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Accurate Orbit Determination Strategies for the Tracking and Data Relay Satellites*

D. H. Oza, D. T. Bolvin, J. M. Lorah, and T. Lee
Computer Sciences Corporation (CSC)
Lanham-Seabrook, Maryland, USA

C. E. Doll
Goddard Space Flight Center (GSFC)
Greenbelt, Maryland, USA

Abstract

The National Aeronautics and Space Administration (NASA) has developed the Tracking and Data Relay Satellite (TDRS) System (TDRSS) for tracking and communications support of low Earth-orbiting satellites. TDRSS has the operational capability of providing 85-percent coverage for TDRSS-user spacecraft. TDRSS currently consists of five geosynchronous spacecraft and the White Sands Complex (WSC) at White Sands, New Mexico. The Bilateration Ranging Transponder System (BRTS) provides range and Doppler measurements for each TDRS. The ground-based BRTS transponders are tracked as if they were TDRSS-user spacecraft. Since the positions of the BRTS transponders are known, their radiometric tracking measurements can be used to provide a well-determined ephemeris for the TDRS spacecraft.

For high-accuracy orbit determination of a TDRSS user, such as the Ocean Topography Experiment (TOPEX)/Poseidon spacecraft, high-accuracy TDRS orbits are required. This paper reports on successive refinements in improved techniques and procedures leading to more accurate TDRS orbit determination strategies using the Goddard Trajectory Determination System (GTDS). These strategies range from the standard operational solution using only the BRTS tracking measurements to a sophisticated iterative process involving several successive simultaneous solutions for multiple TDRSs and a TDRSS-user spacecraft. Results are presented for GTDS-generated TDRS ephemerides produced in simultaneous solutions with the TOPEX/Poseidon spacecraft. Strategies with different user spacecraft, as well as schemes for recovering accurate TDRS orbits following a TDRS maneuver, are also presented. In addition, a comprehensive assessment and evaluation of alternative strategies for TDRS orbit determination, excluding BRTS tracking measurements, are presented.

1.0 Introduction

This paper assesses the accuracy achievable using various techniques for performing Tracking and Data Relay Satellite (TDRS) orbit determination using the Goddard Trajectory Determination System (GTDS), which is an operational batch least-squares orbit determination system, and the Orbit Determination Error Analysis System (ODEAS) covariance analysis system, both used within the Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD).

The TDRS System (TDRSS) is a geosynchronous relay satellite network, which currently consists of five geosynchronous spacecraft and the White Sands Complex (WSC) located at White Sands, New Mexico. Three of the five TDRSs (TDRS–East, TDRS–West, and TDRS–Spare, located at 41 degrees, 174 degrees, and 62 degrees west longitude, respectively) actively support tracking of TDRSS–user spacecraft. One of the remaining TDRSs (located at 275 degrees west longitude) is used only for satellite communications, while the other TDRS (located at 46 degrees west longitude) is being reserved for future use. TDRSS can provide 85– to 100–percent coverage, depending on spacecraft altitude. The Bilateration Ranging Transponder System (BRTS) provides range and Doppler tracking measurements of the TDRSs for TDRS orbit determination.

Currently, the operational accuracy requirement for TDRS orbit determination is 600 meters (3σ), which is driven by Space Transportation System (STS) support. The TDRS orbit accuracy requirements for other currently supported FDD missions are less strict. Current operational procedures at FDD produce TDRS orbits accurate to 150 meters (3σ). For future mission support, however, the TDRS orbit determination accuracy requirements will become more stringent. For example, the upcoming Earth Observing Satellite (EOS) AM-1 accuracy requirement for TDRS orbits is 75 meters (3σ), which is not met by current operational TDRS orbit determination solutions. This requirement raises the need to develop improved technical approaches and procedures.

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Previous FDD precision orbit determination analysis results indicated that TDRS orbit determination errors are a significant error source in TDRSS-user orbit determination (Reference 1). To obtain high-accuracy TDRSS-user orbits, new methods are needed that improve and refine TDRS orbit determination accuracy over the current operational support procedure.

The current operational method for determining TDRS orbits uses the radiometric ranging measurements acquired through BRTS. For standard support, only the range measurements are used over 42-hour arcs to determine position, velocity, a solar pressure coefficient, and a range measurement bias in a separate solution for each TDRS. Previous analysis (Reference 2) demonstrated that a dramatic improvement in overlap consistencies, reducing them from the 40- to 50-meter level for a separate solution for TDRS to the 20- to 30-meter level, was possible by performing simultaneous TDRSs/TDRSS-user orbit determination using a low-Earth orbiting TDRSS-user satellite. Since this earlier analysis in 1990, the force modeling used at the FDD has improved significantly, most notably after the launch of TOPEX. With better force modeling for a low-Earth orbiting TDRSS-user, which will reduce dynamic errors, it is expected that in a simultaneous solution the TDRS orbit accuracy can be improved compared to the earlier analysis. This concept is further developed and exploited in the current analysis.

A variety of innovative techniques for enhancing TDRS orbit determination accuracy, most of which involve the generation of a series of simultaneous TDRSs/TDRSS-user orbit solutions to calibrate the TDRSS range measurement biases, are developed and analyzed. In this study, the TDRSS users investigated are the Ocean Topography Experiment (TOPEX)/Poseidon, Earth Radiation Budget Satellite (ERBS), and Landsat-4 spacecraft. It is important to note that, just as TDRS orbit accuracy affects TDRSS-user orbit determination accuracy, TDRSS-user accuracy also affects TDRS orbit accuracy when performing simultaneous TDRS/TDRSS-user orbit determination. Since TDRSS-user orbit determination error is normally dominated by geopotential and atmospheric drag errors, higher altitude spacecraft such as TOPEX/Poseidon will significantly reduce these detrimental effects on TDRS orbit determination and provide more accurate estimates of the TDRS orbits. Therefore, the simultaneous TDRS/TDRSS-user solutions using the lower-altitude ERBS and Landsat-4 spacecraft are not expected to provide as accurate TDRS orbits as those determined using TOPEX/Poseidon. For completeness, the accuracy of the current FDD TDRS operational orbit determination procedure is also assessed. Because of the future support load expected of each TDRS and the frequent TDRS maneuvers required to maintain stationkeeping, additional analysis is performed to develop methods for improving the accuracy of TDRS postmaneuver solutions using extremely short TDRS postmaneuver data spans.

