estimated parameters based on simulated TDRSS tracking data and a suitable emulation of user navigation processing software. The following two subsections describe the specific tracking configurations and scenarios assumed for the covariance and simulation analyses.

2.1 TRACKING CONFIGURATION

The assumed TDRSS/ATDRSS tracking configuration includes two active spacecraft located in circular, 2° inclined geosynchronous orbits stationed nominally at 41°W and 171°W. The EOS platform is assumed to be in a 705 km, 98.2° (Sun-synchronous) orbit with ascending node passage set at 1:30 PM (GMT) on the epoch date: 1 December 1997. Onboard tracking data is assumed to be acquired from TDRS forward link transmissions via scheduled service (one-way Doppler with TONS-I) or continuously broadcast navigation beacon signals (pseudorange and one-way Doppler with TONS-II).

2.2 TRACKING SCENARIOS

If no constraints on EOS antenna pointing or other mission operations are assumed, tracking contacts could be selected within time intervals defined by TDRS/ATDRS line-of-sight visibility and geometrical considerations. The

latter implies satellite selection (41°W or 171°W) to achieve the highest change in Doppler during a tracking pass. This corresponds to choosing the TDRS/ATDRS with the highest angle (θ) between its radius and the EOS orbit normal. (The maximum Doppler rate occurs when ⊖ = 90°.) Two tracking scenarios based on a "best TDRS/ATDRS" criterion are shown in Figure 2.

During normal mission operations, TDRSS/ATDRSS will support the EOS mission with a minimum of one equivalent single access (SA) channel for communication services. Since there may be as many as three spacecraft in orbit simultaneously, time sharing of SA resources is likely. Consequently, for TONS-I EOS tracking, during communication contacts may not necessarily satisfy the "best TDRS/ATDRS" and placement criteria shown in Figure 2.

To assess the potential sensitivity to occasional missed (lost/unavailable) contacts or nonoptimal (poor geometry) contacts, several alternative "degraded" scenarios were considered. On the other hand, the option to schedule occasional TDRSS/ATDRSS multiple access forward link (MAF) tracking contacts to supplement inopportune or unavailable SA contacts is feasible for EOS. Consequently, other scenarios with a combination of degraded contacts and supplemental (5-minute) contacts, where appropriate, were also considered. Table 1 lists the assumed set of scenarios used for analysis.

3.0 COVARIANCE ANALYSIS OF EOS NAVIGATION PERFORMANCE

To evaluate the potential navigation performance for EOS using TONS, an upgraded version of the Sequential Error Analysis (SEA) program [11,12] was used. The program assumes Extended Kalman Filter (EKF) processing of the tracking data and computes the uncertainty in an EOS platform's orbit, time and/or frequency determination as a function of various error sources, and time from a specified epoch. The following subsections discuss the assumed tracking model inputs to the SEA program (see Figure 3) and the OD/TD/FD performance results corresponding to the tracking scenarios defined in Table 1.

3.1 TRACKING MODEL PARAMETERS

Table 2 lists the a priori uncertainties in the basic parameters assumed to be estimated for EOS navigation: three position, three velocity, clock bias and clock drift (or frequency bias in TONS-I). Uncertainties in various systematic and random error sources contribute to the overall covariance of the estimated parameters. The 1σ values of all error sources included in the analysis for TONS-I are listed in Table 2. Changes or additions pertinent to TONS-II are listed in an adjacent column. Since the error analysis is linear, the results for any particular systematic contributor may be scaled up or down to note the impact of values other than those stated here.

