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Filter Parameter Tuning Analysis for Operational Orbit Determination Support*

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Abstract

The use of an extended Kalman filter (EKF) for operational orbit determination support is being considered by the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD). To support that investigation, analysis was performed to determine how an EKF can be tuned for operational support of a set of Earth-orbiting spacecraft. The objectives of this analysis were to design and test a general purpose scheme for filter tuning, evaluate the solution accuracies, and develop practical methods to test the consistency of the EKF solutions in an operational environment. The filter was found to be easily tuned to produce estimates that were consistent, agreed with results from batch estimation, and compared well among the common parameters estimated for several spacecraft. The analysis indicates that there is not a sharply defined "best" tunable parameter set, especially when considering only the position estimates over the data arc. The comparison of the EKF estimates for the user spacecraft showed that the filter is capable of high-accuracy results and can easily meet the current accuracy requirements for the spacecraft included in the investigation. The conclusion is that the EKF is a viable option for FDD operational support.

Introduction

This paper discusses the results of a filter parameter tuning analysis for operational orbit determination support. The filter program used in the analysis was the personal computer (PC)-based Real-Time Orbit Determination/Enhanced (RTOD/E)** System. This program provides orbit determination capabilities for Tracking and Data Relay (TDRS) System (TDRSS)-supported user spacecraft and simultaneously estimates the states for two relay and one user spacecraft using TDRSS and the Bilateration Ranging Transponder System (BRTS) range and Doppler data. The data used in the analysis included one-way return-link Doppler tracking data for those spacecraft equipped with an ultra-stable oscillator (USO), which provides an accurate reference frequency. A more detailed discussion of the analysis is presented in Reference 1.

The analysis had the following three objectives:

- **To design a general purpose scheme** for tuning an extended Kalman filter (EKF) for operational support of a spacecraft
- **To evaluate the accuracies** achievable with RTOD/E against the accuracies attained with the batch least-squares orbit determination program of the Goddard Trajectory Determination System (GTDS)
- **To develop methods to test the consistency** of the EKF solutions independently of external results

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Parameter Tuning

The tunable parameters of RTOD/E are the following:

- **Gauss-Markov process noise model parameters** (base parameter value, decay time, and parameter variances) for the following estimation parameters:
  - **Tracking data biases** on the BRTS and the two-way tracking measurements, with separate biases by data type, estimated separately by data pass
  - **Drag** and **solar radiation pressure coefficients**
- **Random-walk process noise model parameters for the USO frequency bias** (base parameter value, additive deweighting variance, and associated time interval) and the **constant oscillator frequency drift** (for one-way data only)
- **Gravity auto-correlation parameters** for user spacecraft
- **Measurement noise standard deviation, measurement data rate**, and **data editing criteria**
- **Omission** and **commission degree variances** for Earth gravity models and **Error in the Earth's central body term** for the TDRS gravity process noise model

The analysis was designed assuming that the characteristics of a filter that performs orbit estimation satisfactorily are as listed below. A well-tuned filter should:

- Apply the majority of the correction from the first few measurements of a pass to the spacecraft position-velocity states.
- Bound the drag and solar radiation pressure coefficients and data biases to acceptable limits, which can be established from other estimates.
- Allow the estimates for the drag and solar radiation pressure coefficient to vary within a range of approximately 5-20 percent over a period of 1 to several days. Also, do not return to the "base" value but keep the estimate when propagating after the end of a data pass.
- Edit anomalous data.
- Produce realistic estimates of errors, consistent with comparisons with other estimates, as well as consistent with past experience in orbit determination and results from error analysis studies.

A parameter tuning procedure was developed with these characteristics in mind, and results from following the procedure were tested and evaluated as described in the following sections of this paper.

Analysis and Results

The data used for the tunable parameter analysis were TDRSS tracking data collected at GSFC for use in Flight Dynamics Division (FDD) orbit determination for periods from October 1990 to mid-December 1992. The TDRSS user spacecraft were the Earth Radiation Budget Spacecraft (ERBS), the Cosmic Background Explorer (COBE), the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE), Landsat-4, and the Ocean Topography Experiment (TOPEX)/Poseidon. These spacecraft were tracked by TDRS-3, -4, and -5 in east-west pairs. This report primarily discusses analysis for orbit determination of ERBS, COBE, EUVE, Landsat-4, and TOPEX supported by TDRS-4 and TDRS-5 for the early weeks of November, 1992. The spacecraft-specific parameters and findings for the RTOD/E results are summarized for the user spacecraft in Table 1 and for the TDRSs in Table 2.