Because of the potential cost associated with replacing the aging BRTS transponders, analysis is also performed to create and assess a number of alternative techniques for performing TDRS orbit determination without the use of BRTS tracking measurements. These new, innovative methods utilize a variety of tracking sources, including the new Second TDRSS Ground Terminal (STGT) tracking, telemetry and command (TT&C) tracking measurements. Alternative TDRS orbit determination strategies, including those that make use of Global Positioning System (GPS) technology, are also addressed. For the strategies, an orbit determination accuracy assessment is not performed through data reduction, but estimates of the accuracy achievable for the TDRS orbit determination are obtained by covariance analysis error estimates using ODEAS. Estimates of the errors on the TDRS orbit states are generated using realistic error sources, and the results are evaluated.

Based on the TDRS orbit determination solutions, short- and long-term orbit predictions are routinely generated by the FDD for use in planning and scheduling spacecraft activities. As the orbit determination accuracy requirements become more stringent, so too will the prediction accuracy requirements. However, the effects of the improved TDRS orbit determination techniques on orbit prediction, though important, are beyond the scope of this investigation and will not be addressed here.

The GTDS batch least-squares orbit determination and ODEAS covariance analysis procedures and evaluation methods used are presented in Section 2.0. An accuracy assessment of the precision TDRS solutions using improved techniques in GTDS is contained in Section 3.0. Section 4.0 discusses the results of strategies for performing TDRS orbit determination that include BRTS tracking measurements and addresses the postmaneuver recovery of TDRS orbit solutions. Section 5.0 describes the results of TDRS orbit determination strategies that exclude BRTS tracking measurements. Section 6.0 provides the conclusions and recommendations of this study.

2.0 Analysis Methodology

This section describes the tracking measurements and analysis procedures used in this study and the methods for assessing the analysis results.

2.1 Strategies and Tracking Measurements

Table 1 summarizes the various TDRS orbit determination techniques analyzed and evaluated in this study. It also includes a general description of the tracking measurements used for each type of orbit determination solution. For some analyses, additional measurement types were added. These additional measurement types are described below.

Table 1. Summary of TDRS Orbit Determination Strategies and Tracking Measurements

Orbit Determination Solution Concept	Solution Description	Tracking Measurement Description
BRTS (Current Baseline)	Using existing BRTS for TDRS-only orbit determination	BRTS range measurements for TDRSs
BRTS + User	Using existing BRTS for simultaneous TDRS + user orbit determination	BRTS range measurements for TDRSs; TDRSS range and two-way Doppler for TDRSS-user
BRTS + K-band	Using STGT K-Band TT&C range measurements and remote BRTS for TDRS-only orbit determination	BRTS and TT&C range measurements for TDRSs
TDRS Ground Network (GN)	Using GN tracking of TDRS for TDRS-only orbit determination	GN range and two-way range-rate measurements for TDRSs
K-band + user	Using STGT K-Band TT&C range measurements and simultaneous TDRS + user orbit determination	TT&C range measurements for TDRSs; TDRSS range and two-way Doppler measurements for TDRSS-user
TDRS GN + User	Using GN tracking of TDRS and simultaneous TDRS + user orbit determination	GN range and two-way range-rate measurements for TDRSs; TDRSS range and two-way Doppler for TDRSS-user
User GN + User TDRSS	Using simultaneous TDRS + user orbit determination with GN and TDRSS tracking of user	GN range and two-way range-rate and TDRSS range and two-way Doppler measurements for TDRSS-user

Tracking measurements from a variety of sources were used in this study. TDRSS tracking measurements for the GTDS orbit determination solutions were obtained primarily from TDRS-4 and TDRS-5, though, for some analyses, tracking measurements from TDRS-6 were used. These measurements consist of two-way Doppler and range measurements of the user spacecraft via each TDRS, except when the user spacecraft was TOPEX, when one-way return Doppler measurements were also included. BRTS two-way range measurements were used for the TDRSs and, for the TDRS-4 postmaneuver recovery analysis, BRTS two-way Doppler and White Sands antenna azimuth-elevation angle measurements were also included. TT&C range measurements were used for some of the TDRS orbit determination covariance analyses. For GN tracking of the user spacecraft, two-way range and two-way range-rate measurements were used.

BRTS tracking coverage of each TDRS spacecraft typically consists of twelve to fifteen 5-minute passes per day. TT&C tracking of the TDRSs is nearly continuous. In covariance analysis, we used a tracking schedule comparable to that for BRTS. The TDRS tracking of the TOPEX spacecraft consisted of an average of 10 passes of one-way return Doppler measurements and 11 passes of two-way range and Doppler measurements per day, with the average pass lasting 40 minutes. TDRSS tracking of the ERBS spacecraft typically consisted of 12 tracking passes per day, with each pass averaging 10 minutes in duration. The GN tracking of ERBS consisted of an average of two 10-minute passes per day. For Landsat-4, each TDRSS pass lasted 5 to 20 minutes, with approximately 6 to 7 passes per day.

2.2 Orbit Determination Methods and Modeling

This section describes the orbit determination methods and modeling used to generate the batch least-squares GTDS solutions and the batch least-squares covariance analysis results.

2.2.1 Orbit Determination

Batch least-squares solutions were generated and analyzed for a number of TDRSS-supported spacecraft for the TOPEX Cycle 5 and Cycle 21 timespans. Cycle 5 is the fifth 10-day TOPEX groundtrack repeat cycle and covers the period from 17:32 hours universal time coordinated (UTC) on November 1, 1992, through 21:33 hours UTC on November 11, 1992. Cycle 21 is the 21st 10-day TOPEX groundtrack repeat cycle and covers the period from 09:08 hours UTC on April 9, 1993, through 11:06 hours UTC on April 19, 1993. These periods were selected because they contained minimal TOPEX spacecraft attitude perturbations and minimal TDRS spacecraft orbit and attitude maneuvers. The batch least–squares estimation algorithm used by GTDS for this analysis is the same as that used for operational navigation support of the TDRSs by the GSFC FDF. The procedure used for operational support includes using the BRTS range measurements and solving for the TDRS spacecraft state, the solar radiation pressure coefficient, and the White Sands ground antenna range measurement bias. The modeling and state estimation parameters used for this analysis have been modified and enhanced to provide more accurate results and to take advantage of modeling and techniques not currently in operational use. The standard technique developed for obtaining more accurate TDRS orbit solutions using GTDS, referred to as the analytic calibration of biases (ACB) technique, involves performing a series of simultaneous TDRSs/TDRSS-user solutions to calibrate a set of relative range measurement biases for each source of range measurement error in the TDRSS. Because this technique was developed using the TOPEX/Poseidon spacecraft as the TDRSS-user, the ACB method will be presented in this section in terms of the TOPEX modeling and measurement types. For other TDRSS users, such as ERBS and Landsat-4, the modeling and measurement types will vary slightly, but the basic ACB technique is the same. The slight deviations in the standard ACB technique, as well as the deviations to the standard force modeling and parameters to suit other TDRSS users, will be described later in the results sections. The TOPEX and TDRS ACB standard force modeling and parameters used in this study are provided in Table 2. Any deviations for special runs are noted where applicable.