3.1.1 Dynamic Model Errors

Errors in force modeling (gravitational harmonics, GM, C_D, C_R) introduce orbit propagation errors in the interval between tracking passes. Values in Table 2 for the gravitational harmonics are based on the GEM-T1 model [13,14]. Their contributions were evaluated individually and the composite effect determined based on the root-sum-square (rss) of errors due to individual harmonics.
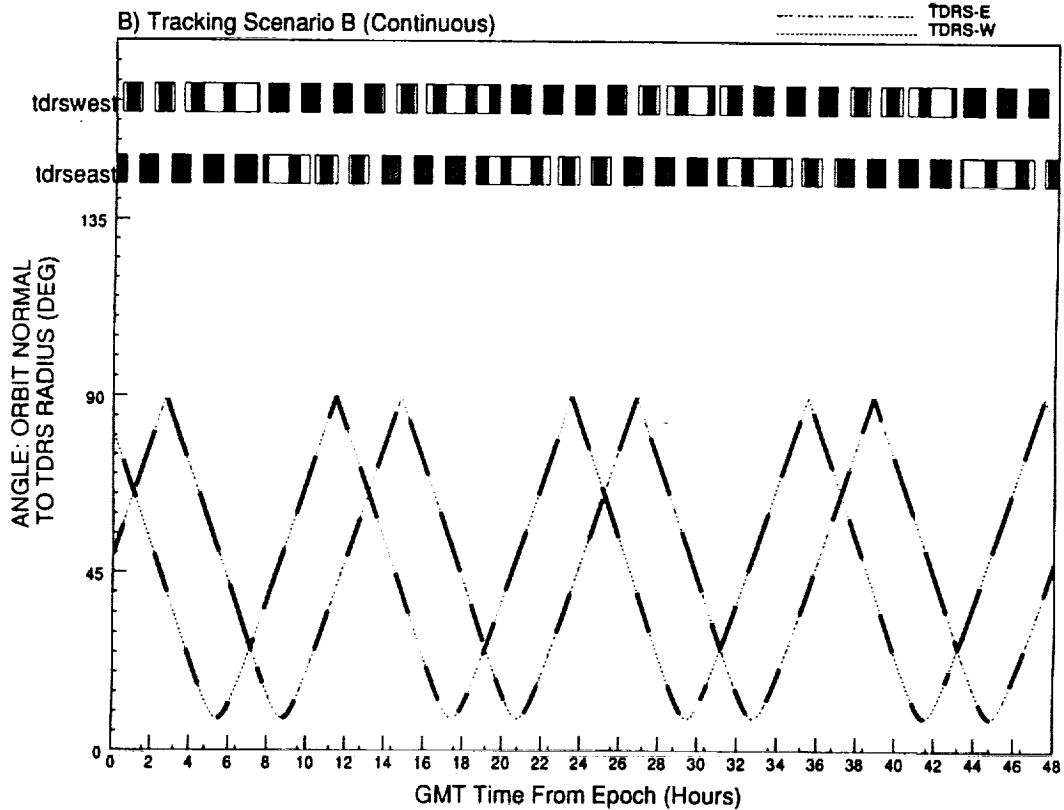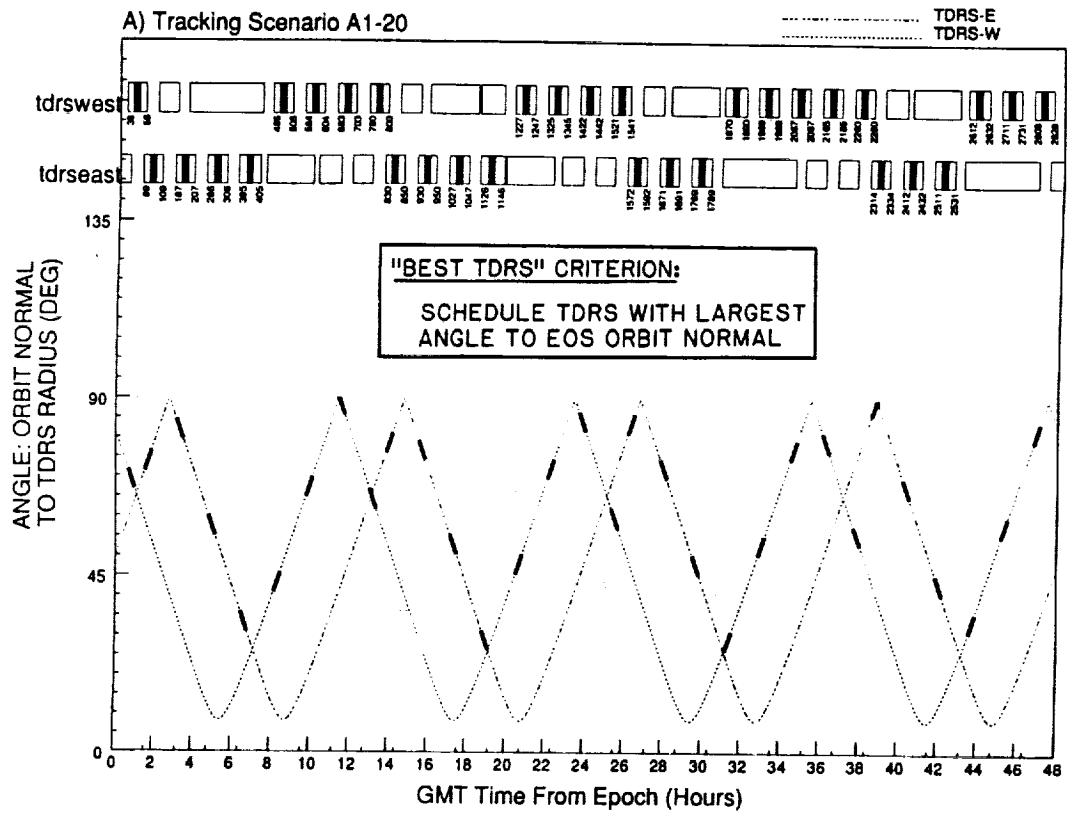
A) Tracking Scenario A1-20

"BEST TDRS" CRITERION:

SCHEDULE TDRS WITH LARGEST
ANGLE TO EOS ORBIT NORMAL

B) Tracking Scenario B (Continuous)

Figure 2: Sample Tracking Scenarios and Angle Between EOS Orbit Normal
and TDRS Radius

Table 1
EOS Tracking Scenarios With TONS

| TONS Mode	Tracking Scenario	Tracking Contacts	TDRS Scheduling Criteria
TONS–I	A1–20 A1–10 A1–5	One Pass/Orbit (20 Mins) "　　　　(10 Mins) "　　　　(5 Mins)	Best Geometry "　　　" "　　　"
	C1–20 C2–20	One Pass/Orbit (20 Mins) Same Except Two Omitted Each Day	Arbitrary Geometry "　　　"
	C3–20 C4–20	One Pass/Orbit (20 Mins) "　　　　"	Arbitrary Geometry, East Only Arbitrary Geometry, West Only
	C1–20+ C2–20+	One Pass/Orbit (20 Mins)+ Selected 5 Min Contacts Same Except Two 20 Min Contacts Omitted Each Day	Arbitrary Geometry Best Geometry Same
TONS–II	B1	Continuous Tracking (Except In ZOE)	Best Geometry
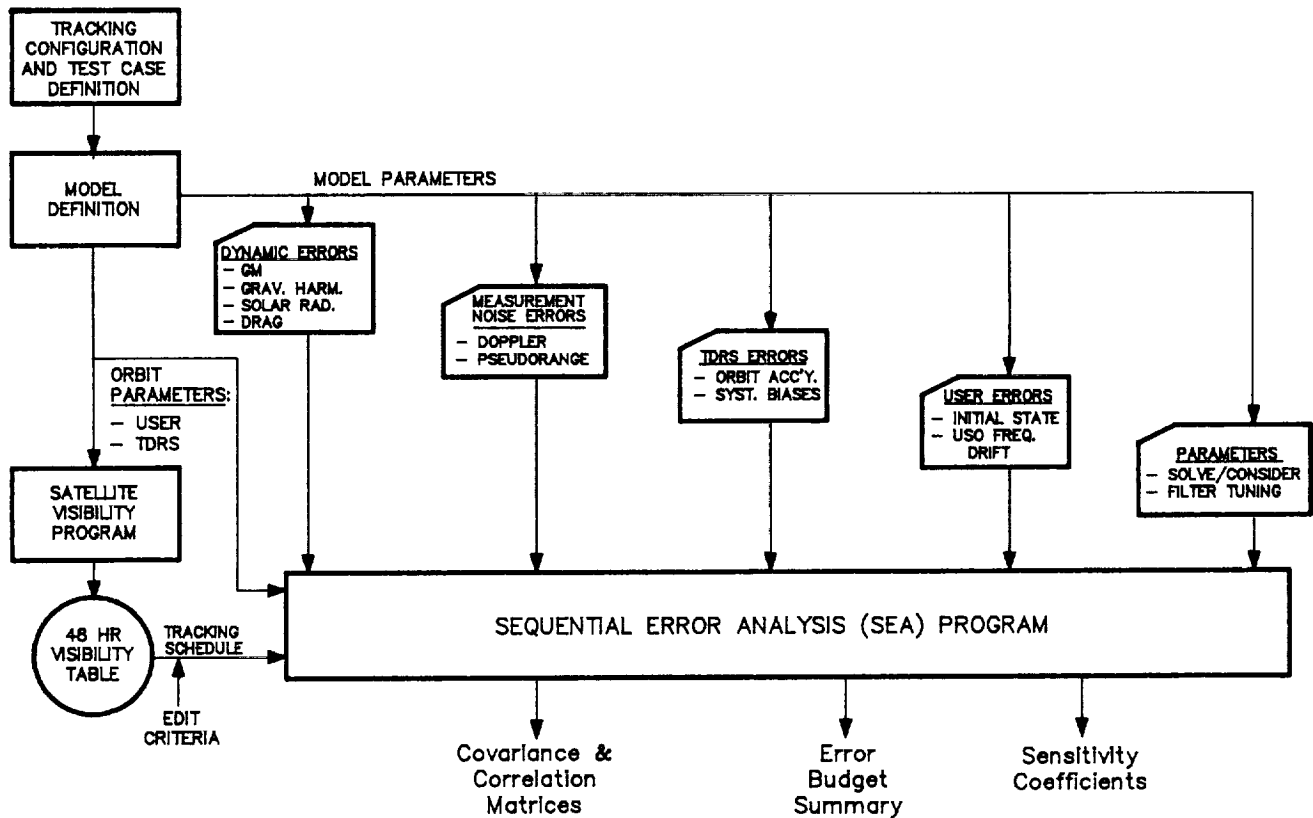
Figure 3: Navigation Performance Evaluation — Overview