Table 1. Filter Run Descriptions and Parameters for User Spacecraft (1 of 3)

General		
Parameters	Values	Comments
Force Model Parameters:	**Reference frame** = B1950.0 **Solar, lunar third-body perturbations** **Solar radiation pressure** **Drag** with Jacchia model **Integration Step** 1 min **GEM T3** Gravity Model (50x50)	Solar radiation pressure is computed for all spacecraft; drag only for user spacecraft.
Data-Related Parameters	**Editing criteria** = 3σ **Data available** = TDRSS range and Doppler, one-way return-link Doppler, BRTS range and Doppler **Data corrections** = tropospheric	RTOD/E also can use one-way forward-link Doppler; ionospheric corrections not available, but data biases are an estimation option.
ERBS		
Parameters	Values	Comments
Mission Description:	**Altitude** = 530 km **Inclination** = 57 deg **Maneuvers** w/thrusters = Yes during data span, modeled w/RTOD/E **Mass** = 2116.0 kg **Area** = 4.6 m^2 **User tracking data** = TDRSS range, Doppler **Data span** = Nov 5–15	Maneuver November 9 between $19^h\,08^m\,49^s$ and $19^h\,16^m\,37^s$, caused some difficulty.
Tunable Parameters: Data Related	**Measurement Data Biases** Decay time = 10 min σ = 4.5 m for range and 0.02 Hz for Doppler **Data rate** = 10 sec	
Tunable Parameters: Other	C_R = 1.2, applied C_D Gauss-Markov σ=0.5, time interval = 14400 min **Auto-correlation Values** (*R*, *I*, *C*) (min) = (15.226, 0.001, 30.153)	Sensitive to base value of C_D; change of 30% in value caused estimation failure. Auto-correlation parameters had to be inflated by 10 times nominal values.
Results:	**Data edited** = 6% **Position RSS 1σ estimated error** = 9–36 m	Reasonable agreement with GTDS solutions.
EUVE		
Parameters	Values	Comments
Mission Description:	**Altitude** = 520 km **Inclination** = 28 deg **No orbit maneuvers** **USO** on board **Mass** = 3245.05 kg **Area** = 16.3 m^2 **User Tracking data** = TDRSS Doppler, one-way return-link Doppler Data span = Nov 5–15	
Tunable Parameters: Data Related	**Data biases** Decay time = 10 min σ = 0.02 Hz for Doppler **Data rate** = 10 sec	
Tunable Parameters: USO	a_1 **deweighting** σ = 5×10^{-14} parts, interval = 10 sec a_2 = -8.1×10^{-11} parts/day	Changing USO a, deweighting σ from 1×10^{-11} to 5×10^{-14} parts removed a daily oscillation in S-band Doppler bias solutions.
Tunable Parameters: Other	C_R = 1.2, applied C_D Gauss-Markov σ=0.5, time interval = 14400 min **Auto-correlation values** (*R*, *I*, *C*) (min) = (1.384, 0.0002, 2.7518)	

Table 1. Filter Run Descriptions and Parameters for User Spacecraft (2 of 3)

EUVE (Cont'd)		
Parameters	Values	Comments
Results:	**Data edited** = 4% **Position RSS 1 σ estimated error** = 5-31 m	Sensitive to base value of C_D; change of 5% in value caused estimation failure. Including/not including the TDRSS range data made a maximum difference of 24 m.
Landsat-4		
Parameters	Values	Comments
Mission Description:	**Altitude** = 690 km **Inclination** = 98 deg **Maneuvers with thrusters** = none during data span **Mass** = 1869.45 kg **Area** = 12.2644 m^2 **User Tracking data:** TDRSS range, Doppler **Data span** = Nov 5–15	
Tunable Parameters: Data Related	**Data biases** Decay time = 10 min σ = 4.5 m for range; 0.02 Hz for Doppler **Data rate** = 10 sec	
Tunable parameters: Other	C_R = 1.5, applied C_D Gauss-Markov σ=1.0, time interval = 14400 min **Auto-correlation values** (*R*, *I*, *C*) (min) = (1.7887, 0.0003, 3.5391)	Insensitive to changes in TDRS C_R Gauss-Markov and *GM* error parameters, as long as one or the other was set to enlarge the TDRS covariances
Results	**Data edited** = 2% **Position RSS 1 σ estimated error** = 4–13 m	
TOPEX/Poseidon		
Parameters	Values	Comments
Mission Description	**Altitude** = 1336 km **Inclination** = 66 deg **Orbit maneuver capability**, none performed during data span **USO** on board **Mass** = 2417.2 kg **Area** = 32 m^2 **User Tracking data** = TDRSS Doppler, one-way return-link Doppler **Data span** = Nov 5–19	Venting was not modeled.
Tunable Parameters: Data Related	**Data biases** Decay time = 10 min σ = 0.02 Hz for Doppler **Data rate** = 20 sec	
Tunable Parameters: USO	a_1 **deweighting** σ = 2.5×10^{-14} parts, interval = 20 sec a_2 = 1.8×10^{-11} parts/day	Slope of estimated S-band Doppler bias indicates a_2 changed to ≈ 2.6×10^{-11} parts/day about Nov 11, 1992. Long-term filter behavior sensitive to changes in this term. A daily oscillation was seen in estimated S-band Doppler bias, not removed by changing USO a_1 deweighting σ.
Tunable Parameters: Other	C_R Gauss-Markov σ=0.25, time interval = 14400 min C_D Gauss-Markov σ=1.0, time interval = 14400 min **Auto-correlation values** (*R*, *I*, *C*) (min) = (3.2043, 0.0172, 6.3120)	
Results	**Data edited** = 3% **Position RSS 1 σ estimated error** = 1.5–2.2 m	Best results when parameters set for a small position/velocity covariance.

