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Cosmic Background Explorer (COBE) Navigation With TDRSS One-Way Return-Link Doppler in the Post-Helium-Venting Phase*

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ABSTRACT

A navigation experiment has been performed which establishes USO-frequency-stabilized one-way return-link Doppler TDRSS tracking data as a feasible option for mission orbit determination support at the Goddard Space Flight Center Flight Dynamics Facility (GSFC FDF). The study was conducted using both one-way and two-way Tracking and Data Relay Satellite System (TDRSS) tracking measurements for the Cosmic Background Explorer (COBE) spacecraft. Tracking data for a 4-week period immediately following the depletion of the helium supply was used. The study shows that, for both definitive orbit solution and short-term orbit prediction (up to 4 weeks), orbit determination results based on one-way return-link Doppler tracking measurements are comparable to orbit determination results based on two-way range and two-way Doppler tracking measurements.

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INTRODUCTION

This paper discusses orbit determination analysis results that establish Ultra-Stable Oscillator (USO)-frequency-stabilized one-way return-link Doppler Tracking and Data Relay Satellite (TDRS) System (TDRSS) tracking data as a feasible option for mission orbit determination support at the Goddard Space Flight Center Flight Dynamics Facility (GSFC FDF). The study was conducted using TDRSS tracking measurements for the Cosmic Background Explorer (COBE) spacecraft.

COBE is the first, and so far the only, spacecraft supported by the FDF to be tracked with USO-stabilized one-way return-link noncoherent Doppler tracking measurements. COBE orbit determination analysis has therefore served as a flight-test of the one-way tracking system. Future use of TDRSS one-way Doppler tracking measurements will be required by the Ocean Topography Experiment (TOPEX) and the Explorer Platform/Extreme Ultraviolet Explorer (EP/EUVE) TDRSS Onboard Navigation (TONS) experiment. Both of these future experiments will utilize USOs similar to the USO carried by COBE for Doppler frequency reference. TOPEX requires very high precision orbit determination using one-way return-link Doppler tracking. For example, velocity changes brought about by in-plane TOPEX spacecraft maneuvers must be determined to within 0.1 millimeter per second (Reference 1). The EP/EUVE TONS experiment will use one-way forward-link Doppler tracking data for a ground-based emulation of onboard navigation. The EP/EUVE TONS experiment will benefit from the USO performance evaluation techniques discussed in this paper (see Reference 2 for a discussion of the EP/EUVE TONS experiment). Reference 3 provides background information about the COBE spacecraft and describes the USO and its role in one-way orbit determination.

Previous COBE navigation analysis (Reference 3) utilized tracking measurements obtained during the period COBE was venting helium from a Dewar used to cool one of its science experiments. This period began soon after COBE launch on November 18, 1989, and lasted until September 1990. This venting phase work accomplished three objectives: (1) verification of algorithms for one-way navigation with real data, (2) determination of the flight performance of the USO coupled to the second-generation TDRSS transponder, and (3) qualification of TDRSS noncoherent one-way return-link Doppler tracking data for FDF mission support of COBE. Since this work involved analysis of an orbit that was being perturbed by helium venting, the third objective stated above only addressed whether the one-way data can support COBE mission requirements. Overlap ephemeris comparisons on the order of hundreds of meters and 4-week orbit prediction errors on the order of hundreds of kilometers characterized both one-way and two-way orbit determination capabilities during the venting phase. Thus, accuracy assessment was severely limited.

This paper covers the second phase of the COBE navigation experiment, which was initiated on September 27, 1990, after the helium was depleted. One-way tracking measurements for October and the last 4 days of September 1990 were used for orbit determination with a research version of the Goddard Trajectory Determination System (GTDS). The objective of this phase of analysis was to reassess the suitability of one-way tracking measurements for orbit determination during a more quiescent period of the COBE mission, when greater orbit determination accuracy is possible. Orbit solutions were generated using the best force models and processing options available within the GTDS environment. Such an effort was warranted only when the unmodeled venting perturbations were no longer a factor. Although additional one-way solution accuracy was achieved during the postventing phase analysis, these one-way solutions do not represent the best possible with one-way tracking systems. The primary accuracy-limiting factor during the postventing phase is the poor COBE tracking geometry, which results from limitations of the COBE TDRSS antenna pattern coverage. More discussion of the COBE tracking geometry follows in the analysis section of this paper.

This paper discusses the consistency, compatibility, and predictive capability of one-way solutions relative to two-way solutions. Additionally, the performance of the USO in the in-flight environment is addressed.