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The error due to atmospheric drag is modeled as an uncertainty in the drag coefficient, C_D. Although C_D would likely be an estimated parameter, a residual effect is assumed to remain and is treated as a consider parameter with 1σ uncertainty equal to 10% of the assumed nominal value ($C_{D_o} = 2.2$). (While this is extremely conservative, further scrutiny would not be needed unless drag becomes dominant) The impact of this error is directly proportional to the atmospheric density (ρ) and spacecraft area-to-mass ratio (A/m). Computations for ρ were based on a Harris-Priester atmospheric density model and elevated solar flux levels in the range of 225-325 x 10^{-22} watts/M^2/Hz to assess worst case conditions. The A/m algorithm listed in Table 2 was provided by the EOS Project.

Assumed uncertainties in the gravitational constant (GM) and solar pressure coefficient (C_R) are conservative (i.e., high). Since their impact tends to be relatively small, more refined values are unnecessary.

3.1.2 Measurement Processing Errors

Errors in updating the estimated parameters with each new measurement arise from errors in the tracking data and errors in modeling the measurements.

Errors in the tracking data were characterized in terms of equivalent range and range-rate noise uncertainties and system biases. Random measurement error values listed in Table 2 are representative of scheduled (SSA/MA) services using the EOS high gain antenna for TONS-I and the proposed ATDRSS S-band navigation beacon service using an omni-antenna for TONS-II. Although lower random errors would apply if the HGA is available for TONS-II, the more conservative assumption was made for analysis.

The 1σ pseudorange bias values represent the composite of a residual, uniformly distributed $\pm$ 10m bias attributed to the ground stations, ATDRS and user components. This is also a conservative assumption based on ATDRSS specifications, [9] although it is not particularly significant for OD accuracy, since it primarily affects TD accuracy. The range-rate bias error of 0.1 mm/sec (1σ) was included primarily to observe potential sensitivity, but in any case, it should be absorbed in the reference oscillator bias estimate.

Frequency drift in the EOS reference oscillator appears as a range-rate error which affects Doppler measurement accuracy and as a clock bias acceleration error $\ddot{B}$ which affects pseudoranging accuracy. Oscillator drift was defined as a systematic error with a 1σ uncertainty of 10^{-10} parts per day, a level which is consistent with USO performance specified for the TONS and COBE navigation experiments.[4,15] This value is also conservative, since $\ddot{B}$ can be calibrated to a few parts in 10^{11} per day or better and virtually modeled out based on long-term trending of the frequency bias estimates and/or observation residuals analysis.

Uncertainties in the TDRS orbit contribute directly to the measurement modeling error. The 1σ orbit error assumed in Table 2 for TONS-I is representative of current TDRS tracking accuracy. The 1σ error for TONS-II is consistent with the ATDRS tracking goals [8] and the results of recent studies on tracking improvements.[16,17]

Table 2
Key Tracking Model Parameters for EOS Covariance Analysis

Parameter		1 σ Errors	
		TONS I	TONS II
Estimated	EOS $\left\{ \begin{array}{l} H,C,L \\ \dot{H},\dot{C},\dot{L} \end{array} \right.$ Orbit (A Priori)	1000 m 1 m/sec	1000 m 1 m/sec
	EOS $\left\{ \begin{array}{l} B \\ \dot{B} \end{array} \right.$ Clock (A Priori)	N/A 2×10^{-7} parts	1 msec 2×10^{-7} parts
Unestimated Systematic Errors $\left(\begin{array}{c} \text{Consider} \\ \text{Parameters} \end{array} \right)$	Atomospheric Drag (ΔC_D) *	10%	10%
	Grav. Constant (GM)	0.1 ppm	0.1 ppm
	Grav. Harmonics (30 x 30)	GEM–T1 Uncertainties	GEM–T1 Uncertainties
	Solar Radiation (C_R)	10%	10%
	Systems Biases $\left\{ \begin{array}{l} R \\ \dot{R} \end{array} \right.$	N/A 0.1 mm/sec	10 M 0.1 mm/sec
	TDRS Orbit	50 m	25 m
	USO Drift $\ddot{B}$	10^{-10} ppd	10^{-10} ppd
Random Measurement Errors	Range σ_R	N/A	5 m
	Range Rate $\sigma_{\dot{R}}$	2 mm/sec	5 mm/sec
	Parameter	Value	
Other Tracking Parameters	– Filter Tuning:		
	— User Vel. Process Noise	10^{-9} m^2/sec^3	
	— Clock Rate Process Noise	10^{-6} nsec^2/sec^3	
	– Tracking Contacts	See Scenarios in Table 1	
	– Data Rate	One/10 sec	

* Drag Coefficient (C_D) is assumed to be estimated (by the user navigation algorithm) with a residual error (ΔC_D) treated here as a consider parameter. (Nominal C_D =2.2, Area/Mass = .001+.0163 |Sin θ|, (in m^2/Kg) where θ = spacecraft true anomaly from descending node)

3.1.3 Filter Tuning Parameters

Filter tuning refers to adjustment of the Kalman filter gains to control the weight given to prior estimates. The objective is to achieve some balance between uncertainties introduced by new measurements and those caused by propagating prior estimates with an imperfect dynamical model. The filter process noise variance rates listed in Table 2 were used throughout the analysis and found to give reasonable results. No attempt was made to evaluate the use of dynamic tuning techniques which attempt to continually optimize parameters (e.g., in response to measurement residual levels or modeled phenomena).

