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Ionospheric Refraction Effects on TOPEX Orbit Determination Accuracy Using the Tracking and Data Relay Satellite System (TDRSS)*

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ABSTRACT

This investigation concerns the effects on Ocean Topography Experiment (TOPEX) spacecraft operational orbit determination of ionospheric refraction error affecting tracking measurements from the Tracking and Data Relay Satellite System (TDRSS). Although tracking error from this source is mitigated by the high frequencies (K-band) used for the space-to-ground links and by the high altitudes for the space-to-space links, these effects are of concern for the relatively high-altitude (1334 kilometers) TOPEX mission. This concern is due to the accuracy required for operational orbit-determination by GSFC and to the expectation that solar activity will still be relatively high at TOPEX launch in mid-1992.

The ionospheric refraction error on S-band space-to-space links was calculated by a prototype observation-correction algorithm using the Bent model of ionospheric electron densities implemented in the context of the Goddard Trajectory Determination System (GTDS). Orbit determination error was evaluated by comparing parallel TOPEX orbit solutions, applying and omitting the correction, using the same simulated TDRSS tracking observations. The tracking scenarios simulated those planned for the observation phase of the TOPEX mission, with a preponderance of one-way return-link Doppler measurements.

The results of the analysis showed most TOPEX operational accuracy requirements to be little affected by space-to-space ionospheric error. The determination of along-track velocity changes after ground-track adjustment maneuvers, however, is significantly affected when compared with the stringent 0.1-millimeter-per-second accuracy requirement, assuming uncoupled premaneuver and postmaneuver orbit determination. Space-to-space ionospheric refraction on the 24-hour postmaneuver arc alone causes 0.2 millimeter-per-second errors in along-track delta-v determination using uncoupled solutions. Coupling the premaneuver and postmaneuver solutions, however, appears likely to reduce this figure substantially. Plans and recommendations for response to these findings are presented.

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1. INTRODUCTION

Continuing improvement of the physical models and mathematical methods of orbit determination is necessary to meet stringent accuracy requirements for missions such as the Ocean Topography Experiment (TOPEX). One area for possible improvement is the methods used to correct the Tracking and Data Relay Satellite System (TDRSS) metric tracking data for the effects of atmospheric refraction. The Goddard Trajectory Determination System (GTDS) currently omits correction for such effects on spacecraft-to-spacecraft (S/C-to-S/C) tracking links.

Goddard Space Flight Center (GSFC) is to provide operational orbit determination support for TOPEX maneuver planning and evaluation. This is not to be confused with the definitive orbit determination that will be performed in support of the scientific data analysis. Some operational orbit-determination accuracy requirements for TOPEX appear to challenge the current capabilities of GTDS and the TDRSS. This report presents the results of a study conducted to determine whether inclusion of an atmospheric correction for S/C-to-S/C links is necessary to satisfy TOPEX requirements.

1.1 MOTIVATION AND OBJECTIVES OF ANALYSIS

The main effect of the atmosphere on S/C-to-S/C relay legs is caused by the free electrons of the ionosphere, which extend to altitudes above 3000 kilometers (km). To evaluate this effect, it is necessary to integrate the free electron density along the S/C-to-S/C relay communication path. An electron density model (the Bent Ionospheric Model, Reference 1) is already implemented in GTDS (Reference 2), but some expense would be involved in coding the required numerical integration and in documenting, testing, and certifying the code and the algorithm for operational use. Because the electron density model is expensive to compute, use of such a correction would also impose an additional burden on Flight Dynamics Facility (FDF) computer resources. Therefore, before implementing the correction, it is prudent to study the size of the orbit-determination effects to see whether accuracy requirements for current or future missions are seriously affected.

Two aspects of the TOPEX mission combine to make it perhaps the only one that, in the near term, requires the S/C-to-S/C ionospheric refraction correction. First is the stringency of the orbit-determination accuracy requirements. Second is that the early mission will occur during the later stages of the current solar maximum period. High solar activity causes the ionospheric electron-density distribution to increase and to extend to higher altitudes. The relatively high altitude of TOPEX will not render it completely immune to ionospheric refraction effects under these circumstances. The effects will be much smaller than the effects on lower altitude missions, but they must be judged relative to the stringent TOPEX accuracy requirements.

The two operational orbit-determination regimes in the TOPEX mission scenario (Reference 3) are distinguished by the tracking coverage and the orbit-determination accuracy requirements. The first regime coincides with the TOPEX mission Assessment Phase. The second regime combines the Initial Verification and Observation phases of the TOPEX mission plan. In this paper, the second regime will be referred to as the Observation Phase.

In the Assessment Phase, TDRSS tracking is planned to consist of 40 minutes (min) per revolution of two-way coherent S-band range and Doppler tracking plus nearly continuous one-way return link Doppler coverage during the remaining time. Stated accuracy requirements (References 3 and 4) for this regime consist of premaneuver requirements and postmaneuver requirements. The former are applicable to orbital quantities determined using tracking available over arcs of up to several days immediately before each orbit-adjust maneuver. The latter apply to the determination of changes in the orbit caused by the maneuver, not necessarily to the accuracy of postmaneuver orbit determination. This important distinction is drawn because of the possibility that some sources of orbit-determination error may cancel in the subtraction of premaneuver from postmaneuver determinations. Postmaneuver accuracy requirements must be satisfied using tracking extending no more than 24 hours after the maneuver. Both types of requirements depend on the type of orbit maneuver; that is, "calibration," "coarse," or "precision."