Table 2. Standard Parameters and Options Used in the GTDS Solutions

Orbit Determination Parameter or Option	GTDS Values*	
	TOPEX	TDRSs
Estimated parameters	Orbital state, thrust coefficients, coefficient of solar radiation pressure (C_R), USO bias and drift	Orbital state, coefficient of solar radiation pressure (C_R), spacecraft transponder delay, BRTS transponder delays
Integration type	Cowell 12th order	Cowell 12th order
Coordinate system of integration	Mean-of-J2000.0	Mean-of-J2000.0
Integration step size (seconds)	60 seconds	600 seconds
Tracking measurements	TDRSS two-way Doppler TDRSS one-way return Doppler TDRSS two-way range	BRTS two-way range
Measurement span	See text	See text
Data rate	1 per minute	1 per 20 seconds
Differential correction (DC) convergence parameter	0.00005	0.00005
Editing criterion	3σ	3σ
Ionospheric editing criterion	Central angle greater than 79.48 degrees	-
Measurement weight sigmas	Doppler: 10 millihertz Range: 1.5 meters	2 meters
Satellite area model	Variable mean area model	Constant, 40 meters^2
Satellite mass	2417.2 kilograms	TDRS-5: 1973.1 kilograms TDRS-4: 1853.6 kilograms
Geopotential model	70 x 70 JGM-2	20 x 20 JGM-2
Atmospheric density model	Jacchia-Roberts	N/A
Solar and lunar ephemerides	DE-200	DE-200
Coefficient of drag (C_D)	2.3 applied	N/A
Ionospheric refraction correction Ground-to-spacecraft Spacecraft-to-spacecraft	 Yes No (central angle edit instead)	 Yes N/A
User-spacecraft antenna offset correction	Constant radial, along-track, cross-track	No
Tropospheric refraction correction	Yes	Yes
Polar motion correction	Yes	Yes
Solid Earth tides	Yes	Yes
Ocean tides	No	No
Plate motion	No	No
Earth radiation pressure	No	No

*JGM = Joint Gravity Model; N/A = not applicable

The simultaneous TDRS/TDRSS-user solution arcs used in this analysis were selected to avoid all TDRS maneuvers and angular momentum unloads, wherever possible, while maintaining the longest possible data spans. Previous analysis has shown that longer TDRS/TDRSS-user data arcs provide more accurate solutions. In addition, central angle editing was used to mitigate the effects of ionospheric refraction on the TDRS–to–TDRSS-user tracking link. All measurements with a central angle larger than 79.5 degrees were excluded to eliminate all measurements below the TDRSS-user local horizon.

The ACB technique estimates, in a methodical manner, a set of relative range measurement biases for each source of range measurement error within the TDRSS. In the standard ACB technique, a total of six solutions are generated. The first five solutions are simultaneous TDRSs/TDRSS-user solutions used to obtain the best possible TDRS trajectories. The final solution is a TDRSS-user-only solution that uses the best estimated TDRS trajectories determined from the previous simultaneous solutions.

The first solution determines, through analysis of BRTS range residuals, which BRTS transponders have range biases relative to the TDRSS range measurements for the TDRSS-user. The second solution estimates a "pseudo" TDRSS-user transponder delay through the estimation and differencing of BRTS and TDRSS-user range measurement biases. The next three solutions determine the best possible TDRS orbits using the information obtained from the first two simultaneous solutions and iteratively estimating the BRTS, "pseudo" TDRSS-user and TDRSs transponder delays. The final solution is a TDRSS-user-only solution using the TDRSs' trajectories obtained from the final iterative simultaneous solution.

The details of the standard ACB technique, using TOPEX as the TDRSS user, are described below:

Solution (1):

Purpose:	Solution (1) determines which BRTS transponders appear to have biases in the range tracking measurements relative to the TDRSS range measurements of TOPEX, which is accomplished through examination and analysis of the BRTS range residuals resulting from the solution. This information will be used in Solution (3).
Solution Type:	Simultaneous TOPEX/TDRSs
Tracking Measurements:	BRTS range measurements for the TDRSs and TDRSS range and two-way and one-way return Doppler for TOPEX
Range-Measurement-Related Parameters:	Estimate range measurement biases on the TOPEX range measurements at the White Sands ground antennas.

Solution (2):

Purpose:	Solution (2) determines a "pseudo" TOPEX transponder delay. This information will be used in Solution (3).
Solution Type:	Same as Solution (1)
Tracking Measurements:	Same as Solution (1)
Range Measurement-Related Parameters:	Estimate range measurement biases on the TOPEX range measurements at the White Sands ground antennas. Estimate range measurement biases on the BRTS range measurements at the White Sands ground antennas. Determine the pseudo TOPEX transponder delay by differencing the BRTS range bias and the TOPEX range bias for each White Sands ground antenna, and then averaging these differences to obtain a single average White Sands ground antenna range bias. This average White Sands ground antenna bias serves as an approximation for the TOPEX transponder delay.

Solution (3a):

Purpose:	Solutions (3a), (3b), and (3c) use the information from Solution (1) and Solution (2) to obtain the best possible TDRS orbits for use in Solution (4). Solution (3a) is the first iteration for estimating the best possible TDRS orbits.
Solution Type:	Same as Solution (1)
Tracking Measurement:	Same as Solution (1)
Range Measurement-Related Parameters:	Estimate the BRTS transponder delays for the "biased" BRTS transponders identified in Solution (1). Apply the average White Sands ground antenna bias (pseudo TOPEX transponder delay) determined in Solution (2) to each White Sands ground antenna. Estimate the TDRS transponder delays for each TDRS.

Solution (3b):

Purpose:	Solution (3b) is second step in the iterative process to obtain the best possible TDRS orbits.
Solution Type:	Same as Solution (1)
Tracking Measurements:	Same as Solution (1)
Range Measurement-Related Parameters:	Apply the BRTS transponder delays determined in Solution (3a) to the corresponding "biased" BRTS transponders. Estimate the White Sands ground antenna biases (pseudo TOPEX transponder delay) for each White Sands ground antenna. Apply the TDRS transponder delays determined in Solution (3a) to the corresponding TDRS.