REVIEW OF COBE CHARACTERISTICS RELEVANT TO ORBIT DETERMINATION

The COBE spacecraft was placed in a nearly circular Sun-synchronous orbit with an altitude of 900 kilometers and an inclination of 99 degrees. The spacecraft has no orbit maneuver capability. The primary influences on the orbit evolution are the gravitational, atmospheric drag, and (prior to September 27, 1990) helium venting forces.

The USO onboard COBE provides a command-selectable external stable reference frequency to either of the two onboard TDRSS user transponders. It has a reference frequency of 19.056393 megahertz and a prelaunch measured long-term drift of -4×10^{-11} parts per day (Reference 4). The drift of the USO, when coupled to the COBE second-generation TDRSS transponder, has been determined from previous flight analysis to be better than 5×10^{-11} parts per day in magnitude. The USO is used as the source frequency for one-way noncoherent Doppler data extracted from the TDRSS return-link signal at the White Sands Ground Terminal (WSGT), as depicted in Figure 1. The TDRSS tracking data for these evaluations were derived from both the S-band Single-Access (SSA) and Multiple-Access (MA) TDRSS services.

Details of the one-way return-link Doppler measurement model can be found in Reference 3.

ANALYSIS PROCEDURE

The orbit determination performed for this analysis was based on the least-squares batch estimation algorithm available in GTDS. (Reference 5 gives a detailed discussion of this algorithm.) In addition to COBE orbit determination using TDRSS tracking measurements, the analysis also involved TDRS-East and TDRS-West orbit determination using Bilateration Ranging Transponder System (BRTS) tracking measurements. Although simultaneous solution of relay and user satellite orbits is possible, the TDRS orbits were predetermined for this study.

This study utilized the the force models summarized in Table 1 and the processing options summarized in Table 2 for user and relay orbit determination. In particular, the Goddard Earth Model (GEM)-T2 geopotential model (Reference 6) provided coefficients through