Table 1. Filter Run Descriptions and Parameters for User Spacecraft (3 of 3)

COBE		
Parameters	Values	Comments
Mission Description	**Altitude** = 880 km **Inclination** = 99 deg **No orbit maneuver capability** **Mass** = 2055. kg **Area** = 17.8 m^2 **User tracking data:** return-link one-way Doppler **Data span** = Nov 5–15	
Tunable Parameters: Data Related	**Data rate** = 10 sec	
Tunable Parameters: USO	a_1 **deweighting** $\sigma = 5.0\times10^{-14}$ parts, interval of 10 sec $a_2 = -3.0^{-11}$ parts/day	S-band Doppler bias estimate improved, but not significantly, by changing a_1 noise; estimator follows noise in data by changing USO frequency bias estimates.
Tunable parameters: Other	C_R = 1.42, applied C_D Gauss-Markov σ=0.5, time interval = 14400 min **Auto-correlation** values (*R, I, C*) (min) = (2.1739, 0.0020, 4.2959)	
Results	**Data edited** = 3% **Position RSS 1 σ estimated error** = 6-10 m	S-band Doppler bias estimate of significantly poorer quality than GTDS estimates.

Table 2. Filter Run Descriptions and Tunable Parameters for Relay Spacecraft

Parameters	Values	Comments
Mission Description:	**Geosynchronous, low-inclination,** tracking relay spacecraft; **no orbit maneuvers** during data spans	Momentum unloading maneuvers (attitude maneuvers performed with thrusters) occurred.
Force Model Parameters	**Integration step** 1 min **GEM T3** gravity model (8×8)	
Tunable Parameters: Data-Related	**BRTS data biases** Decay time = 60 min σ = 4.5 m for range; 0.02 Hz for Doppler **Measurement noise** Range = 4.0 m Doppler = 0.02 Hz (0.004 for TOPEX)	Measurement noise does not differentiate by type (i.e., range noise applies to all ranges, Doppler noise applies to all Doppler).
Tunable Parameters: Other	C_R Gauss-Markov σ=0.05, time interval = 14400 min *GM* error = 5.0	Increasing *GM* error from 0.05 to 5.0 (2 orders of magnitude) increased TDRS position σ by a factor of 2–3. Trajectories estimated using a C_R noise of 0.3 plus a *GM* error of 0.05 were very close to estimates with a C_R noise of 0.05 plus a *GM* error of 5.0. Both terms increase the TDRS position/velocity covariance; decreasing one while increasing the other left the covariance approximately the same.
Results:	**Position RSS 1σ estimated error:** 10–30 m (slightly lower with TOPEX/Poseidon)	

RTOD/E computes the user spacecraft position/velocity noise covariance matrix contribution arising from the geopotential errors using the auto-correlated gravity modeling technique described in Reference 2. The gravity error is approximated with an integration of a matrix product that includes a diagonal 3x3 matrix with diagonal elements equal to the constant auto-correlation integrals for the spacecraft. The auto-correlation integrals are computed for each spacecraft based on its approximate orbit and the geopotential model used.

Experiments with the geopotential error process noise matrices for the user spacecraft showed that the computed values for the auto-correlation integrals using this technique produced a spacecraft position-velocity covariance that was small in comparison to the expected errors in the solutions. However, further experimentation showed that better results were obtained for the estimator with a somewhat small covariance. The ERBS processing needed an inflation of the auto-correlation parameters by 10 times to continue past both the November 9 ERBS yaw maneuver and TDRS-4 momentum unloading. ERBS was the only spacecraft for which this inflation was necessary.

Three of the spacecraft in this analysis carried USOs. In RTOD/E, the USO oscillator bias is modeled as a random-walk process with a linear drift term. The bias is propagated as

$$b(t_{i+1}) = b(t_i) + a_2 \cdot \Delta t \tag{1}$$

where

$b(t_{i+1})$ = fractional frequency bias at time t_{i+1}, initialized as a_1 from the user input
a_2 = constant oscillator frequency drift, input by the user
t_{i+1}, t_i = times of current and previous updates, respectively
Δt = $t_{i+1} - t_i$

The USO frequency bias variance is propagated from t_i to t_{i+1} as

$$P(t_{i+1}) = \hat{P}(t_i) + d \tag{2}$$

where
$\hat{P}(t_i)$ = updated bias variance at t_i
$P(t_{i+1})$ = predicted bias variance at t_{i+1}
d = filter deweighting variance = $[N + (v/D)]\sigma^2$
D = time interval associated with the deweighting
N = number of intervals of length D in $(t_{i+1} - t_i)$
v = fractional part of D in $(t_{i+1} - t_i)$ so that $t_{i+1} - t_i = ND + v$
σ = deweighting standard deviation

The effect of this random walk model is to add a process noise of σ^2 every D time interval. The values for the USO parameters used for the final EUVE estimates add an error of 5×10^{-14} parts (0.00011 Hz) in a 10-second time interval, which adds a total of approximately 1.0 Hz per day. Similar levels of error were used for TOPEX/Poseidon and COBE.