Solution (3c):

Purpose:	Solution (3c) is the final step in the iterative process to obtain the best possible TDRS orbits.
Solution Type:	Same as Solution (1)
Tracking Measurements:	Same as Solution (1)
Range Measurement-Related Parameters:	Same as Solution (3a), except apply the individual White Sands ground antenna biases (pseudo TOPEX transponder delay) determined in Solution (3b) to each corresponding White Sands ground antenna.

Solution (4):

Purpose: Solution Type:	Solution (4) uses the TDRS orbits obtained from Solution (3c) to determine the best possible TOPEX-Only
Tracking Measurements:	TDRSs two-way and one-way return Doppler for TOPEX
Range Measurement-Related Parameters:	Not applicable. Range measurements eliminated to minimize the effect of TOPEX range measurement bias modeling errors on the TOPEX trajectory

The ACB procedure is schematically depicted in Figure 1.

2.2.2 Covariance Analysis

Batch least-squares covariance analysis using ODEAS was performed to analyze the accuracy of a number of alternative TDRS orbit determination strategies. These strategies exclude the use of BRTS tracking measurements and utilize several other tracking measurements types. The force and error models used for the covariance analysis mimic the parameters that would typically be used for TDRS orbit determination and are provided in Table 3.

Table 3. Landsat-4 and TDRS Error Sources and Associated 3σ Uncertainties

Parameter or Option	3σ Uncertainty		
GM (Earth)	GMx($3x10^{-8}$)		
Earth Gravity Field	300% of (JGM2 - $JGM2_{clone}$) (70x70)		
Drag Coefficient for Landsat-4	Estimated		
Solar Radiation Pressure Coefficient	30% for Landsat-4 2% for each TDRS		
Solar Flux	5% for 0-24 hours and 15% for 24-34 hours		
Station Position	3 meters each local tangent x, y, and z		
Tropospheric Refraction	45%		
Ionospheric Refraction	100%		
Measurements	Noise-σ	Weight-σ	Bias
Landsat-4 TDRSS two-way Range-Rate (meters/sec)	$2.82x10^{-3}$	$3.2765x10^{-2}$	0
Landsat-4 TDRSS two-way Range (meters)	1.5	10	7
BRTS two-way Range (meters)	1.5	30	7
TT&C two-way Range (WHSK↔TDRS) (meters)	1.5	30	3
GN two-way Range for TDRS (meters)	3	40	30
GN two-way Range for Landsat-4 (meters)	1.5	20	15
GN two-way Range-Rate for Landsat-4 (meters/sec)	0.001	0.1	0

N/A = not applicable

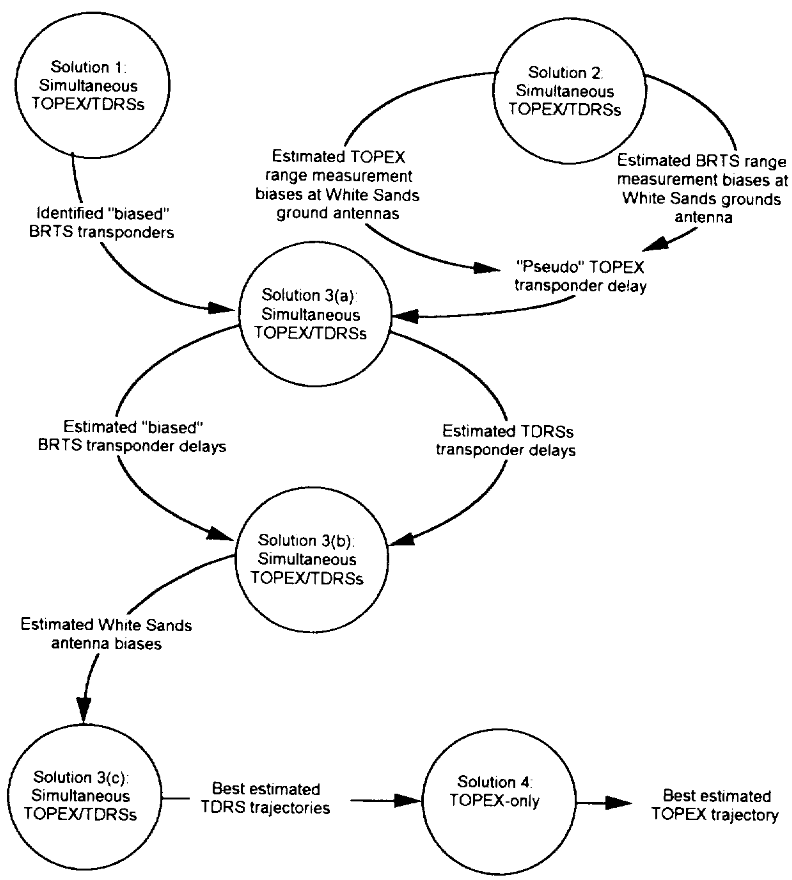

Figure 1. A Schematic of the ACB Procedure

3.0 Precision TDRS Orbit Determination Results

The accuracy of the TDRS orbit determination solutions generated in this study is assessed through comparisons with high-accuracy TDRS precision orbit ephemerides (POEs) generated by the Precision Orbit Determination (POD) team, using the Geodynamics (GEODYN) System, within the Space Geodesy Branch located at GSFC. The TDRS POEs are generated using the high-precision TOPEX/Poseidon POEs as an input measurement type to the TDRS orbit determination process. The TDRS POEs are estimated to be accurate to within 3 meters in total position based on preliminary covariance analysis results as well as analysis results using the TOPEX POEs (Reference 3). The definitive orbit determination requirements for the TOPEX/Poseidon POEs include a maximum 39–centimeter (3σ) radial position error. The availability of the independent orbit determination solutions generated by the Space Geodesy Branch provides a unique opportunity to evaluate the accuracy of the orbit determination systems used by the FDD for operational navigation and analysis support.

Using the standard ACB method described in Section 2.2.1 with the TOPEX spacecraft as the TDRSS user, 5-day TOPEX, TDRS-4, and TDRS-5 orbit determination solutions were generated covering the period 00:00 hours UTC on November 7, 1992, through 00:00 hours UTC on November 12, 1992, which corresponds to the latter portion of TOPEX Cycle 5. The TDRS ephemerides were compared at 10-minute intervals with the corresponding TDRS-4 and TDRS-5 POEs in orbit plane coordinates.