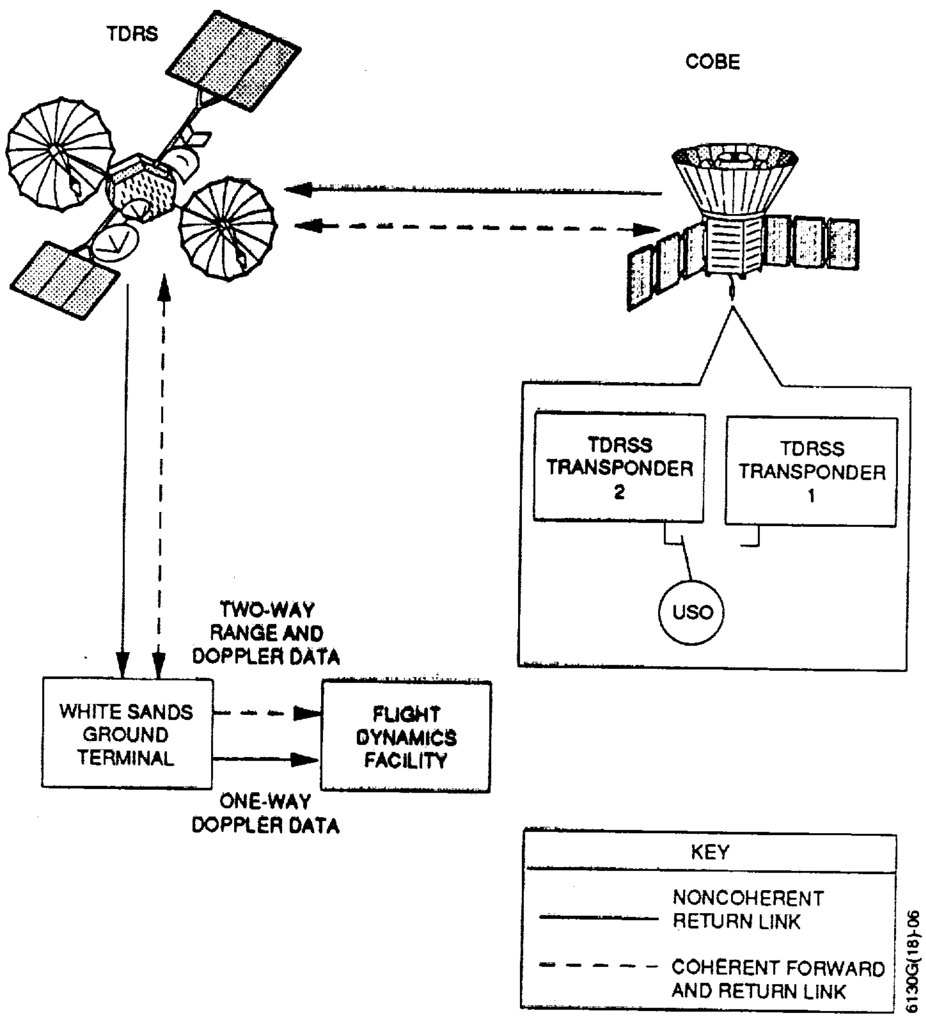

Figure 1. USO COBE Experiment Overview

Table 1. Summary of Modeling Options

OPTION	SPACECRAFT	
	COBE	TDRS-EAST AND TDRS-WEST
GEOPOTENTIAL	GEM-T2 50 x 50, EQUATIONS OF MOTION GEM-T2 4 x 0 (TRUNCATED), VARIATIONAL EQUATIONS	GEM-T2 8 x 8 (TRUNCATED), EQUATIONS OF MOTION GEM-T2 4 x 0 (TRUNCATED), VARIATIONAL EQUATIONS
THIRD-BODY EFFECTS	SUN, MOON (POINT-MASS)	SUN, MOON (POINT-MASS)
SOLAR RADIATION PRESSURE	APPLIED WITH C_R = 1.42	COEFFICIENT ESTIMATED
POLAR MOTION	YES	YES
ATMOSPHERIC DRAG	JACCHIA-ROBERTS MODEL; C_D = 2.3; HISTORICAL F10.7 SOLAR FLUX, GEOMAGNETIC, AND TEMPERATURE DATA; C_D VARIATION ESTIMATED	NEITHER APPLIED NOR ESTIMATED
EARTH TIDES	GEOPOTENTIAL COMPENSATED; LOVE NUMBER = 0.29; LAG ANGLE = 2.5 DEGREES	GEOPOTENTIAL COMPENSATED; LOVE NUMBER = 0.29; LAG ANGLE = 2.5 DEGREES
SATELLITE AREA	SPHERE WITH DIAMETER = 4.76 METERS	SPHERE WITH DIAMETER = 6.32 METERS
SATELLITE MASS	2055 KILOGRAMS	TDRS-East: 1984.87 KILOGRAMS (9/27/90–10/4/90) 1984.77 KILOGRAMS (10/5/90–10/31/90) TDRS-West: 1991.85 KILOGRAMS

Table 2. Summary of Processing Options

OPTION	SPACECRAFT	
	COBE	TDRS-EAST AND TDRS-WEST
NUMERICAL INTEGRATION	12th-ORDER FIXED-STEP COWELL; 60-SECOND STEPSIZE	12th-ORDER FIXED-STEP COWELL; 600-SECOND STEPSIZE
REFERENCE FRAME	MEAN EQUATOR AND EQUINOX OF J2000.0 FOR INTEGRATION AND SOLAR/LUNAR/PLANETARY (SLP) EPHEMERIS	MEAN EQUATOR AND EQUINOX OF J2000.0 FOR INTEGRATION AND SLP EPHEMERIS
MEASUREMENT DATA AND DATA RATE	ONE-WAY DOPPLER: 10 SECONDS TWO-WAY DOPPLER: 10 SECONDS RANGE: 10 SECONDS	BRTS DOPPLER: 10 SECONDS BRTS RANGE: 10 SECONDS
EDITING CRITERIA	ATMOSPHERIC EDITING: HORP*/CENTRAL ANGLE = 830 KILOMETERS/70 DEGREES (SEE TEXT) RESIDUAL EDITING: 3 σ	3 σ RESIDUAL EDITING
STANDARD DEVIATIONS USED FOR EDITING AND WEIGHTING	ONE-WAY DOPPLER: 0.13 HERTZ TWO-WAY DOPPLER: 0.25 HERTZ RANGE: 30 METERS	BRTS DOPPLER: 0.003 HERTZ BRTS RANGE: 10 METERS
IONOSPHERIC REFRACTION	NO CORRECTION	GROUND-TO-RELAY LEG CORRECTED
TROPOSPHERIC REFRACTION	GROUND-TO-RELAY LEG CORRECTED	GROUND-TO-RELAY LEG CORRECTED
ESTIMATOR	BATCH WEIGHTED LEAST SQUARES	BATCH WEIGHTED LEAST SQUARES
ESTIMATED PARAMETERS	POSITION, VELOCITY, ATMOSPHERIC VARIATION COEFFICIENT (ρ_1); USO FREQUENCY BIAS AND DRIFT	POSITION, VELOCITY, AND SOLAR REFLECTIVITY COEFFICIENT (C_R)

* HORP = HEIGHT OF RAY PATH

degree and order 50. The complete coefficient set was incorporated in the COBE solutions; the coefficient set was truncated at degree and order 8 for the relay satellites. Additionally, historical solar flux, geomagnetic, and exospheric temperature data were used with the Jacchia-Roberts atmospheric density model. The cross-sectional areas of the COBE and Tracking and Data Relay Satellite (TDRS) spacecraft were assumed constant. The error associated with this assumption was compensated by estimating the atmospheric drag variation coefficient (ϱ_1) for COBE and estimating the solar reflectivity coefficient (C_R) for the TDRSs. The effects due to polar motion, Earth tides, and atmospheric refraction of the tracking signal were taken into account. These corrections are discussed in References 7 and 8.