TOPEX/Poseidon science data processing requires accurate orbit estimation for the ocean topography data analysis. For that reason, highly precise orbit ephemerides (POEs) were computed by the GSFC Space Geodesy Branch from laser ranging and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking data. The POEs provided a highly accurate independent comparison for the RTOD/E solutions. The details of how these solutions were generated are presented in Reference 3. Four cases are extracted and presented in Figure 1 and Table 3 to show the effects of changes in the tunable parameters on the comparisons. The daily root mean square (RMS) of the total position differences between these four cases and the trajectories from the POEs are plotted in Figure 1. These values have been computed on a daily basis, and are plotted for the comparisons made for November 7–18, 1992. Table 3 shows the variations among the tunable parameters for these cases. Of these terms, the solar radiation pressure coefficient (C_R), the *GM* error, and the range measurement noise primarily affected the TDRSs solutions. The USO noise in Case A, 1×10^{-14} parts, was too small, and excessive one-way data were edited. As seen in Figure 1, after November 8 this case compares the least well with the POE. Case B does not begin to compare well with the POE until November 11. Case C had the best of the comparisons, coming to within 2.3 meters of the POE solution on November 12. Case D did not compare as well as Case C with the POE, but its TDRS trajectories agreed better with the GTDS for TDRS-4 and about as well for TDRS 5. The plot shows the long timespan necessary to distinguish the performance of the filter with different sets of tunable parameters.

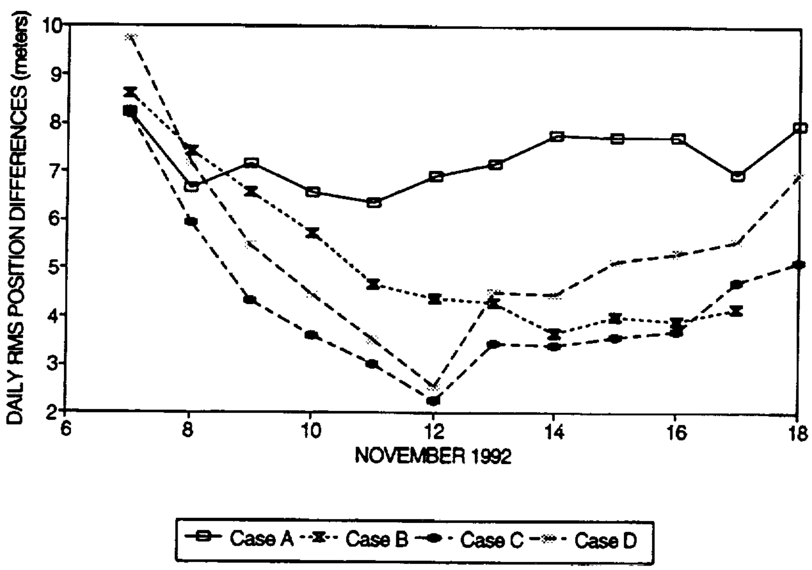

Figure 1. Daily RMS Values From Differences Between RTOD/E and POE TOPEX/Poseidon Trajectories

Table 3. Effects of Changing TOPEX/Poseidon Tunable Parameters

	Case A	Case B	Case C	Case D
C_R Gauss-Markov σ	0.3	0.3	0.3	0.01
GM Error	0.05	0.05	5.0	5.0
a_1 Deweighting σ (10^{-12} parts) Time Interval	0.01 10	0.1 10	0.1 10	0.025 20
a_2 (10^{-11} parts/day)	1.7	1.7	2.0	1.8
BRTS Range Noise	0.4	0.4	4.0	4.0
Comparison With GTDS Solution (best daily RMS)	NA	3 m	2.07 m	3.6 m
Comparison With TDRS GTDS Solutions (best daily RMS)	NA	20 m	18.1 m	17.4 m
Comments	Deletes excessive data	Fair POE comparison	Best POE comparison	Final tunable parameter set

Figure 2 shows the estimated S-band Doppler bias from Case D, and, for comparison, the estimated bias from the GTDS solution from November 7–17. An oscillation with a frequency of .8 to .9 day was present in all of the TOPEX/Poseidon solutions, and was not diminished by decreasing the value of the a_1 deweighting σ. This is in contrast with the EUVE results, where a similar oscillation was removed by decreasing the deweighting σ. Other effects of changes to the tunable parameters on the TOPEX/Poseidon solutions are summarized in Table 1.

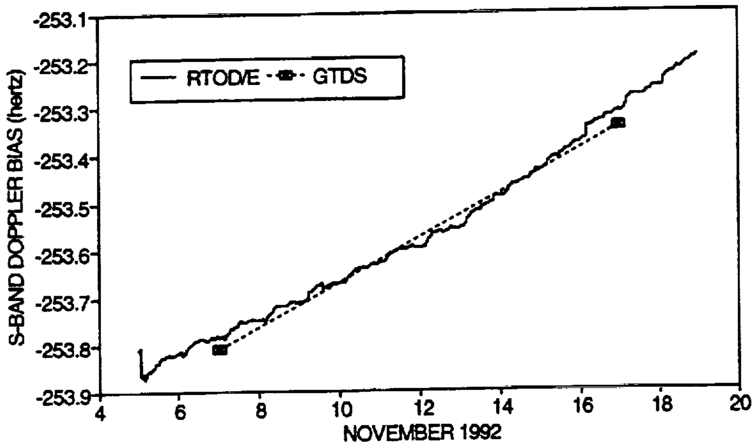

Figure 2. Estimated S-Band Doppler Bias for TOPEX/ Poseidon USO From RTOD/E and GTDS

The scheme for setting the tunable parameters which resulted from the analysis is as follows:

1. Obtain the auto-correlation integrals for omission plus commission errors appropriate to the geopotential model, and degree and order of that model, that will be used. Propagate the user and covariance to determine the rate of covariance growth. Also, inspect the TDRS covariance growth to determine if it will be sufficient, or will need an inflation of the *GM* error. It may be necessary to increase the default auto-correlation integrals if the user spacecraft has an attitude maneuver performed with thrusters or the *GM* error if one or both TDRSs perform a momentum unloading maneuver (which uses thrusters).