The root-sum-square (RSS) position differences between the Cycle 5 TDRS-4 GTDS solution (3c) and the corresponding POE are shown in Figure 2. The root-mean-square (RMS) of the RSS position difference is 4.3 meters, with a maximum difference of 9.4 meters. The RMS differences in the radial, along-track, and cross-track components are 1.2, 3.4, and 2.4 meters, respectively. The RSS position differences between the Cycle 5 TDRS-5 GTDS solution (3c) and the corresponding POE are shown in Figure 3. The RMS of the RSS position difference is 3.6 meters, with a maximum difference of 8.8 meters. The RMS differences in the radial, along-track, and cross-track components are 1.4, 2.8, and 1.9 meters, respectively.

Additional TDRS-4 and TDRS-5 GTDS solutions using the ACB technique with TOPEX were generated within the Cycle 5 timespan and compared with the corresponding TDRS POEs. TDRS-4, TDRS-5, and TOPEX solutions were generated for a 5-day period extending from 00:00 hours UTC on November 4, 1992, through 00:00 hours UTC on November 9, 1992, corresponding to the middle portion of TOPEX Cycle 5. The RMS of the RSS position differences between the GTDS ephemerides and the TDRS POEs were 11.2 meters for TDRS-4 and 11.2 meters for TDRS-5, somewhat larger than the previous 5-day results. The reason for the degraded comparison results for TDRS-5 is the inclusion of tracking measurements following a TDRS-5 momentum unload, which were edited in the previous 5-day solution. Previous analysis shows that inclusion of the postmomentum wheel unload tracking measurements can degrade solution accuracy. The reason for the degraded TDRS-4 solution is still under investigation.

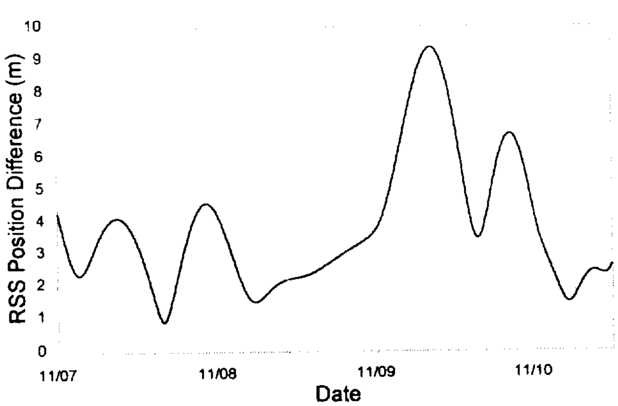

Figure 2. Position Differences Between TDRS-4 POE and GTDS TDRS-4 Ephemerides

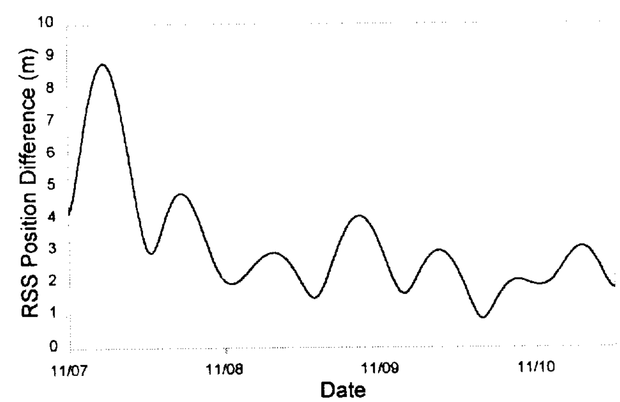

Figure 3. Position Difference Between TDRS-5 POE and GTDS TDRS-5 Ephemerides

Longer 7-day TDRS-4, TDRS-5, and TOPEX solutions were also generated for a period extending from 00:00 hours UTC on November 4, 1992, through 00:00 hours UTC on November 11, 1992. The RMS of the RSS position differences were 15.1 meters for TDRS-4 and 11.3 meters for TDRS-5. It is believed that the cumulative effects of the TDRS-4 and TDRS-5 momentum wheel unloads are the cause of the less favorable ephemeris comparison results compared with the 5-day solutions.

4.0 Strategies for TDRS Orbit Determination Solutions

This section discusses several strategies for obtaining high-accuracy TDRS trajectories from simultaneous solutions from the ERBS and Landsat-4 spacecraft. Section 4.1 presents the results for the ERBS and Landsat-4 spacecraft using the standard ACB method described in Section 2.2.1. The accuracy of these trajectories is assessed by parallel comparisons with high-accuracy TDRS POE trajectories described in Section 3.0. A "quick-look" approach for determining TDRS trajectories using Landsat-4 is presented in Section 4.2. Section 4.3 describes several scenarios for accurately determining the postmaneuver trajectory of a TDRS spacecraft within 2 hours of its maneuver.

4.1 ERBS and Landsat-4 Cycle 5 ACB Results

The measurements for the ERBS and Landsat-4 spacecraft ACB runs came from a 6-day timespan from November 4, 1992, through November 10, 1992. These dates were chosen so that the solution arc overlaps with the TDRS POE solution arc. During this time, ERBS and Landsat-4 were being tracked by TDRS-4 and TDRS-5. This study uses the TDRSS two-way range and Doppler measurements, as well as the two-way BRTS range measurements. The comparison of the resulting TDRS trajectories with the TDRS POEs can be seen in Table 4. Also included in this table for comparison purposes are the results from the TOPEX analysis described in Section 3.0. Note that the TDRS-5 trajectory is consistently better than the TDRS-4 trajectory. This is as expected, since the geometry of the three BRTS stations tracking TDRS-5 is better than the geometry of the two stations tracking TDRS-4.

Table 4. Comparison of Various TDRS-4 and TDRS-5 Trajectories With the TDRS POEs

Spacecraft	TDRS-5 RMS in meters)	TDRS-4 (RMS in meters)
TOPEX 5-day	3.6	4.3
ERBS	12.190	44.876
Landsat-4	13.476	30.810

4.2 Landsat-4 Cycle 5 "Quick-Look" Results

A "quick-look" solution would be very attractive for use in an operational environment as long as the accuracy of the resulting TDRS trajectories remained high. There is the added benefit of obtaining trajectories for several TDRSs at a time. The "quick-look" scenario is a pared down version of the standard ACB method. It consists of a single simultaneous solution with a user spacecraft and two TDRS spacecraft corresponding to step 3(a) of the standard ACB method. The first ACB step can be skipped by assuming that the same BRTS ground transponders are biased with respect to the TDRSS-user range measurement type; the transponder delay for each of these "biased" BRTS stations is estimated. The second ACB method step consists of finding the relative biases between the TDRSS-user range measurements and the BRTS range measurements. This step can be skipped by assuming there is a typical value for the relative bias and using that value in the single simultaneous solution. This section presents results from this quick-look scenario for the Landsat-4 spacecraft.