3.2 OD PERFORMANCE RESULTS

EOS navigation performance based on TONS-I or TONS-II capabilities was evaluated for each of the tracking scenarios defined in Table 1 and for both moderate and high atmospheric density levels. Altogether, 20 cases were considered (see Table 3), and for each the errors in an EOS platform's position, clock bias, and clock drift (or frequency bias for TONS-I) were computed over 48 hours. A sample of the position error profiles for two cases provided in Figure 4 shows the 1σ errors due to individual error contributors and the 1σ total (RSS) error.

A summary of the OD performance is given for each case in Table 3 in terms of 1σ errors (peak total and mean total).* Mean errors in all cases and even peak errors in all but three cases are within the current EOS position accuracy requirement of 33 meters (1σ).** Results for tracking scenario B indicate that TONS-II could also support the EOS position accuracy goal of 17 meters (1σ). With respect to error sources, the sample plots in Figure 4 show that gravity modeling error is the predominant contributor. Effects of drag model uncertainty are not as significant but do increase during intervals with missed or poor geometry contacts. However, this sensitivity (as indicated by the results for tracking scenarios C1-20 and C2-20) is readily mitigated with a few supplemental (5-minute) tracking contacts (as indicated by the results for scenarios C1-20+ and C2-20+).

3.3 TD/FD PERFORMANCE RESULTS

In addition to EOS orbit determination both TONS-I and II will enable transponder reference frequency determination (FD) by estimating the USO frequency bias. With the availability of pseudorange data via ATDRSS beacon tracking, TONS-II could support EOS time determination by estimating the onboard clock bias. The covariance analysis also provided an evaluation of EOS time and frequency determination (TD/FD) performance. Table 3 lists the mean 1σ FD errors over 48 hours for each case considered (after settling of initial transients). These results are clearly well below the current operational requirements for transponder reference frequency uncertainty (± 700 Hz). Evaluation of potential TD performance with TONS-II (tracking scenario B) indicates 1σ clock bias errors of 100 - 120 nsec (after settling of initial transients).

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* The errors listed in Table 3 are the maximum and average over 48 hours (after settling of initial transients) of the 1σ total position errors.

** The current EOS position accuracy requirement of 100m (3σ) and the goal of 50m (3σ) have each been divided by 3 for performance comparison purposes.

Table 3
EOS OD/FD Performance Using TONS (via Covariance Analysis)

TONS Mode	Atmos. Density Level*	Tracking Scenario	1σ OD Error (m)		1σ FD Error** (mHz)
			Mean	Peak	Mean
I	Moderate	A1–20	13	22	39
		10	16	24	60
		5	20	30	94
		C1–20	15	25	32
		C2–20	17	29	33
		C1–20+	13	21	29
		C2–20+	14	23	30
		C3–20	17	33	55
		C4–20	16	27	30
II	Moderate	B1–Continuous	9	13	28
I	High	A1–20	15	24	42
		10	18	28	66
		5	23	36	99
		C1–20	16	32	33
		C2–20	18	36	34
		C1–20+	14	23	30
		C2–20+	14	25	32
		C3–20	18	37	50
		C4–20	17	33	51
II	High	B1–Continuous	9	14	29

* Moderate: $0.2{-}0.7 \times 10^{-12}\,kg/m^3$ (Solar Flux = 225 Watts/m^2/Hz)

High: $0.3{-}1.8$ " " = 325 "

** At S–Band (2106.4 MHz)
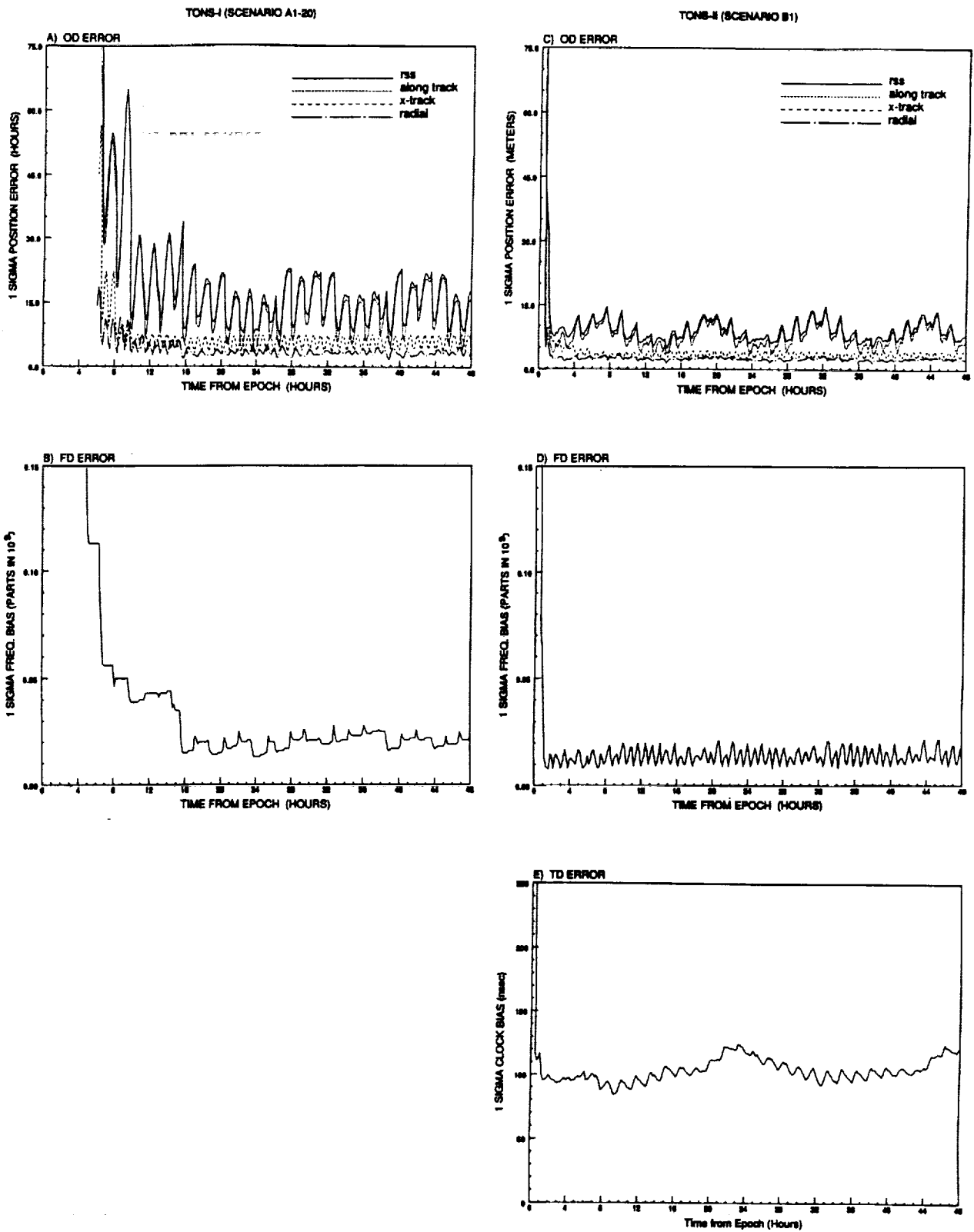
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Figure 4: Sample EOS OD/FD/TD Errors for TONS-I & TONS-II (from Covariance Analysis)