TDRSS tracking in the Observation Phase is to consist of 40 min per revolution of one-way Doppler tracking and one 10-min two-way range and Doppler pass per day. Precision maneuvers will continue, at reduced frequency, and the two-way coverage will be enhanced to 40 min per revolution for three revolutions after each such maneuver. The associated premaneuver and postmaneuver accuracy requirements are the same as in the Assessment Phase. An additional requirement for the Observation Phase applies to orbit determination that will be performed on several-day arcs between the maneuvers. This solution process is required to contribute less than 225 meters (m) to the prediction of the longitude of equator crossing 30 days after the end of the solution arc.

Table 1 quantifies the accuracy requirements. The accuracies for calibration maneuvers are those required for calibrations of the 1-Newton thrusters; requirements for calibrations of the 22-Newton thrusters are less stringent. Each number in the "Combined" column (Table 1) is the minimum of all required accuracies for each quantity; that is, the accuracy that the orbit-determination system must be able to achieve. All stated requirements are three-standard-deviation error limits. All orbital quantities involved in these requirements are osculating quantities.

Of the three sets of accuracy requirements for orbit determination associated with maneuvers, the precision requirements pose the greatest challenge to system capabilities. Attaining these accuracies will be no more difficult in the Assessment Phase than in the Observation Phase because tracking coverage will be more extensive. The study was therefore performed using tracking scenarios corresponding to the Observation Phase.

1.2 DESIGN AND DESCRIPTION OF THE STUDY

TOPEX orbit determination using simulated TDRSS tracking data was performed both with and without an ionospheric refraction correction. The two sets of results were compared, with particular attention to the differences in orbital quantities for which there are specific accuracy requirements. If these differences are not found to be small compared to the corresponding accuracy requirements, the ionospheric effects will be significant to the mission orbit-determination accuracy and presumably should be corrected.

This study is based on the assumption that the postmaneuver change determination is to be performed by subtracting quantities determined using separate premaneuver and

Table 1. TOPEX Operational Orbit-Determination Accuracy Requirements

SOLUTION TYPE	ORBIT PROPERTY	CALIBRATION (1 nt)	COARSE	PRECISION	COMBINED
PREMANEUVER STATUS	PERIOD, T (ms)	4	4		4
	SEMIMAJOR AXIS, a (cm)			100	100
	ECCENTRICITY, e (10^{-6})	10	10	5	5
	INCLINATION, I (10^{-6} deg)	1000	1000	100	100
	ARGUMENT OF LATITUDE (10^{-6} deg)	5000	5000		5000
POSTMANEUVER CHANGE	PERIOD, δ T (MS)		2		2
	SEMIMAJOR AXIS, δ a (cm)			20	20
	INCLINATION, δ I (10^{-6} deg)		500	100	100
	VELOCITY CHANGE ALONG-TRACK δV_a (mm/s)	0.1	4.0	0.1	0.1
	VELOCITY CHANGE CROSS-TRACK δV_c(mm/s)	10	20	10	10
	VELOCITY CHANGE RADIAL δV_r (mm/s)	2	10	2	2
BETWEEN MANEUVERS (OBSERVATION PHASE)	30-DAY PREDICTION OF E-W POSITION AT EQUATOR CROSSING (m)	N/A	N/A	N/A	225

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postmaneuver tracking arcs. This is a standard procedure at the Flight Dynamics Facility of GSFC, but it does not make use of the fact that the spacecraft position is continuous through the maneuver.

An alternate orbit determination scenario for postmaneuver requirements involves solving for maneuver thrusting parameters in a unified solution arc, including both premaneuver and postmaneuver tracking. The results of this study are not directly applicable to this unified orbit determination scenario. Plausible arguments will nevertheless be made to estimate ionospheric error bounds on along-track velocity change error for this scenario.

A further assumption in the design and analysis of this study is that the effects of ionospheric refraction on the separate premaneuver and postmaneuver orbit determination solutions are not highly correlated under random variations of the tracking schedule and the solar activity. The ionospheric error in the differences between premaneuver and postmaneuver solutions is not expected to be systematically less than the ionospheric error in either separate solution. Because errors in the relatively short postmaneuver arc are expected, in general, to exceed those in the premaneuver arc, the assumption relieves us of the burden of analyzing a long premaneuver arc preceding each of our several postmaneuver arcs. This assumption is inapplicable to other error sources in TOPEX orbit determination (such as gravitational constant error); this implies that overall TOPEX error analysis must be performed with coordinated premaneuver and postmaneuver arcs (References 5 and 6).

Effects of ionospheric refraction on postmaneuver accuracy requirements were studied using four 24-hour postmaneuver arcs with simulated tracking data scheduled according to the Observation Phase postmaneuver tracking requirements. Four arcs were used to attempt to sample over relevant variables, such as season and orbital orientation. The impact on the premaneuver accuracy requirements was studied using a single 7-day arc of routine Observation Phase simulated tracking.

While this analysis may prove that implementation of a full ionospheric correction is necessary for the satisfaction of the TOPEX accuracy requirements, it cannot show it to be sufficient. There are two reasons for this. First, the actual accuracy attainable by an ionospheric refraction correction model, and thus the fraction of ionospheric error that may remain after correction, is unknown. Second, the current analysis only treats the ionospheric refraction contribution to the orbit-determination error. A full orbit-determination error analysis for TOPEX is beyond the scope of this work.