The Landsat-4 quick-look analysis covers the same timespan and uses the same measurement types as the ACB analysis. A value of 17.83 meters from a previous ACB solution with the ERBS is used as the relative bias between the TDRSS-user range and the BRTS range measurement types. The resulting TDRS-4/5 accuracies are 72.1 meters and 20.5 meters RMS. The ACB method yields relative bias values of 5.4 meters and 3.1 meters for TDRS-4 and TDRS-5, respectively; this generates a TDRS trajectory accuracy of 30.8 meters for TDRS-4 and 13.5 meters for TDRS-5. The difference between the ACB and quick-look trajectories is 53.5 meters for TDRS-4 and 12.9 meters for TDRS-5. Because of this sensitivity of the TDRS trajectories to the input relative bias, this quick-look method should be studied in greater detail before adopting it for routine use.

4.3 TDRS-4 Cycle 5 Postmaneuver Recovery Results

Occasionally, it is necessary to maneuver a TDRS to ensure that it remains within its designed stationkeeping window. The goal is to develop methods and procedures using 2 hours of postmaneuver tracking measurements from the maneuvered TDRS to recover the trajectory of a maneuvered TDRS to better than 600 meters to satisfy current requirements and to better than 75 meters (3σ) for future requirements.

The analysis reported in this section focuses on the time immediately following a TDRS-4 maneuver on November 4, 1992. The tracking measurement span used is 01:00 to 03:00 UTC, where 01:00 UTC is just after the TDRS-4 maneuver burnout. The strategy is to try a variety of cases, concentrating on simultaneous solutions with a TDRSS-user spacecraft and a second, nonmaneuvering TDRS. Both spacecraft have good solutions, which will help constrain the solution for the maneuvering TDRS. There is the additional benefit of being able to use longer measurement arcs for these latter two spacecraft.

This study uses TDRS-5 and TOPEX for the second TDRS and the TDRSS-user spacecraft, respectively. The various scenarios, the measurement types used, and the results of comparing the TDRS-4 trajectory with the high-accuracy TDRS-4 POE are shown in Table 5. The 40-hour and 5-day timespans for TDRS-5 and TOPEX start earlier and end at the same time as the TDRS-4 arc. The 40-hour arc is used to approximate the arc length used in operational TDRS solutions, while a 5-day arc gives the best solutions in a standard ACB analysis with TOPEX. The BRTS-only TDRS-4 solution uses the setup for normal operational TDRS orbit determination. The remaining solutions were all generated in a single simultaneous solution that corresponds to solution 3(a) of the standard ACB procedure, treating TDRS-4 and TDRS-5 the same except for the length of the measurement arcs. The previous TOPEX/TDRSs simultaneous solution 1 and solution 2 analysis results were used as input to the solution 3(a) generated in the current analysis. Because none of the nominal cases were close to the 75-meter (3σ) goal, some "nonnominal" runs were investigated, where TDRS-5 and TDRS-4 were treated differently. TDRS-5 followed the normal procedure, while for TDRS-4, more types of measurements were added, and the parameter set estimated was different.

Note that case D1 (the first attempt at a nonnominal solution) is close to the 75-meter (3σ) goal. Several refinements improve the numbers slightly. Also note that excellent results can be obtained for the shorter timespans in case C1. An interesting note is that the estimated values for the TDRS-4 solar reflectivity coefficient (C_R) were generally between 3 and 9 for most of the nonnominal solutions, whereas, the expected value is around 1 to 1.5. Normally, this solution would be considered questionable, but the excellent agreement with the POE lends confidence to its accuracy.

The results of this analysis show that it is possible to meet the 600-meter (3σ) goal using standard ACB methods and the 75 meter (3σ) goal using slightly modified ACB procedures. To further improve the accuracy of TDRS orbit determination solutions following a maneuver, it is recommended that a three-dimensional thrust scaling algorithm be implemented into GTDS. With this enhancement, both premaneuver and postmaneuver tracking measurements can be processed in a single orbit determination arc to scale an input nominal thrust profile in three separate components.

5.0 Alternative TDRS Orbit Determination Strategies Without BRTS

Section 5.1 presents a summary of the orbit determination and error analysis results for TDRS orbit determination strategies that exclude BRTS tracking measurements. Section 5.2 describes the details of orbit determination analysis using GN tracking measurements of the TDRSS-user spacecraft instead of BRTS tracking measurements for the TDRSs. Additional alternative TDRS orbit determination strategies described by other authors are presented in Section 5.3.

Table 5. Summary of Postmaneuver Recovery Results

Case	Solution Type	Measurement Types	Orbit Determination Arc Lengths	Total RMS (m) of compare with TDRS-4 POE
A	TDRS-4 only	BRTS range for TDRS-4	2-hours	12102.08
B	Standard ACB: TOPEX/TDRS-4/TDRS-5 simultaneous	BRTS range for TDRS-4 and TDRS-5; TDRS-4 range and two-way Doppler for TOPEX; TDRS-5 range and two-way and one-way Doppler for TOPEX	TDRS-4: 2 hours TDRS-5: 2 hours TOPEX: 2 hours	2188.03
C	Standard ACB: TOPEX/TDRS-4/TDRS-5 simultaneous	BRTS range for TDRS-4 and TDRS-5; TDRS-4 range and two-way Doppler for TOPEX; TDRS-5 range and two-way and one-way Doppler for TOPEX	TDRS-4: 2 hours TDRS-5: 40 hours TOPEX: 40 hours	258.05
C1	Same as C, except for TDRS-4: 1. Estimate user range bias for White Sands antenna 2. Do not estimate BRTS transponder delays 3. Change integration stepsize from 600 to 180 seconds	Same as C	Same as C	19.79
D	Standard ACB: TOPEX/TDRS-4/TDRS-5 simultaneous	BRTS range for TDRS-4 and TDRS-5; TDRS-4 range and two-way Doppler for TOPEX; TDRS-5 range and two-way and one-way Doppler for TOPEX	TDRS-4: 2 hours TDRS-5: 5 days TOPEX: 5 days	149.18
D1	Same as D, except for TDRS-4: 1. Estimate user range bias for White Sands antenna 2. Do not estimate BRTS transponder delays 3. Change integration stepsize from 600 to 180 seconds	Same as D	Same as D	27.54
D2	Same as D1, except do not estimate TDRS-4 transponder delay	Same as D, except add White Sands azimuth-elevation angle tracking measurements	Same as D	23.42