2. Set the user spacecraft drag process noise σ to a value between 0.5 (for drag-perturbed spacecraft such as EUVE) and 1.0 (for spacecraft such as TOPEX in orbits with less drag perturbation), and set the associated Gauss-Markov time interval to a long enough time to make the model effectively a random walk model.

3. Set the TDRS solar radiation pressure process noise standard deviation to a relatively small value (0.05 was one example) and also set the time interval to a large number. This gives C_R estimates that compare well with GTDS estimates for TDRS solutions done with BRTS data only. The only user spacecraft for which C_R was estimated was TOPEX. The process noise standard deviation was set to 0.25, a value that gave results that allowed (along with the drag noise used) RTOD/E to accommodate the anomalous thrusting TOPEX experienced.

4. Set the standard deviations on the biases for BRTS range and Doppler data to accommodate the unmodeled effects of ionospheric refraction and station location errors. The values used in this analysis were 4.5 m for the range and 0.02 Hz for the Doppler. The time interval used was immaterial, since these are local solve-for parameters that are reset to the a priori values at the end of each pass. The biases on the TDRSS range and Doppler are set similarly, except that they are not local parameters in this implementation, and need a time value larger than a pass length, but small enough to return to the a priori before the next pass begins.

5. Set the USO estimation parameters to be commensurate with previous estimates, or the oscillator specifications if no previous estimate exits. The drift needs to be calibrated by evaluating long frequency bias estimates, and changed as necessary.

The appropriate level of the tunable parameters was checked with the assessment criteria, with particular attention to the variances on the estimated parameters.

GTDS Solutions

GTDS was used to compute batch-estimation orbit solutions for the TDRSS user and TDRSs for comparison with the RTOD/E solutions. The user spacecraft orbit determination solutions were computed separately from the TDRS orbit solutions, with all user spacecraft estimation performed with the same TDRS orbits. The TDRS spacecraft orbit determination was performed using techniques identified for the TOPEX/Poseidon analysis described in Reference 3. To improve the estimation accuracy, the TDRS data spans were selected to avoid all maneuvers and momentum unloads. Only BRTS range data were used. The ground tracking [White Sands Ground Terminal (WSGT)] antenna biases were estimated to correct for errors in the calibration of the range-zero sets and the measurement of the applied user and TDRS spacecraft transponder delays. Specific force and observation modeling options used in the analysis are given in Table 4.

In general, in the user spacecraft orbit determination solutions, the state, station range biases or USO transmit frequency and frequency drift biases, and two (sometimes three) drag modeling correction terms were estimated. The TOPEX/Poseidon solutions estimated eight thrust factors, instead of drag, to compensate for an anomalous unmodeled force acting on the spacecraft.

As with the TDRSs, station range biases were estimated for each of the WSGT antennas. The software used for the analysis had limitations (since removed) preventing the use of station range bias solve-fors in conjunction with the USO bias and drift estimation. Therefore, TDRSS range data were not used when USO-based one-way return Doppler data were available.

The EUVE batch estimation options are generally the same as those used in the TDRSS Onboard Navigation System (TONS) experiment for comparison with the TONS filter (Reference 3). In particular, the standard deviations for the included tracking data types are the same as the TONS processing, which differ from the nominal operational values used for the other spacecraft.

The batch orbit determination solution performance was quantified using solution overlaps and data type mean and standard deviations of the solution residuals. User solutions were overlapped by 50 percent of the data span, with the exceptions of COBE, which had no overlapping solutions, and ERBS, which experienced a yaw turn on November 9. TDRS solution ephemeris consistency was measured by comparing a 12-hour predictive extension to the next definitive period.

Figure 3 shows results of the overlap comparisons of the GTDS solutions for Landsat-4, EUVE, and ERBS. These solutions were 2-day arcs with 1-day overlaps, except for ERBS, around the yaw maneuver on November 9. The TOPEX comparison shown in Figure 3 is against the POE. The COBE solution was a single arc through the entire data span, so there were no overlaps.

Assessment Summary

The assessment criteria and results are summarized in the following:

Anomalous behavior: Criteria: The anomalies noted were divergence, editing of much or all of the tracking data for a satellite, or extreme values of C_D or C_R. Results: Anomalous data editing was often traced to inappropriate values of C_D, or to unmodeled attitude maneuvers of the user or TDRS spacecraft.