1.3 PREVIOUS STUDIES

References 7 and 8 describe previous studies of the orbit-determination effects of the S/C-to-S/C refraction correction. Using real and simulated tracking data for the Earth Radiation Budget Satellite, Solar Maximum Mission, and Solar Mesosphere Explorer at both high and low solar activities, these studies investigated the effects of uncorrected ionospheric refraction on orbit determination for spacecraft in the 500- to 600-km altitude range. For the lower end of this altitude range, this effect was shown to produce ephemeris differences of 30 to 100 m over 34-hour definitive arcs at maximum solar activity. Effects of this size significantly hinder the continuing effort to improve orbit-determination precision and accuracy. There are, however, no near-term missions in this altitude range whose accuracy requirements are threatened by this level of error. References 7 and 8 do not establish an operational need to correct for the S/C-to-S/C ionospheric refraction.

A somewhat fuller discussion of the methods of the current study may be found in Reference 9.

1.4 ORGANIZATION OF THE PAPER

The remainder of this paper comprises three sections. Section 2 describes the methods of analysis, including tracking data simulation. Section 3 describes and discusses the results. Section 4 describes the conclusions and makes recommendations for implementing the ionospheric refraction correction and for TOPEX orbit-determination techniques.

2. ANALYTICAL METHODS

2.1 ORBIT AND TRACKING DATA SIMULATION METHODS

The data simulation methods comprise the orbital initial conditions, the orbit propagation methods, the measurement simulation methods, and the choice of tracking data distribution.

Orbital initial conditions at several epochs were based on the reference set of Brouwer mean elements given in Table 2. These elements were adapted from Reference 10 and, according to that source, represent a frozen orbital shape (i. e., there is no secular change in eccentricity and mean anomaly). The goal of TOPEX orbit adjustment maneuvering will be to keep the groundtrack on a 10-day, 127-orbit repeat cycle. To provide initial conditions for orbit simulations at epochs other than June 6, 1992, therefore, only the Brouwer mean longitude of ascending node and the mean anomaly needed to be changed. The former was regressed by 2.2005 deg/day. The latter was advanced exactly 12.7 revolutions per rotation of the Earth, relative to the regressing TOPEX orbital plane.

Table 2. Brouwer Mean Orbital Elements in the TOD Coordinate System at 0000 UTC of Epoch Date

ORBITAL ELEMENT	VALUE
EPOCH, t_0	6/21/1992
SEMIMAJOR AXIS, a_0 (km)	7713.3869
ECCENTRICITY, e_0	0.0011399
INCLINATION, i_0 (deg)	64.606
RIGHT ASCENSION OF NODE, Ω_0 (deg)	139.552
ARGUMENT OF PERIGEE, ω_0 (deg)	270
MEAN ANOMALY, M_0 (deg)	0

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Four 24-hour sets of tracking data were simulated. The epochs were chosen so that the four data sets would sample over the first quadrant of the angle between the Sun and the orbit normal and provide some relevant seasonal variation as well. The simulation epochs and Sun angles are given in Table 3. The orbit simulation for the 7-day arc also used the October 27, 1992, epoch. Note that monthly ionospheric maps (Reference 11) at fixed solar activity show generally high ionospheric densities in October and low densities in June. All orbit simulations were initialized at 0000 UTC of the dates shown in Table 3.

The optional methods and models used in the orbit and tracking simulations are presented in the "TOPEX Simulation" and "Relay Orbit" columns of Table 4. Observation simulation used the TDRSS version of the Research and Development (R&D) GTDS Data Simulation program. The measurement noise amplitudes were chosen to resemble the actual high-frequency noise observed in TDRSS measurements. It was not possible to include either ionospheric or tropospheric refraction effects in the data simulation because of R&D GTDS

Table 3. Simulation Epoch Dates, Sun-to-Orbit-Normal Angles, and Tracking Intervals

EPOCH DATE (0000 UTC)	SUN ANGLE (deg)	TRACKING PERIOD (UTC)
JUNE 9, 1992	2.8	$00^h\ 11^m\ 38^s$-$24^h\ 11^m\ 37^s$
OCTOBER 3, 1992	30.5	$01^h\ 01^m\ 33^s$-$24^h\ 19^m\ 48^s$
OCTOBER 17, 1992	61.5	$00^h\ 23^m\ 08^s$-$24^h\ 13^m\ 07^s$
OCTOBER 27, 1992	89.9	$01^h\ 27^m\ 17^s$-$25^h\ 05^m\ 18^s$
OCTOBER 27, 1992	89.9	$00^h\ 59^m\ 50^s$-NOVEMBER 2, $23^h\ 59^m\ 40^s$

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software limitations. These and other sources of orbit error were included by choosing different options for the GTDS solution process than were used in simulation, as discussed in Section 2.2.

Every effort has been made to simulate tracking schedules representative of the actual tracking scenarios planned for the Observation Phase, as described in Section 1.1. The basic element of simulated tracking coverage per spacecraft revolution is one 35-min pass, through either TDRS-East(E) or TDRS-West(W), of one-way downlink S-band Doppler (TD1S) tracking. The definition of tracking visibility was usually restricted to times when the tracking relay elevation, as seen from the user spacecraft and measured relative to the local horizontal plane, was greater than 5 deg. The mean ionospheric correction is a strong function of this relay elevation (Reference 9), and, to control the effect of ionospheric corrections, atmospheric editing on this variable will be advisable for operational TOPEX orbit determination. Variations on this theme include substitution of 20 min of two-way coherent tracking (TD2S and TR2S) for 35 min of one-way; allowing tracking at relay elevations down to 0 deg; and phasing the tracking pass at the beginning, middle, or end of the visible interval.