Prior to the availability of a TONS-II capability for autonomous onboard updating of the EOS time reference, conventional TDRSS two-way ranging operations utilizing the USCCS could be employed. Clock corrections would be determined and uplinked to the EOS time management system at a rate dependent upon the time maintenance requirement (T_{MAX}), the USCCS accuracy (~1 µsec), and the time reference oscillator (TRO) stability. For example, with a TRO long-term stability of 10^{-10} parts per day clock updates would be required about every two days for T_{MAX} = 10 µsec (or ~ 22 days for T_{MAX} = 100 µsec). Current EOS specifications [2] relax the time maintenance requirement to 100 µsec when updated by ground-based operations, a sacrifice in capability to reduce the ground support impact.

Although a tradeoff between TRO stability and T_{MAX} relaxation might be considered, another alternative is to utilize TONS-I FD capabilities to reduce the frequency of USCCS operations. This approach is based on calibrating the clock drift, assuming that the TRO and transponder reference (USO) frequencies can be derived from a common source. Future TDRSS transponders will likely be configured to accept a standard external reference frequency (e.g., 5 or 10 MHz vs the current 19.056392 MHz). Figure 5a indicates the relevant onboard elements and data interfaces.

The Onboard Navigation System (ONS) would provide a mean offset ($\overline{\Delta f}$) in the reference oscillator frequency (f_o) over an appropriate averaging interval (T_{AVG}), and the time management system would compute a corresponding incremental clock correction, $(\overline{\Delta f}/f_o)T_{AVG}$. Figure 5b illustrates hypothetical clock drift profiles with and without FD correction data twice per day. Given the FD performance stated in Table 3 and T_{AVG} = 0.5 day, the corresponding 1σ uncertainty in the clock updates would be ≤ 1.5 µsec. This level of incremental correction accuracy would be sufficient to support the 10 µsec maintenance requirement with occasional USCCS updates for absolute recalibration. Alternatively, clock corrections derived from long-term ground-based modeling (similar to the COBE/USO characterization [18]) could provide even tighter time maintenance accuracy and longer intervals between USCCS updates. With the eventual availability of TONS-II, however, continuous estimation of both clock bias and drift would enable time maintenance at the sub-microsecond level.
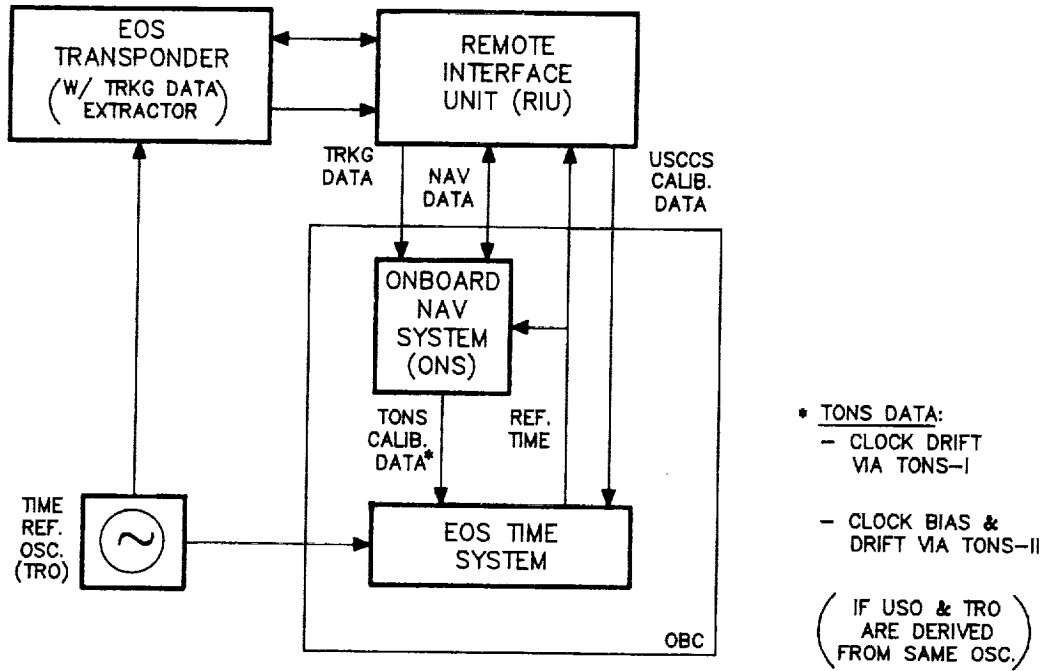
4.0 SIMULATION ANALYSIS OF EOS NAVIGATION PERFORMANCE

To complement the covariance analysis approach in evaluating TONS for supporting EOS navigation it was decided to assess particular performance sensitivity concerns through simulation and to compare estimated parameters against reference or truth data. An upgraded version of GSFC's R&D GTDS program, known as the Navigation Processing System (NPS) [19, 20] was used for all major simulation functions: ephemeris generation, data simulation, (Kalman) filter processing, and ephemeris comparisons. An overview of the simulation elements used for EOS OD/FD performance evaluation is shown in Figure 6. Truth orbits for an EOS platform and two TDRSs were generated and used in conjunction with a USO model and particular tracking scenarios (as defined in Table 1) to produce simulated TDRSS one-way forward Doppler data.*

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* Pseudorange tracking data generation and processing capabilities were not available in the current NPS program, but OD/FD performance evaluations for TONS-II were not significantly affected, since Doppler tracking data is the most effective aid to OD/FD. The need for pseudorange data is primarily for the time-determination function (which was not simulated).