5.1 TDRS Orbit Determination Error Analysis Results

Orbit determination error analysis was undertaken to investigate and evaluate alternative TDRS orbit determination strategies without the use of BRTS tracking measurements. Table 6 summarizes the orbit determination error analysis results for TDRS orbit determination strategies that exclude BRTS tracking measurements. The table includes a brief description of the technique, the estimated 3σ accuracy of the resulting solutions, and the major error sources associated with the estimated solution accuracy. For the error analysis, all simultaneous TDRS/TDRSS-user solutions were 34-hours long and used

Landsat-4 as the TDRSS user. The Landsat-4 tracking measurement distribution was the same as that currently used for operational support. The major error sources for both Landsat-4 and the TDRSs are provided in Table 3. The major strengths and weaknesses for practical application of each strategy in Table 6 have been discussed elsewhere (Reference 4).

Table 6. Alternative Technical Approaches That Exclude BRTS

Technique	Description	3σ RSS Accuracy	Basis of Accuracy Statement	Primary Error Contributors
TDRS GN	Use of GN tracking of TDRS for TDRS-only orbit determination	164 meters (TDRS-4) 125 meters (TDRS-5)	Mean 3σ error from covariance analysis using 30 meter GN range bias assumed TDRS-4 tracked by Madrid and Ascension TDRS-5 tracked by Goldstone and Canberra	Measurement biases: 123 meters for TDRS-4; 85 meters for TDRS-5
K-band + User TDRSS	Use of STGT K-Band TT&C range data and simultaneous TDRS+user orbit determination	67 meters (TDRS-4) 57 meters (TDRS-5)	Mean 3σ error from covariance analysis of simultaneous Landsat-4 and TDRS orbit determination based on a 10 meter two-way range bias for K-Band TT&C	Tropospheric refraction: 35 meters for TDRS-4; 38 meters for TDRS-5
TDRS GN + User TDRSS	Use of GN tracking of TDRS and simultaneous TDRS+user orbit determination	73 meters (TDRS-4) 74 meters (TDRS-5)	Mean 3σ error from covariance analysis using 30 meter GN range bias TDRS-4 tracked by Madrid and Ascension TDRS-5 tracked by Goldstone and Canberra	Measurement biases: 38 meters for TDRS-4; 41 meters for TDRS
User GN + User TDRSS	Use of simultaneous TDRS+user orbit determination with GN tracking of user	84 meters (TDRS-4) 81 meters (TDRS-5)	Mean 3σ error from covariance analysis No BRTS No direct tracking of TDRS-4 and TDRS-5 are used	Measurement biases: 45 meters for TDRS-4; 44 meters for TDRS-5

Among the strategies that eliminate the BRTS tracking measurements, the "K-band + user" approach is the most attractive for meeting the future accuracy requirement of 75 meters (3σ). Figure 4 shows the dependence of the 1σ TDRS orbit determination position error on the K-Band TT&C range uncertainty when using the K-band + user approach. The dominant error source in the TDRS position is tropospheric refraction, which is the leading contributor to the 16- to 17-meter error when there was no range data uncertainty. The additional position errors resulting from the range data uncertainty are linear in nature. An 18- to 19-meter two-way TT&C range data bias (9 to 9.5 meters one-way) will permit TDRS orbit determination accuracies of 150 meters (3σ). TDRS orbit determination accuracies of 75 meters (3σ) are possible if the two-way uncertainty is 7 to 7.5 meters (3.5 to 4 meters one-way).

TDRS orbit determination analysis was performed using the available TT&C tracking measurements from December 1994 and January 1995. These results were not included since the quality of the tracking measurements during this period were not yet at expected operational support levels.

5.2 TDRS/User-GN Orbit Determination Analysis Results

This section reports on the orbit determination analysis undertaken to study the feasibility of using tracking of a TDRSS-user spacecraft from GN stations to replace BRTS measurements in determining TDRS orbits in simultaneous solutions. For this study, the user spacecraft was ERBS. The timespan covered is 22:00 hours UTC on April 10, 1993, through 22:00 hours UTC on April 15, 1993, during which there was good GN tracking of ERBS. This corresponds to the middle part of Cycle 21 for TOPEX.

The method used for generating the TDRSs/ERBS simultaneous solutions using GN measurements is performed in three steps, analogous to the ACB method. The BRTS measurements are replaced by GN range and range-rate measurements from Wallops Island, Goldstone, and Merritt Island. Additionally, TDRSS two-way range and Doppler are used, but no TDRSS one-way Doppler. Furthermore, the GN measurements are downweighted 50 percent from nominal, i.e., the range measurement weight is increased from 20 to 30 meters while the range-rate measurement weight is changed from 10 to 15 cm/sec. In the first step, the ground stations whose range measurements are biased relative to the TDRSS range measurements are identified. In the second step, the ERBS transponder delay is directly estimated, in contrast to the standard ACB case where the relative biases between different range types are determined. In the third step, the user transponder delay from step 2 is applied, while the TDRS transponder delays are estimated (as they are in the standard ACB scenario). Nominally, only those ground stations whose range measurements are biased relative to the TDRSS range measurement type (determined in step 1) have their range biases estimated. However, more accurate results are obtained when the range biases for all the GN tracking stations are estimated.