Comparison with external solutions: Criteria: Comparisons were made with GTDS solutions and with precision ephemerides provided for TOPEX. When the RTOD/E and GTDS solutions are made on the same basis (same reference frame, same atmospheric model data, and same Earth orientation data), the results should agree to within their cumulative accuracies. Results: All of the user- and TDRS-estimated trajectories from the final parameter set for the November data have been compared to the companion GTDS solutions. The comparisons for TOPEX were

Table 4. Parameters and Options Used in the GTDS Solutions

Orbit Determination Option	User Spacecraft	TDRS
Estimated Parameters	Orbital state: position and velocity Drag ($a_{1..3}$): all except TOPEX Thrust (8 constants): TOPEX C_R: COBE and TOPEX WSGT range biases: ERBS and Landsat-4 USO bias and drift: COBE, EUVE and TOPEX	Position and velocity C_R WSGT range biases
System of Integration	Mean-of-J2000	Mean-of-J2000
Integration Step Size	60 sec	600 sec
Tracking Measurements	Two-way Doppler (TD2S): all except COBE Two-way range (TR2S): ERBS and Landsat-4 One-way Doppler (TD1S): COBE, EUVE, TOPEX	BRTS range
Data Span	2 Days: ERBS, Landsat-4, and EUVE 8 Days: COBE 10 Days: TOPEX	See text
Data Rate	1 per 10 sec (1 per 60 sec for TOPEX)	1 per 10 sec
Editing Criterion	3σ Central angle to local horizon	3σ
Measurement Weight σ	TD2S: .25 Hz (.1 Hz for EUVE) TR2S: 30 m (10 m for EUVE) TD1S: .13 Hz (.075 Hz for EUVE)	10 m
Area	COBE: 17.8 m^2 ERBS: 4.7 m^2 Landsat-4: 12.3 m^2 EUVE: 16.3 m^2 TOPEX: variable mean area model	40 m^2
Mass	COBE: 2155.00 kg ERBS: 2116.00 kg Landsat-4: 1869.45 kg EUVE: 3243.05 kg TOPEX: 2417.20 kg	Approximately 1950 kg, as appropriate for fuel state
C_D	2.2 (2.3 for COBE)	N/A
C_R	COBE: Estimated ERBS: 1.2 Landsat-4: 1.5 EUVE: 1.2 TOPEX: Estimated	Estimated
Atmospheric Density Model	Jacchia-Roberts	N/A
Geopotential Model	GEM-T3 50x50	GEM-T3 20x20
Ionospheric Refraction Ground-to-S/C S/C-to-S/C	 Yes No (central angle edit instead)	 Yes N/A
Antenna Offset	Constant radial—cobe: -1.0 m (positive up) ERBS: 0.0 m Landsat-4: 2.5 m EUVE: 0.0 m TOPEX: 3.0 m	No
Tropospheric Refraction	Yes	Yes
Polar Motion	Yes	Yes
Solid Earth Tides	Yes	Yes

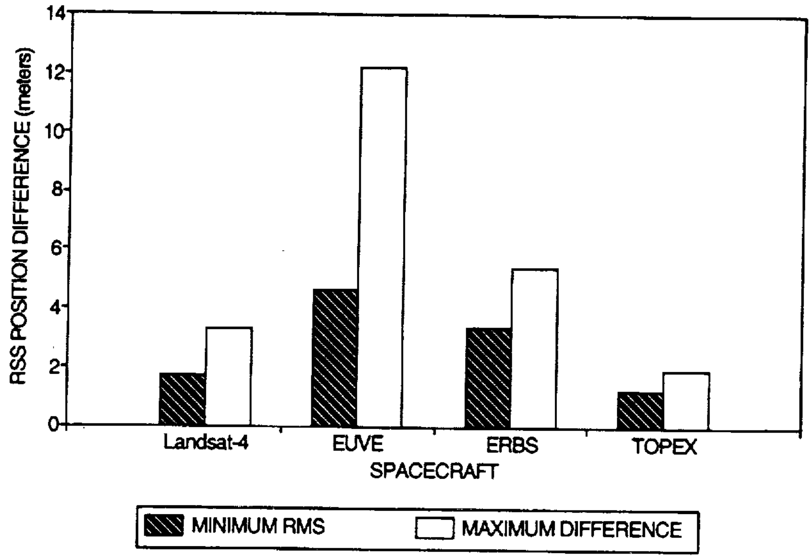

Figure 3. GTDS Overlap Comparisons

consistent with the comparisons with the POE solutions. The comparisons for COBE, EUVE, ERBS, Landsat-4, TDRS-4, and TDRS-5 all were considered reasonable. There was no evidence of a bias in the differences, as they were evenly distributed about zero. Figure 4 shows a plot of the daily RMS values for the differences of the RTOD/E and GTDS solutions for these spacecraft. The COBE estimate shows significantly more disagreement due to poor tracking geometry. Figure 1, given earlier, shows a comparison of RTOD/E and POE results for TOPEX.

Comparison of TDRS solutions: Criteria: Since the same TDRSs are used to support several spacecraft, the various estimates of the same TDRS orbits can be compared. Agreement to within the accuracies of the TDRS solutions (approximately 50 m) is expected from the filter estimates. Results: The TDRS solutions prepared by RTOD/E from the final set of tunable parameters for October and November were compared with TDRS solutions from RTOD/E solutions for other user spacecraft. These generally show mutual agreement to within 50 m (1 σ), with some excursions.