A) ONBOARD CONFIGURATION

EOS TRANSPONDER (W/ TRKG DATA EXTRACTOR)

REMOTE INTERFACE UNIT (RIU)

TRKG DATA

NAV DATA

USCCS CALIB. DATA

ONBOARD NAV SYSTEM (ONS)

TONS CALIB. DATA*

REF. TIME

TIME REF. OSC. (TRO)

EOS TIME SYSTEM

OBC

* TONS DATA:
- CLOCK DRIFT VIA TONS-I

- CLOCK BIAS & DRIFT VIA TONS-II

(IF USO & TRO ARE DERIVED FROM SAME OSC.)

B) EXAMPLE OF EOS CLOCK DRIFT COMPENSATION VIA TONS-I

REF. OSC. STABILITY 10^{-10} PPD

W/O TONS-I COMPENSATION

W/ TONS-I COMPENSATION

CLOCK OFFSET (μSEC)

100 80 60 40 20 10 8 6 4 2 1

0 1 2 3 4 5 6 7 8 9 10

LAST USCCS UPDATE
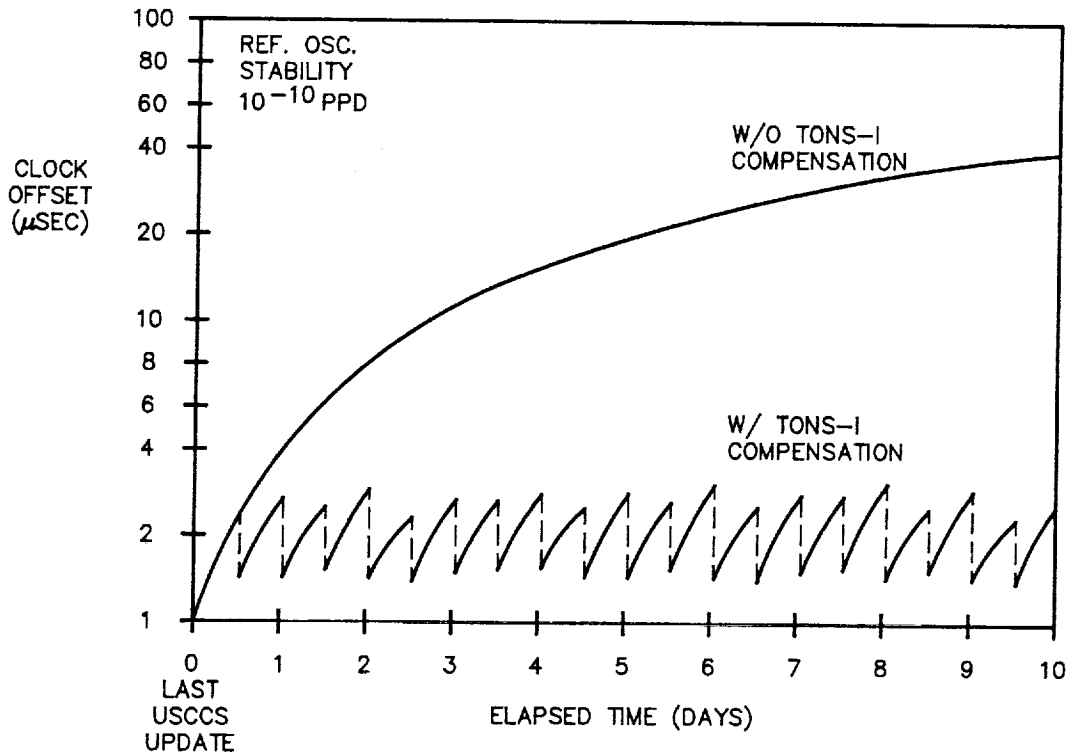
ELAPSED TIME (DAYS)

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Figure 5:   TONS Utilization for EOS Time Maintenance Support

Table 4
Key Tracking Model Parameters for Simulation Analysis

Parameters	Truth (DATASIM)	Model (FILTER)
USO Bias (parts)	1×10^{-12}	1×10^{-7}*
" Drift (ppd)	1×10^{-10}	3×10^{-10}*
Drag Model (ρ_1) **	0	50% *
Grav. Harmonics	GEM-T2 (50 x 50)	GEM-T1 (21 x 21)
TDRS Ephemeris { 41° W	GEM-9 (4 x 4)	GEM-9 + PRIORI (2 x 0) offset +
TDRS Ephemeris { 171° W	"	GEM-9 + PRIORI (4 x 4) offset +

* A Priori Values at Epoch

** Drag error modeled in terms of Scalar offset to drag coefficient $C_D = C_{Do} (1 + \rho_1)$.
(See footnote to Table 2 for other related parameters).