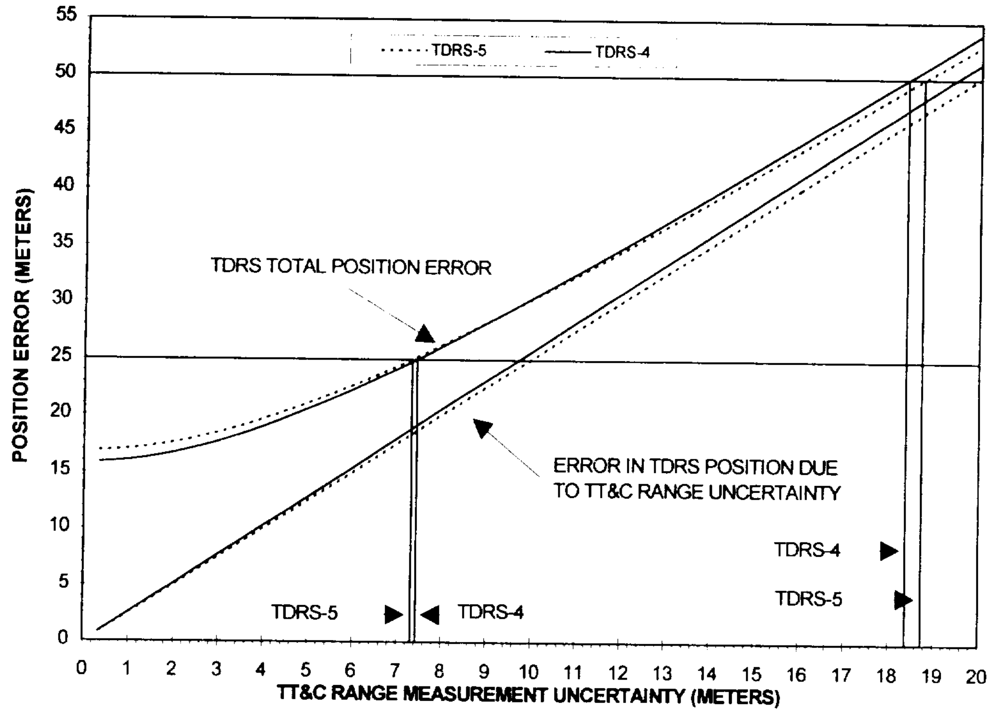

Figure 4. TDRS Orbit Determination Error as a Function of the TT&C Two-Way Range Uncertainty

Since there are no TDRS POEs for this time period, the quality of the TDRS trajectories produced using the GN method is assessed by comparing the trajectories with those produced from standard TDRS/TOPEX ACB solutions. The TDRS-4 GN trajectory differs from the TOPEX ACB trajectory by 69.486 meters RMS. For TDRS-5, the RMS value is 82.049 meters. These differences are comparable to the analysis error estimates of about 80 meters in Table 6. An additional indication of the TDRS accuracy can be obtained by using the TDRS trajectories as input for a TOPEX-only solution. The resulting TOPEX trajectory can be compared with the Cycle 21 TOPEX POE. Table 7 gives this result on the last line and also includes a sampling of TOPEX accuracies obtained through ACB methods over several time periods.

Table 7. Comparison of TOPEX POEs with TOPEX Ephemerides Determined From Various Simultaneous TDRS Ephemerides

Source of TDRS Orbit Files	TOPEX Solution Compared With POE RMS (Radial RMS) in Meters
TOPEX ACB solution: 7 days, Cycle 5	2.20 (0.28)
TOPEX ACB solution: 5 days, Cycle 6	1.60 (0.46)
ERBS ACB solution: 6 days, Cycle 5	3.60 (0.31)
TOPEX ACB solution: 5 days, Cycle 21	3.06 (0.30)
ERBS ACB solution: 5 days, Cycle 21	1.82 (0.52)
ERBS simultaneous solution GN tracking (no BRTS): 5 days, Cycle 21	16.06 (0.75)

These ERBS results suggest that using the modified ACB technique with GN tracking measurements in place of BRTS does not produce as accurate solutions as those that include the BRTS tracking measurements, which could result from several factors. First, the relatively sparse amount of GN tracking of the user may not be sufficient to eliminate the effects of GN data noise and provide an adequate link to the ground to determine the TDRS orbits. More dense GN tracking of the TDRSS-user spacecraft may eliminate the effects of noise and improve the TDRS orbits. Second, the modified ACB technique, developed to accommodate the replacement of the BRTS tracking with the GN tracking, may not be optimal. Further refinements to this modified ACB technique may also improve TDRS orbit determination accuracy. It is interesting to note that the BRTS-included results in Table 7 indicate that three of the five solutions meet the stringent 39-centimeter (3σ) precision orbit determination radial accuracy requirement, indicating the relative merits of the ACB technique.

5.3 Other Strategies

Other authors have performed analyses for TDRS orbit determination using Global Positioning System (GPS) technology (Reference 5) and TDRSS-user satellite laser ranging (SLR) tracking measurements (Reference 3). The attainable TDRS orbit determination accuracy using SLR tracking measurements is approximately 3 meters (1σ), while the GPS method produces TDRS orbits estimated accurate to 50 meters (1σ). The major strengths and weaknesses for practical application of these strategies are discussed in Reference 4.

6.0 Conclusions and Recommendations

A number of orbit determination strategies have been analyzed and the achievable accuracy levels assessed. The primary goal of identifying technical approaches and procedures that meet the future TDRS orbit determination accuracy requirement of 75 meters (3σ) with and without the use of BRTS was achievable. In addition, several schemes for recovering accurate TDRS orbits following a TDRS maneuver were examined.

For performing high-accuracy TDRS orbit determination solutions with the use of BRTS tracking measurements, simultaneous solutions of the TDRS along with a well-chosen TDRSS-user are recommended. A detailed procedure for the analytical calibration of biases is outlined that significantly reduces the systematic errors arising from the biases in the range measurements. With simultaneous solutions of TDRS-4 and TDRS-5 with TOPEX, TDRS orbit determination solutions are obtained that are accurate to better than 15 meters. Simultaneous solutions with a TDRSS-user at a lower altitude, which experiences higher geopotential and atmospheric perturbation errors, will result in somewhat larger errors for TDRS solutions. Technical procedures are identified that can be good candidates for use in operations after further refinements.

High-accuracy TDRS postmaneuver solutions have been determined within 2 hours after a TDRS stationkeeping maneuver by exploiting the tracking measurements and orbits of a TDRSS-user and another TDRS, the orbits of which were not perturbed by the orbit-adjust maneuver. Accuracies of better than 25 meters are demonstrated. However, for robust and reliable procedures for postmaneuver recovery, it is recommended that the TDRS thrust vector be estimated so that premaneuver tracking information for the perturbed TDRS can be gainfully utilized.

A number of TDRS orbit determination strategies have been examined that exclude BRTS tracking measurements. The most attractive of these strategies is one that involves performing simultaneous solutions of the TDRSs with a TDRSS-user using the TDRSS tracking measurements for the user and the TT&C range measurements for the TDRS as the tie to the ground. Covariance analysis indicates that an accuracy of better than 25 meters (1σ) can be achieved provided that the TT&C range measurement uncertainty can be brought below about 7 meters. Once the actual measurements indicate that the uncertainties are below 7 meters, an orbit determination study is recommended to validate the covariance analysis results.

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