C_D values for user spacecraft: Criteria: The GTDS DC solutions were used for comparison of the drag parameter estimates. Results: It was observed that RTOD/E was sometimes quite sensitive to the value for the C_D Gauss-Markov base parameter. Comparisons with the GTDS results were generally acceptable. Figure 5 shows the comparison of the EUVE RTOD/E results with the GTDS estimates.

C_R values for TDRSs: Criteria: The GTDS solutions provide estimates of these values used for comparison. In addition, since the same TDRS will be estimated repeatedly with different spacecraft, the different C_R estimates can be compared, and their mutual agreement used as a measure of filter solution quality. Results: The comparison of the RTOD/E estimates of C_R with the GTDS solutions for the November 12–19 data span showed significantly more variation from RTOD/E than from GTDS. For both the October and November data sets, the RTOD/E solutions showed reasonable mutual agreement.

Biases on the BRTS range: Criteria: A bias in excess of 15 m is unacceptable. Results: Isolated instances of large range biases were observed in otherwise acceptable cases following TDRS momentum unloading maneuvers.

S-band bias: Criteria: The S-band bias is the effect of the USO bias on the one-way return-link Doppler tracking data. The RTOD/E results were compared with GTDS estimates of this bias. Results: The values for the S-band bias were all acceptable. An example was shown in Figure 2. The filter was sensitive to the a_2 constant value (frequency drift). It could not accommodate values in error by 25 percent in long data arcs, and would delete excessive one-way data at the end.

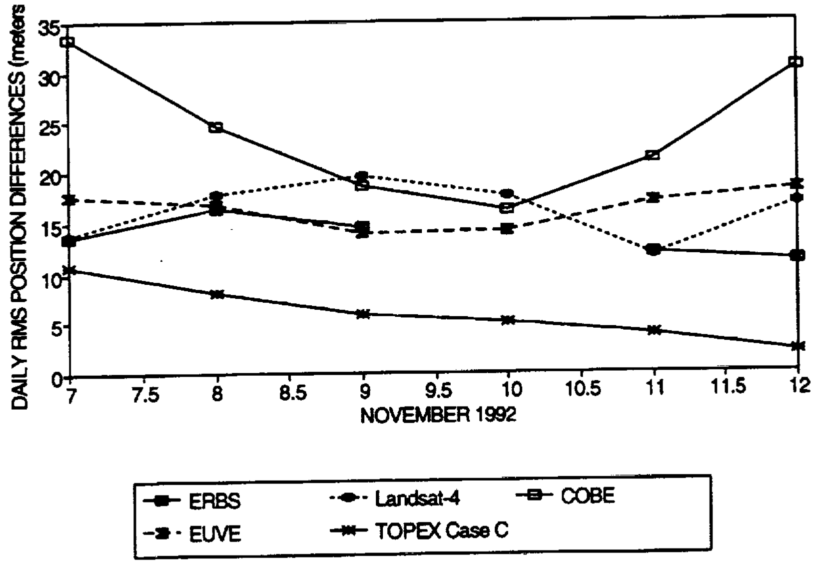

Figure 4. Daily Root-Mean-Square Differences for RTOD/E and GTDS Estimated Trajectories

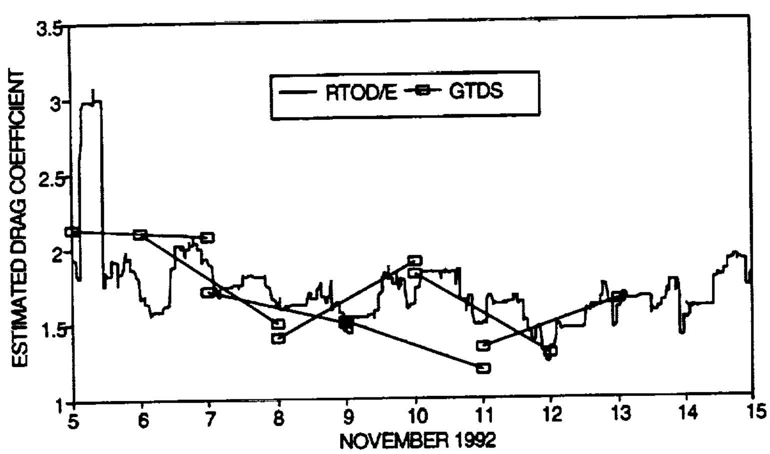

Figure 5. Estimated EUVE C_D From RTOD/E and GTDS

Data statistics: Criteria: The numbers of accepted and rejected observations of valid data are examined after the filter has stabilized, and the residuals are examined to look for any patterns in data rejection. Results: Deleting a significant portion of the data or deleting data in specific patterns were found to be good indicators of problems in the solution quality. Solutions with excessive amounts of data deleted did not compare well with the external results.

Covariance magnitudes: Criteria: The standard deviations of the estimated positions, C_D, C_R, and USO bias were examined. These are expected to stay within reasonable values, based on previous experience with orbit determination and orbit determination error analysis. Once the filter has completed the initial stabilization process, the covariance is expected to stay bounded in both maximum and minimum values as long as the data rate and frequency stay approximately the same and there are no spacecraft maneuvers. Unacceptable behavior includes taking extremely small or continuously decreasing values during the entire data span. Results: Acceptable values for the covariances were achieved for all parameters. It was observed that the best comparisons were obtained when the covariance was tuned to be somewhat small as judged by comparisons with external solutions, so that the filter did not react rapidly to new data. Unfortunately, then the covariance does not respond quickly to anomalous events, leading to some cases in which the residuals were outside the acceptance criteria for multiple passes, sometimes rejecting all data and diverging.