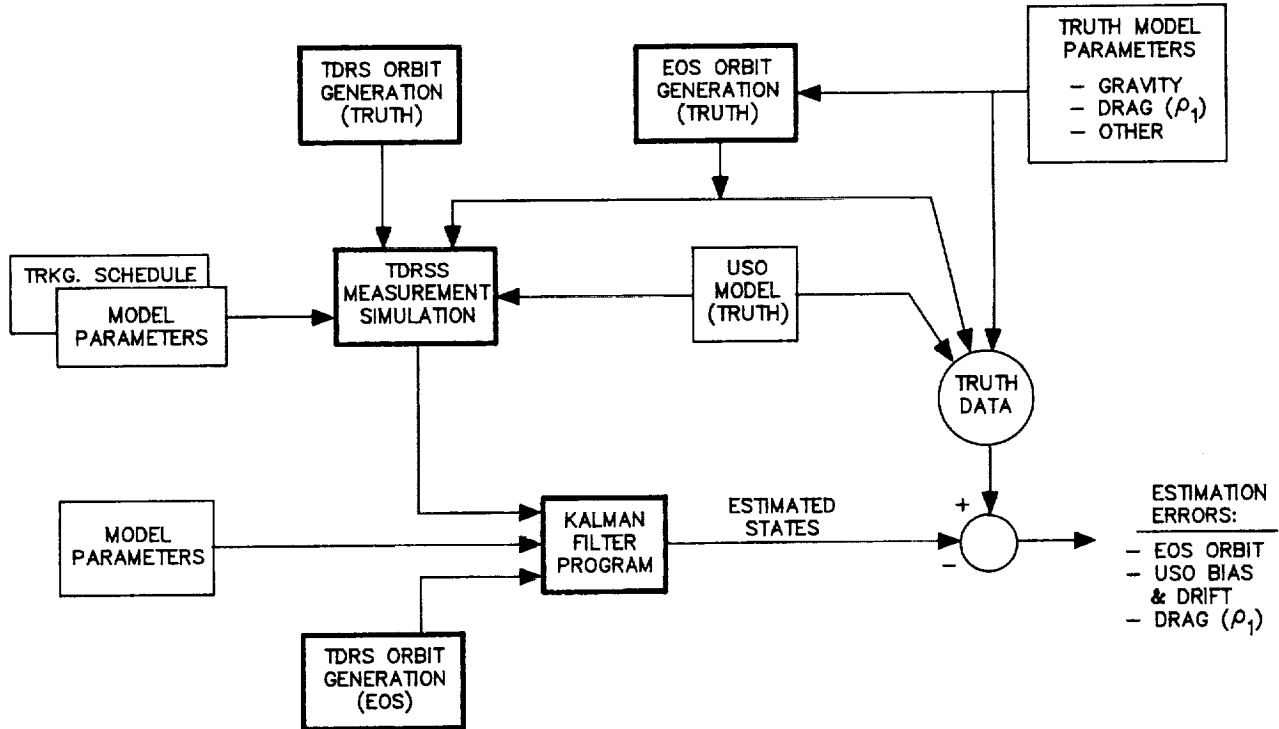+ To produce nominal ($\leq$ 50 m) or 3 X nominal ($\leq$ 150 m) TDRS ephemeris errors

Figure 6:   Overview of Navigation Performance Simulation

Processing of the simulated tracking data is performed by an EKF program which, analogous to user navigation software, is provided with TDRS orbit data (nontruth) and various tracking model parameters. The estimated parameters comprise EOS position and velocity states, USO bias and drift states and a drag model parameter (ρ_1). Error profiles for performance evaluations were derived by comparing truth and estimated parameter data over a specified time interval.

Three particular issues (missed or poor geometry tracking contacts, TDRSS/ATDRSS ephemeris uncertainty, and drag estimation capability) were selected for analysis. The following subsections discuss the assumed tracking model parameters and the performance results.

4.1 TRACKING MODEL PARAMETERS

Initial errors in the EOS orbit were set at the same levels assumed in Table 2 for the covariance analysis. Table 4 lists the a priori offsets in the USO bias and drift parameters assumed to be estimated. The initial offset for ρ_1 was set arbitrarily at 0.5* with the objective of observing estimation convergence characteristics relative to the 10% residual error assumption made for C_D as a consider parameter in the covariance analysis (see Table 2).

For this analysis, only errors in significant unestimated parameters were assumed, specifically errors in gravity harmonics modeling and user (EOS) knowledge of TDRS orbits. For TDRS orbit error modeling, a non-truth orbit was derived by reducing the assumed gravity model (4x4 to 2x0) and/or offsetting the epoch state vector as noted in Table 4. These model parameters were selected to reflect expected TDRS (or ATDRS) tracking performance for TONS-I (or II) assuming upgraded BRTS (or APLS) capabilities ($\leq$ 75m - 3σ).[17] An off-nominal error model with degraded TDRS accuracy ($\leq$ 150m 3σ) was used to assess sensitivity in a TONS-I application prior to a BRTS upgrade or APLS implementation.

Numerical values for other modeled parameters, measurement noise and bias, and drag model parameters (platform A/m, solar flux level, etc.) were set at the same levels used in the covariance analysis. Filter tuning was adjusted (via velocity state noise level) to accomodate cases with degraded TDRS ephemeris accuracy.

4.2 PERFORMANCE RESULTS

EOS navigation processing was simulated for four tracking scenarios assuming the nominal modeling parameters stated in Table 4. These were repeated for off-nominal TDRS/ATDRS tracking errors to assess performance sensitivities. Altogether, eight cases were considered (see Table 5) and for each case the errors in platform position, velocity, and USO frequency bias were computed over 48 hours. Sample plots of the position error profiles (truth-estimated position vs time) are provided in Figure 7.

A summary of the OD performance results is given in Table 5 in terms of the peak and RMS errors (after settling of initial transients). The data indicate reasonable overall agreement between the OD errors computed for corresponding covariance and simulation analysis cases based on TONS-I and TONS-II. However, the contributions of TDRS ephemeris error at the levels assumed for simulation are clearly dominant over those due to the gravity modeling error. Determining potential sensitivity to missed or poor geometry tracking contacts and/or degraded TDRS orbit information was the intent in comparing performance between the selected TONS-I scenarios: A1-20, C1-20 and C1-20+. As indicated by the results in Table 5, however, there is no clear distinction since each

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* This equates to an initial offset of 50% from the truth model where $\rho_1 = 0$ (i.e., $C_D = (C_{Do})$). See footnote in Table 5 for parameter definitions.