Data simulation for the four 24-hour postmaneuver arcs was scheduled according to the following rules:

- The observation interval and the Doppler count interval are both 10 seconds (sec).
- The first three passes consist of 20 min each of two-way range and Doppler tracking.
- One 35-min pass of one-way Doppler tracking occurs in each succeeding revolution.
- Fifty percent of the passes begin at the beginning of the restricted visibility interval, 25 percent end at the end; the remainder are centered in the visible interval.
- TDRS-E and TDRS-W are used at random after the first three revolutions.
- Visibility is generally cut off at 5-deg relay elevation, but one two-way pass and one one-way pass per day extend to zero elevation.

Table 4. Models and Parameters for Data Simulation and Orbit Determination (1 of 2)

MODELS AND PARAMETERS	TOPEX SIMULATION	TOPEX DC	RELAY ORBIT
INTEGRATION TYPE	12TH-ORDER FIXED-STEP COWELL	12TH-ORDER FIXED-STEP COWELL	12TH-ORDER FIXED-STEP COWELL
COORDINATE SYSTEM OF INTEGRATION	TRUE OF REFERENCE	TRUE OF REFERENCE	TRUE OF REFERENCE
INTEGRATION STEP SIZE	60 sec	60 sec	600 sec
GEOPOTENTIAL MODEL	GEM-9 (21 x 21)	GEM-L2A (21 x 21)	GEM-L2A (8 x 8)*
ATMOSPHERIC DENSITY MODEL	N/A	HARRIS-PRIESTER, $F = 225, N = 6$	N/A
COEFFICIENT OF DRAG (C_D)	0	2.2 (7-DAY ARC) 0.0 (1-DAY ARCS)	N/A
DRAG SCALING ADJUSTMENT PARAMETER (ρ_1)	N/A	SOLVE-FOR, IN 7-DAY ARC ONLY	N/A
SOLAR/LUNAR EPHEMERIDES	DE-118	DE-118	DE-118
SOLAR/LUNAR GRAVITATION	YES	YES	YES
SOLAR REFLECTIVITY COEFFICIENT (C_R)	1.2	0.8	1.4
SOLAR PRESSURE CONSTANT	0.00457	0.00457	0.00457
POLAR MOTION	NO	NO	NO
SPACECRAFT CROSS-SECTION	17.0 M^2	17.0 M^2	40.0 M^2
SPACECRAFT MASS	2650 kg	2650 kg	2000 kg

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* Except GEM-9 (8 x 8) used for October 3 data simulations only.

Table 4. Models and Parameters for Data Simulation and Orbit Determination (2 of 2)

MODELS AND PARAMETERS	TOPEX SIMULATION	TOPEX DC	RELAY ORBIT
RELAY INCLINATION ERROR	0	+27 x 10^{-6} deg (TDRS-E) -27 x 10^{-6} deg (TDRS-W)	N/A
RELAY MEAN ANOMALY ERROR	0	+41 x 10^{-6} deg (TDRS-E) -41 x 10^{-6} deg (TDRS-W)	N/A
ESTIMATED PARAMETERS	N/A	STATE, LOCAL OSCILLATOR BIAS AND DRIFT, DRAG SCALING (ϱ_1, 7-DAY ONLY)	N/A
DC CONVERGENCE PARAMETER	N/A	0.0001	N/A
DC EDITING	N/A	3-σ	N/A
IONOSPHERIC CORRECTION	NONE	BENT MODEL OR NONE	N/A
TROPOSPHERIC CORRECTION	NONE	NONE	N/A
ANTENNA MOUNT CORRECTION	NONE	NONE	N/A
ATMOSPHERIC EDITING	BY SCHEDULE (SEE TEXT)	NONE	N/A
TR2S NOISE STANDARD DEVIATION	1 M	30 M	N/A
TD2S NOISE STANDARD DEVIATION	0.01 Hz	0.25 Hz	N/A
TD1S NOISE STANDARD DEVIATION	0.01 Hz	0.25 Hz	N/A

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- Two passes are scheduled in the first 2 hours, as if to support immediate postmaneuver orbit determination.

On the assumption that orbit adjustment maneuvers will be scheduled to end at times when tracking is possible, the putative maneuver times (no actual thrusting) were taken to coincide with the first simulated observation (see Table 3). These were also the eventual DC solution epochs. The intervals of tracking data collection were ended just 24 hours thereafter.

Data simulation for the 7-day routine orbit-determination arc was scheduled according to the same rules, with the following exceptions:

- Each day, one 20-min two-way pass replaces a regular 35-min one-way pass, not necessarily at the beginning of the day.
- The data interval for one-way passes is 30 sec (although the Doppler count interval was maintained at 10 sec).
- All passes commence at first visibility (because the precise phasing of individual passes within a 7-day arc is unimportant).
- A total of 17 passes (2 or 3 each day) begin at 0-deg relay elevation, and the rest at 5 deg. On days 2, 4, and 6, one of the 0-deg passes is a two-way pass.