Solution propagation: Criteria: Vectors were extracted from the estimated trajectories and propagated for comparison with later estimated trajectories. Changes in the maximum differences can be used to measure the effect of changes to the tunable parameters on the filter. A procedure was developed that automatically generated a 24-hour predicted ephemeris and a definitive ephemeris for this comparison. Results: The comparison of the predicted versus the estimated was also a major indicator of the relative merits of the runs. However, it can not be blindly applied, as instances arose in which significant amounts of data were deleted for the day selected for the comparison, producing a very good comparison between the predicted and estimated trajectories—since they were basically both predicted. Also, for some cases in which excessive data were deleted at the end, the comparison was done before that part of the data arc, and did not reveal the problem.

The results for November for each of the user spacecraft from the application of these criteria are summarized in Table 5.

Table 5. Summary of Final Results for November Data

Results	ERBS	EUVE	COBE	Landsat-4	TOPEX/ Poseidon
User Data Edited	6%	4%	<1%	2%	3%
Estimated Position Error (1σ) (m)					
TDRS 4	19-31	17-32	16-30	14-31	8-12
TDRS 5	11-27	11-27	10-26	9-26	7-19
User S/C	9-36	5-31	5-10	4-13	1.5-2.2
Predicted vs Estimated (m) (24 hours)					
TDRS 4	261	262	226	261	250
TDRS 5	75	106	118	126	109
User S/C	34 (18-Hour)	327	41	53	15
GTDS Solution Comparisons (best RMS, m)					
TDRS -4	26.7	27.8	40.4	16.6	17.4
TDRS -5	8.4	19.9	64.5	11.7	23.4
User spacecraft	11.1	14.0	16.2	11.7	2.47
TOPEX POE Comparison (best RMS, m)					2.26

Conclusions

The objectives of this filter parameter timing analysis were met. (1) A general purpose scheme for tuning the filter for operational support has been developed and tested. (2) Results are presented for the comparison with GTDS solutions, which are in agreement with the accuracy of the estimation as found by comparison with the TOPEX/Poseidon POE solutions. The comparison of the RTOD/E estimates for EUVE, ERBS, COBE, Landsat-4, and TOPEX/Poseidon with external results shows that the filter is capable of quite accurate results, and can certainly meet the accuracy requirements for daily operational support for the TDRSS user spacecraft and the TDRSs. (3) Methods for testing the consistency of the EKF solutions independently of external results have been proposed and tested.

The following is a summary of the results of the tunable parameter analysis for TOPEX/Poseidon, ERBS, EUVE, Landsat-4, and COBE:

- The best TOPEX/Poseidon comparisons with the POE were obtained when the tunable parameters were set to provide a small covariance, equal to about half the accuracy of the estimated trajectory.

- Very long (2–3 weeks as opposed to 3–4 days) estimation spans may be necessary to distinguish among tunable parameter options. The effect of the USO bias drift parameter on the solution, for example, was not evident with short spans.

- All maneuvers, both attitude and orbit, done with thrusters must be accommodated, either by specific use of maneuver modeling, and/or by enlarging the covariance matrix with the tunable parameters for success in estimating the spacecraft trajectory.

- Drag base value, noise, and decay time—Extremely important for drag-perturbed spacecraft. The decay time must be set long enough for this term to act like a random walk. The test filter is not very tolerant of poor guesses for the base value (a priori value). This would not be acceptable for an operational filter, which must accommodate poor initial estimates.

- C_R Gauss-Markov parameters for TDRSs (base value, noise, and decay time)—Physical reasons would imply that the decay time should be set to a long value, so that this model acts more like a random walk than a Gauss-Markov parameter. The C_R Gauss-Markov standard deviation was adjusted until the estimates were in acceptable agreement with the GTDS results.

- Gravity auto-correlation parameters—These directly affect the size of the user covariance in propagation. The tests have included values from 1 to 100 times the base values for a given spacecraft. The most accurate results were obtained with the unscaled nominal. This produces a position/velocity covariance that is somewhat small considering the comparisons with external results.

- Error in *GM*—This directly affects the size of the TDRS covariances in propagation. The model value for the gravitational model used based on the estimated error in *GM* (.005 km^2/cm^3) is so small that it only adds about a meter over a day of prediction. A value of 5.0 was needed to assist in estimating through TDRS momentum unloading maneuvers.

- Data sampling—Not much of an effect for two-way tracking. The data rate needs to be at least 1-per-20 seconds for 1-way Doppler data for the most accurate results.

- Data editing criteria—Increasing the editing criteria from 3 to 100 or 1000 to get past problems in initialization produced problems with the TDRS solutions (such as spikes in the C_R estimates and exceptionally large range bias estimates) when a bad observation or two was accepted.

- USO bias—RTOD/E appears to estimate the bias with little difficulty for arc lengths of a week or less, but can have difficulty for longer arcs if the drift is not set to a high degree of accuracy. The RTOD/E model cannot accommodate changes in the drift. The bias deweighting factor standard deviation, σ, must be tuned very carefully, in concert with the frequency drift.

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