Table 5
EOS OD Performance Using TONS (Simulation Analysis)

TONS Mode	Tracking Scenario	TDRS/ATDRS Ephem Error	OD Error (m) RMS	Peak	RMS Drag (ρ_1) Error
I	A1−20	Nominal*	16	56	.11
	C1−20		14	45	.13
	C1−20+		14	47	.10
	A1−20	3x Nominal	19	65	.11
	C1−20		17	74	.15
	C1−20+		19	63	.08
II	B1	Nominal**	8	24	.09
	"	3x Nominal	12	29	.11

*Nominal Position Error $\leq$ 50 m (1σ)   **Nominal Position Error $\leq$ 25 m (1σ)
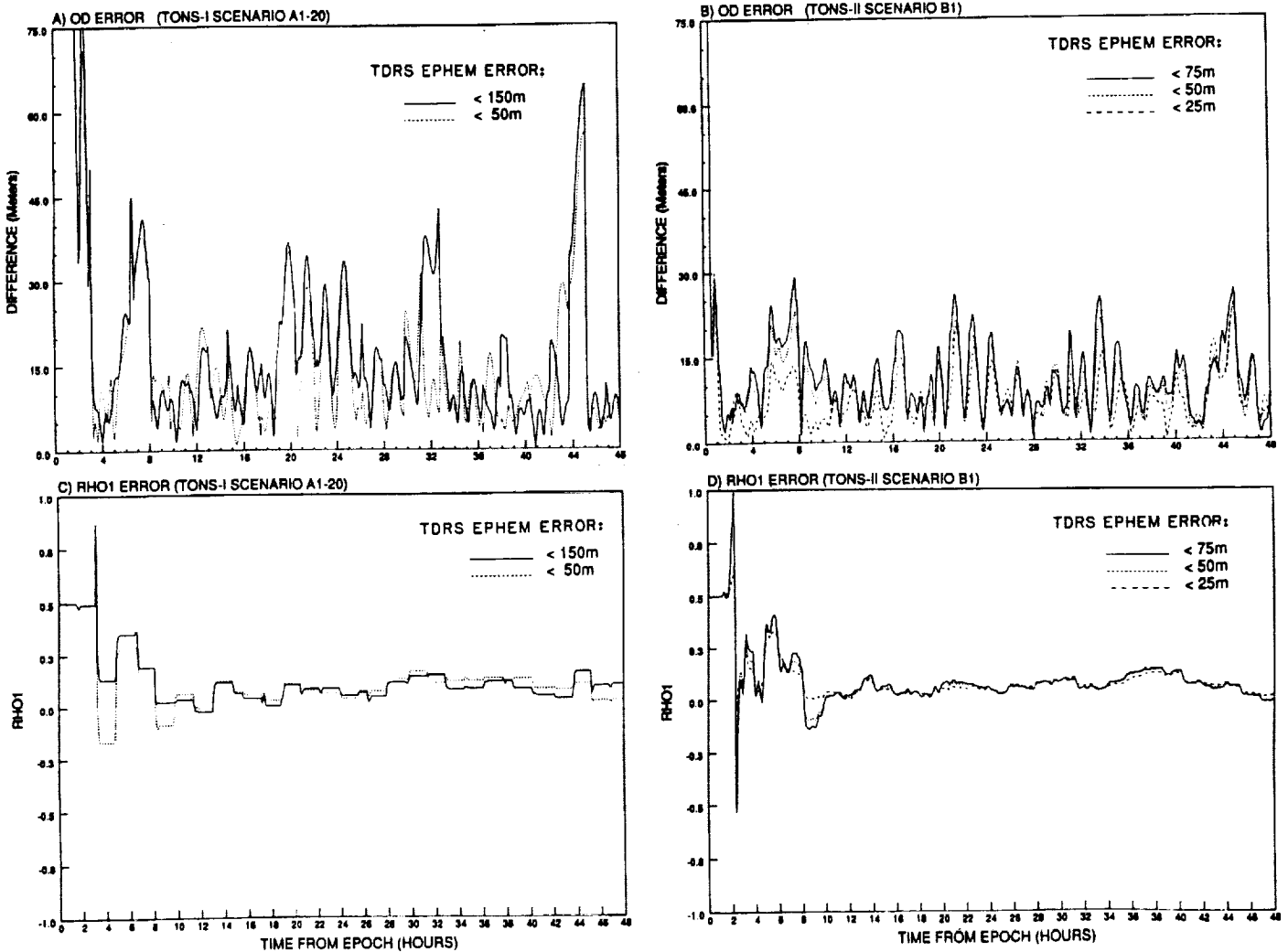

Figure 7:   Sample EOS Position and Drag (ρ_1) Estimation Error Profiles

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is subject to occasional peak errors under the postulated circumstances. Although the baseline OD requirement (100 m) can be supported, less sensitivity in achievable with more distributed tracking which also alternates between TDRSs (or ATDRSs) as in scenario B1.

With respect to atmospheric drag estimation capability, sample plots of the solutions for drag coefficient offset (p_1) from an initial value of 50% are given in Figure 7 for scenarios A1 and B1. Solutions are shown for nominal and above nominal TDRS ephemeris modeling errors. As the results in Table 5 indicate, solutions for p_1 indicate generally good convergence toward the assumed truth value of zero. Offsets are typically on the order of 0.1 or less (which is consistent with the 10% C_D error assumption used in the covariance analysis). Further analysis of the OD performance indicates that the peaks in ephemeris errors are also correlated with intervals requiring extended orbit propagation when the drag model was degraded (i.e., p_1 not converged). In practice, p_1 typically would not converge to zero, because of mismodeling in other drag model parameters and aliasing effects in the estimation process due to other mismodeling (e.g., TDRS/ATDRS ephemeris).

5.0 CONCLUSIONS

The covariance and simulation results for EOS navigation based on TONS indicate that:

- EOS position accuracy is within 25m (1σ) using TONS-I with a nominal scheduled tracking contact of 20 minutes/orbit and 14m (1σ) using TONS-II with unscheduled, near continuous beacon tracking.

    - The current EOS position accuracy requirement, 33m (1σ), could be met by both TONS-I and TONS-II.*

    - The proposed EOS position accuracy goal, 17m (1σ), could also be met by TONS-II (and by TONS-I if more intensive scheduled tracking is provided).

- TONS-I with scheduled service (e.g., 20 min/orbit) is more sensitive to occasional missed, unavailable, or poor geometry contacts than is TONS-II with unscheduled beacon service (near continuous).

- The TONS-II TD capability, 0.1 μsec (1σ), could easily support EOS time reference maintenance requirements ($\pm$ 10 μsec relative to UTC).

- Both TONS-I and TONS-II provide a transponder reference frequency determination (USO FD) capability of better than 0.35 x 10^{-10} parts (1σ), equivalent to 0.1 Hz (1σ) at S-band.

- TONS-I FD capabilities could support maintenance of the EOS time standard if its frequency reference (TRO) and the transponder reference (USO) are derived from a common source. (Incremental corrections to the time standard based on USO FD would lengthen the time between required timing calibrations with the USCCS.

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* The current EOS position accuracy requirement of 100m (3σ) and the goal of 50m (3σ) have each been divided by 3 for direct comparison with covariance analysis results.

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