The 168-hour interval of tracking data collection was begun at 0000 UTC of October 27, 1992. The putative maneuver was at 0000 UTC, November 3.

2.2 ORBIT-DETERMINATION METHODS

Spacecraft orbit determination for this study used IONPRO/GTDS 2.1. This version differs from GTDS principally in that it has the optional capability to calculate and apply corrections to TDRSS tracking observations for the ionospheric refraction on the S/C-to-S/C legs of the relay communication path. Batch least-squares orbit determination was performed by the Differential Correction (DC) program within IONPRO/GTDS.

The orbit-determination options used in this study are presented in the "TOPEX DC" column of Table 4. For each of the five arcs, DC solutions were generated twice, once with and once without observation correction for ionospheric refraction, but with no other differences in the solution conditions.

In the comparison of orbit solutions generated with and without ionospheric error, the effects of small variations in input measurements cancel to first order. The nonlinearities caused by dynamic editing differences spoil this cancellation. In an attempt to provide a realistic set of background observation residuals influencing the dynamic editing and its variation with ionospheric effects, several sources of background orbit-determination error were built into both the ionospherically corrected and uncorrected DC solutions. Comparison of the "TOPEX Simulation" and "TOPEX DC" columns of Table 4 reveals those error sources. Geopotential modeling error (including central gravitational constant) is represented by the difference between the Goddard Earth Models GEM-L2A and GEM-9, both truncated at order and deg 21. Atmospheric density modeling error and tropospheric refraction error are not included. Solar radiation force modeling error is represented by a difference in reflectivity of 50 percent. Measurement noise error is discussed in Section 2.1.

Except for the October 3 arc, all TDRSS relay orbits were generated with options identical to those used in data simulation (see the "Relay Orbit" column of Table 4). Relay orbit error is simulated in this study by varying the initial TDRS relay Keplerian elements from those with which the tracking data were simulated. An oscillatory cross-track error of amplitude 19.9 m was obtained by changing the TDRS-E (-W) inclination by +0.000027 deg (–0.000027 deg). Approximately constant along-track errors of 30.2 m were obtained by changing the TDRS-E (-W) mean anomaly by +0.000041 deg (–0.000041 deg). The data simulations for October 3 were inadvertently performed using GEM-9 rather than GEM-L2A for the relay geopotential. This introduces additional relay orbit error in the solutions for this arc, which is dominated by along-track position error that grows linearly from 0 to 12 m by the end of the arc.

Since available tracking data simulation software lacks the S/C-to-S/C ionospheric refraction capability, ionospheric refraction error was implemented in this study by applying an ionospheric correction to observations that were simulated without the effect. Contrary to the situation that exists during actual orbit determination, the solution obtained here without ionospheric refraction correction is the closest to the true orbit, and the solutions obtained with ionospheric refraction correction are degraded in accuracy. The sign of the orbit-determination error may be opposite to that caused, in reality, by failing to correct real observations, but there is no reason to expect the magnitude to differ.

The observation standard deviations appearing in the "TOPEX DC" column of Table 4 are those whose inverse squares define the weight factors for least-squares estimation. These values are currently used for operational orbit determination. The value used for the one-way measurements (TD1S) has been used for Cosmic Background Explorer (COBE) operational support using an onboard ultra-stable oscillator, as planned for TOPEX.

The convergence tolerance used, 0.0001, is only 2 percent of the standard usage for operational orbit determination. This value was used to minimize the effects of differences in degree of convergence between ionospherically corrected and uncorrected solutions.

2.3 REFRACTION CORRECTION METHODS

The current method of GTDS atmospheric correction of TDRSS tracking observations is to correct all ground-to-space legs for both the ionosphere and the troposphere, except that the ionospheric correction is justifiably ignored for K-band legs because of the inverse-square dependence on frequency. Ionospheric correction is thus applied to the TDRS-to-transponder legs of Bilateration Ranging Transponder System (BRTS) data and not at all to user tracking data. This neglect of refraction correction for the S/C-to-S/C legs is justifiable for the troposphere, which extends only to tens of kilometers, but not, in general, for the ionosphere. IONPRO/GTDS, in contrast, uses one of two algorithms described in Reference 12 to evaluate the electron-density line integrals along the S/C-to-S/C communication paths. The electron-density function, n_e, for the integrals is provided by the existing GTDS implementation of the Bent Ionospheric Model (Reference 2).

In the current study, numerical integration of the electron density is performed using Gaussian integration (Method I of Reference 2). The integral is divided at 3000-km altitude into two segments. The lower altitude segment is evaluated using 20-point Gaussian integration in the path variable, s. The segment above 3000-km altitude is extended to infinity in the direction beyond the relay spacecraft and evaluated by three-point Gaussian integration in the variable

$$u = \exp(-k_5 s) \tag{1}$$

where k_5 is the inverse scale height of the top layer of the segmented Bent model profile.

2.4 SOLAR ACTIVITY SIMULATIONS

The electron-density distribution in the ionosphere is highly dependent on the level of solar activity. As described by the Bent model, it depends primarily on the monthly value of 12-month smoothed solar flux, F_{12}, on the daily solar flux, F, and, to a lesser degree, on the 12-month smoothed sunspot number, R. Values of these parameters were carefully chosen for use in the ionospherically corrected DCs to provide a moderately pessimistic estimate of an extreme ionospheric state in the early TOPEX mission time frame.

A recent prediction (Reference 13) for the two-standard-deviation upper limit of F_{12} for June 1992 (that is, 169), was used for all five DC arcs. With this value of F_{12}, the sunspot number (Reference 14) was derived by solving

$$F_{12} = 63.75 + 0.728\ R + 0.00089\ R^2 \tag{2}$$

Solar flux values around the peak of cycle 19, the previous cycle that most closely resembles the rising portion of the current cycle 22, were studied. In August, 1960, 4 months after cycle 19 had decayed to F_{12} of 169, an apparent solar storm produced a peak daily solar flux of 250 (Reference 15). That daily solar flux value was used for each of the four 24-hour postmaneuver arcs. The daily flux values for August 17-23, 1960, were used for October 27 to November 2, 1992, in the 7-day routine orbit-determination arc. Those F-values, specified in Table 5, have a mean of 215.9.

2.5 EVALUATION METHODS

As stated in Section 1, the basic method of determining the orbit-determination effects of ionospheric refraction was by comparing orbit-determination results obtained without an ionospheric refraction correction to similar results obtained with exactly the same tracking data, but now applying the ionospheric refraction correction. Osculating Keplerian period, semimajor axis, eccentricity, and inclination were calculated from the ephemeris file output of definitive solution trajectories; differences were calculated as functions of time within the definitive arc. The radial, cross-track, and along-track components of velocity differences were obtained from the GTDS ephemeris comparison (COMPARE) program.

Since the TOPEX premaneuver and postmaneuver accuracy requirements apply only to the maneuver time, it would seem necessary only to calculate the ephemeris comparisons at a

Table 5. Solar Activity Simulations

	F12	F	R
24-HOUR ORBIT DETERMINATION ARCS			
JUNE 6, 1992	169.0	250.0	125.4
OCTOBER 3, 1992	169.0	250.0	125.4
OCTOBER 17, 1992	169.0	250.0	125.4
OCTOBER 27, 1992	169.0	250.0	125.4
7-DAY ORBIT DETERMINATION ARC			
OCTOBER 27, 1992	169.0	247.0	125.4
OCTOBER 28, 1992	169.0	250.0	125.4
OCTOBER 29, 1992	169.0	234.0	125.4
OCTOBER 30, 1992	169.0	219.0	125.4
OCTOBER 31, 1992	169.0	201.0	125.4
NOVEMBER 1, 1992	169.0	189.0	125.4
NOVEMBER 2, 1992	169.0	171.0	125.4
MEAN	169.0	215.9	125.4
STANDARD DEVIATION	0.0	30.1	0.0

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solution epoch coincident with this time. Velocity differences, however, vary sinusoidally on the orbital period, while eccentricity and semimajor axis differences have been found to vary more rapidly. If the maneuver is taken to be at some random time before the beginning of the postmaneuver tracking arc, these variations will be sampled over. A single-point comparison may produce values less than the sample averages. To guard against this possibility, Keplerian and velocity comparisons of ephemerides need to be sampled over at least an orbital revolution near epoch. Since the character of the tracking data in the postmaneuver scenarios differs systematically between the initial revolutions of the arc and the later ones, it is unnecessary, and potentially misleading, to extend this sampling over the entire definitive arc. Analytical emphasis was therefore placed on root-mean-squares (rms) over one-orbit samples of ephemeris comparisons; that is, the first 112 min of the postmaneuver arcs and the last 112 min of the premaneuver arc. Single-point samples at epoch and full definitive samples were, however, also calculated for comparison purposes. One-orbit samples were taken at 1-min sampling intervals, whereas longer samples were taken at 10-min sampling intervals.

Detailed analysis of the accuracy requirement for premaneuver determination of the osculating argument of latitude was not performed. The results strongly indicate that this requirement is not in any way challenged by ionospheric refraction error. Analysis (see Reference 9) of the 30-day equator crossing prediction requirement, using orbit determination results for the 7-day arc of simulated tracking data, shows that ionospheric refraction has a negligible impact. Because of space limitations, that analysis will not be discussed in this paper.

3. RESULTS AND DISCUSSION

Table 6 summarizes the corrected and uncorrected DC solutions for each of the five orbit-determination arcs. The first four pairs of solutions represent the four 24-hour postmaneuver arcs, with epochs at the beginnings of the arcs specified in Table 3. The last pair of solutions represents the 7-day arc with DC epoch at the end of the arc, 0000 UTC, November 3, 1992. The results of definitive parallel ephemeris comparison between the corresponding corrected and uncorrected solutions are listed in Table 6 under the "Maximum Compare Position Differences" column.

The numbers of accepted observations shown in Table 6 reflect the absence of DC editing of two-way observations in the 24-hour arcs, except for 44 Doppler observations edited in only the corrected solution for October 27. Although editing of a single one-way observation did occur on October 3, the same rejection was made in both corrected and uncorrected solutions. Thus, October 27 is the only 24-hour solution to partake of the nonlinear effect of a DC editing difference. There is also a difference in the selection of two-way Doppler observations in the 7-day arc.

In keeping with the fact that the refraction correction is applied to unrefracted simulated observations, the corrected solutions generally show inferior fit to the tracking data, as revealed by larger weighted rms residuals and residual standard deviations.

The definitive maximum along-track position differences at the far right of Table 6 do not exceed 2.1 m for the long arc (and are still less for the premaneuver arcs). Thus, the ionospheric effect on determination of argument of latitude is in the neighborhood of 16×10^{-6} deg. The requirement for determination of this quantity will, therefore, not be impacted by ionospheric refraction error and will not be considered further.

Table 7 summarizes the differences between corrected and uncorrected solutions in the quantities related to the remaining TOPEX orbit-determination accuracy requirements. Shown are the actual differences at epoch for each solution and the rms values over one-orbit and full definitive samples as described in Section 2.5. The ionospheric refraction effects on period and eccentricity are smaller by two orders of magnitude than any accuracy requirement. The inclination discrepancies are less than 4 percent of the minimum postmaneuver requirement, except for the October 27 result (13 percent of the requirement) associated with the 10-percent TD2S editing difference. The inclination error for the 7-day arc is only 3 percent of the precision premaneuver inclination accuracy requirement. The rms of the four one-orbit postmaneuver samples of discrepancy in semimajor axis, 1.13 centimeters (cm), barely exceeds 5 percent of the 20-cm accuracy requirement. Premaneuver semimajor axis discrepancies are smaller than that, and also less than 0.3 percent of the corresponding premaneuver accuracy requirement.

The situation revealed by Table 7, with regard to determination of postmaneuver velocity changes, contrasts with that seen for Keplerian elements. The RMS postmaneuver effect on cross-track velocity change determination is only 7 percent of the accuracy requirement, while the premaneuver effect on the same determination is smaller. The RMS postmaneuver effect on radial velocity change determination, however, is 30 percent of the accuracy requirement, and the single premaneuver sample is 45 percent thereof. The along-track

Table 6. DC Summaries for Corrected and Uncorrected Solutions

EPOCH DATE	IONOSPHERIC CORRECTION	NUMBER OF OBSERVATIONS			WEIGHTED RMS	STANDARD DEVIATIONS			ρ_1	LOCAL OSCILLATOR		MAXIMUM COMPARE-POSITION DIFFERENCES (m)			
		TR2S	TD2S	TD1S		TR2S (m)	TD2S (mHz)	TD1S (mHz)		BIAS (mHz)	DRIFT (10^{-9} Hz/sec)	RADIAL	CROSS-TRACK	ALONG-TRACK	TOTAL
6/9	NO	362	362	2072	0.1525	3.14	54.6	32.1	-1	-25.0	807	0.205	0.056	0.592	0.595
	YES	362	362	2072	0.1572	3.35	58.5	32.2	-1	-25.4	822				
10/3	NO	363	363	2109	0.1411	1.75	59.1	29.0	-1	-3.9	67	0.233	0.609	1.614	1.665
	YES	363	363	2109	0.1430	1.90	60.8	20.2	-1	-1.8	-22				
10/17	NO	363	363	2110	0.1115	2.57	23.9	28.8	-1	+ 19.4	-581	0.295	0.404	1.479	1.507
	YES	363	363	2110	0.1138	2.61	22.7	29.4	-1	+ 19.8	-598				
10/27	NO	363	363	2110	0.1090	1.92	29.1	28.3	-1	20.0	-715	0.182	1.859	1.405	2.201
	YES	363	319	2110	0.1125	1.42	33.6	28.9	-1	15.3	-623				
11/3	NO	847	791	5358	0.1437	2.75	44.8	35.4	-0.9953	38.4	79	0.451	0.573	2.052	2.055
	YES	847	835	5358	0.1485	2.70	49.3	35.8	-0.9886	30.2	71				

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Table 7. RMS Values of Definitive Solution Ephemeris Differences (Corrected Solution Minus Uncorrected Solution)

EPOCH DATE	SAMPLED INTERVAL	PERIOD, ΔT (MSEC)	SEMIMAJOR AXIS, Δa (CM)	ECCENTRICITY, Δe (10^{-6})	INCLINATION, ΔI (10^{-6} DEG)	ΔV_r (MM/SEC)	ΔV_c (MM/SEC)	ΔV_a (MM/SEC)	Δa /2144 SEC (MM/SEC)
INDIVIDUAL POSTMANEUVER ARCS									
06/09	EPOCH	0.002	0.12	0.021	-0.42	0.09	0.03	-0.19	0.0006
	1 ORBIT	0.002	0.11	0.017	0.42	0.16	0.04	0.14	0.0005
	DEF. ARC	0.002	0.11	0.017	0.42	0.19	0.04	0.13	0.0005
10/03	EPOCH	0.021	1.64	0.011	-3.76	-0.62	-0.17	0.19	0.0076
	1 ORBIT	0.021	1.59	0.025	3.76	0.52	0.39	0.14	0.0074
	DEF. ARC	0.021	1.59	0.025	3.76	0.58	0.39	0.14	0.0074
10/17	EPOCH	0.016	1.25	0.037	-2.98	-0.55	0.20	0.06	0.0058
	1 ORBIT	0.015	1.12	0.024	2.98	0.32	0.27	0.19	0.0052
	DEF. ARC	0.015	1.12	0.024	2.98	0.49	0.27	0.19	0.0052
10/27	EPOCH	-0.016	-1.23	-0.017	-13.45	0.91	-1.65	0.03	-0.0057
	1 ORBIT	0.015	1.13	0.019	13.46	1.01	1.23	0.11	0.0053
	DEF. ARC	0.015	1.12	0.019	13.46	0.55	1.21	0.11	0.0052
RMS OF FOUR POSTMANEUVER ARCS									
	1 ORBIT	0.015	1.13	0.022	7.15	0.60	0.66	0.15	0.0053
PREMANEUVER ARC									
11/03	EPOCH	-0.002	-0.14	-0.051	-3.17	0.59	-0.17	0.34	-0.0007
	1 ORBIT	0.002	0.18	0.047	3.17	0.89	0.38	0.29	0.0008
	DEF. ARC	0.005	0.35	0.047	3.17	0.88	0.34	0.29	0.0016

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velocity errors exceed the accuracy requirement by 50 to 200 percent, including the premaneuver result.

The last column of Table 7 represents the first term on the right side of the equation

$$\Delta V_a = \frac{\Delta a}{2144 \text{ sec}} - \frac{\Delta r}{1072 \text{ sec}} \tag{3}$$

where Δr is the error in radial position. This equation is the differential form of the *vis viva* equation for the osculating semimajor axis, specialized to TOPEX in the circular orbit approximation. The results for ΔV_a in Table 7 are clearly dominated by the second term. If, however, Equation (3) is applied to changes in quantities computed just before and just after a maneuver, while using the unified orbit determination scenario that does not permit a position discontinuity, the second term exactly cancels (Reference 5), so that

$$\delta \Delta V_a' = \frac{\delta \Delta a'}{2144 \text{ sec}} \tag{4}$$

where δ signifies the postmaneuver-premaneuver difference and the primes remind us that the subtracted quantities are not those of the independent orbit determination scenario. Unless the unified orbit determination scenario actually increases the ionospheric effect on determination of semimajor axis changes, $\delta \Delta V_a'$ will be of the order of the first term in Equation (3) from the original orbit determination scenario. In Table 7, this term averages, for the 24-hour arcs, about 5 percent of the accuracy requirement.

The central processing unit (CPU) time for the corrected 7-day DC was 53.3 min, compared with 13.8 min without ionospheric correction. This difference can easily be cut by a factor of 3 or 4, by changing IONPRO/GTDS so as not to recalculate corrections every DC iteration. It is nevertheless clear that operational use of this correction for TOPEX orbit determination may pose a significant computational burden.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The analysis of the orbit-determination effects of the S/C-to-S/C ionospheric refraction correction shows that, although the effects are small in an absolute sense, they are in some cases comparable with the stringent TOPEX accuracy requirements. Most notably, ionospheric refraction effects cause along-track velocity change errors of up to triple the postmaneuver accuracy requirement. They also cause radial velocity change errors of 20 to 45 percent of the accuracy requirement. On the other hand, ionospheric refraction effects are at the 10 percent level, or less, relative to Keplerian element premaneuver and postmaneuver accuracy requirements. These conclusions are only strictly applicable to the independent postmaneuver orbit determination scenario and to the Observation Phase.

Conclusions about the unified premaneuver and postmaneuver orbit determination scenario are somewhat conjectural. A very strong conjecture is that the semimajor axis change determination in this scenario is no more sensitive to the ionosphere than in the other scenario. In that case, along-track velocity change errors from ionospheric refraction will be reduced to 5 percent of the accuracy requirement. Therefore, the radial velocity change errors may be the most significant.

This analysis does not determine how well the ionospheric error can be reduced by a correction algorithm using the Bent model. A reduction to the 30 percent level is a reasonable guess. At that level, residual ionospheric error may still account for 50 to 100 percent of the allowable error in along-track velocity change.

4.2 RECOMMENDATIONS

This analysis shows that the effects of neglected ionospheric refraction error on TOPEX orbit determination accuracy using a serious candidate solution scheme are very significant relative to that mission's stringent requirements. It certainly implies that this error source is a significant one for orbit determination using the TDRSS in the new decade, and must not be slighted in error analysis.

By employing an alternate orbit determination scenario, it may be possible to avoid immediate implementation of a spacecraft-to-spacecraft ionospheric correction algorithm for GTDS use in TOPEX orbit support. Reliable proof of this remains to be established and should be pursued urgently. It is certainly not possible to meet the current TOPEX accuracy requirements using the FDF standard maneuver support scenario (with separate premaneuver and postmaneuver arcs) lacking such a correction. Unfortunately, global error analysis (References 5 and 6) seems to indicate this goal to be out of reach even with accurate ionospheric correction.

Research into methods of ionospheric correction and into its orbit determination effects should be pursued so that an accurate, efficient correction may be employed, at the latest, during the next solar activity maximum. The errors in candidate ionospheric correction algorithms must be analyzed to establish the level of residual ionospheric error. Orbit determination analysis using real tracking data from COBE, now that it has ceased to vent helium gas, will be useful in this last endeavor. Not only does that mission provide one-way downlink Doppler measurements with the onboard ultrastable oscillator, but its relatively high altitude mitigates the impact of orbit determination error on the evaluation of observation corrections. TOPEX tracking data and precision orbit determination results will eventually be of use in this evaluation, as well.

It is desirable to have the accuracy of the ionospheric correction approach 20 percent. The inherent unpredictability of the ionosphere probably precludes a more accurate correction. The computational burden of ionospheric correction is significant, approximately a factor of 2 in CPU usage, with most of the increase coming from evaluating the Bent model. These two considerations argue in favor of modernizing the ionospheric model, a not inconsiderable effort.

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