Prior to the orbit determination analysis, error analysis was performed using the Orbit Determination Error Analysis Program (ODEAS) in an attempt to find the optimum data arc length for COBE that would enable estimation of the atmospheric drag variation parameter (ϱ_1). High correlations among the state variables were observed in the noise-only covariance matrix for a 34-hour COBE solution arc when ϱ_1 was included in the state. The error analysis showed that 4 days of data would allow ϱ_1 estimation and acceptable levels of geopotential error (at COBE's altitude of 900 kilometers, drag effects are too small to permit short-arc ϱ_1 estimation). The error analysis also showed that the benefits of a long TDRS data arc are diminished by accumulation of gravitational and solar radiation pressure errors. Based on the error analysis, a 4-day, 10-hour arc was selected for COBE and a 40-hour arc was selected for the TDRSs.

Two sets of four separate 40-hour TDRS solutions (one set for TDRS-East and one set for TDRS-West) were utilized for each 4-day, 10-hour COBE solution. The 40-hour arcs were scheduled so that they would overlap by 10 hours.[1] The TDRS solutions involved the estimation of the coefficient of reflectivity, C_R, and were based on BRTS range and Doppler measurements.

Three separate COBE solutions for each of eight 4-day, 10-hour arcs were evaluated: a one-way only solution, a two-way only solution, and a combined one-way and two-way solution. The COBE solutions involved estimation of the drag variation parameter (ϱ_1) and, when one-way data were included, the effective USO frequency bias and drift. The bias estimation, in addition to compensating for the USO bias, accounted for relativistic shifts in the frequency during transmission of the tracking signal. The COBE data arcs matched the schedule followed by FDF Orbit Operations personnel for mission support of COBE. Accordingly, each 4-day, 10-hour data arc started at 0 hours on either a Monday or a Thursday. Thus, alternating overlaps periods of 10 hours and 34 hours occurred.

In an attempt to mitigate the effects of ionospheric disturbance on the tracking measurements (see the analysis results section), atmospheric editing was performed. This editing used a geometric criterion based on the height of ray path (HORP) and the central angle. HORP is defined as the height above the surface of the Earth of the point on an imaginary line connecting the relay and TDRS spacecraft that is closest to the Earth's surface. The central angle is

[1] A slight adjustment had to be made to the data arc scheduling so that a TDRS-East maneuver, which occurred on October 4, 1990, could be accommodated.

measured between the user spacecraft and relay spacecraft position vectors with respect to the center of the Earth. Figure 2 illustrates the HORP (h) and central angle (δ) geometry. For this study, a tracking measurement was not used if its associated central angle was greater than 70 degrees at the same time its associated HORP was less than 830 kilometers.

Since simultaneous one-way and two-way tracking was not available, the one-way and two-way tracking measurement distributions were not identical. However, similar tracking schedules and similar quantities of one-way measurements and two-way measurement pairs allowed valid comparisons of one-way and two-way solutions. Figure 3 shows typical one-way and two-way tracking measurement distributions as they were accepted for orbit determination. The figure covers a 4-day period used for one of the solution arcs.

Three types of ephemeris comparisons were used to evaluate solution consistency and solution compatibility: overlap comparisons, parallel comparisons, and predictive comparisons. Overlap and predictive comparisons both involve comparison of solutions based on the same data type. Parallel comparisons involve a comparison of solutions based on different data types. Each comparison scheme is illustrated in Figure 4. In addition to ephemeris comparison results, the byproducts of the estimation process (such as editing statistics), the RMS of the observation residuals, and the atmospheric drag variation parameter provided a basis for comparison between one-way and two-way solutions. Additionally, the performance of the USO in the in-flight environment was ascertained from an evaluation of the tracking data. The effects of the USO bias and drift on the one-way data and on the solution accuracy were analyzed.

TRACKING DATA EVALUATION RESULTS

The noise and bias characteristics of the USO were computed based on the statistical properties of the one-way measurement residuals. A measurement residual is the algebraic difference between the observed value of a tracking measurement and the computed value of the measurement. The residuals, which are computed during the estimation process, effectively remove orbital variations from the tracking data. Thus, such qualities as random noise variation, S-band frequency bias, and S-band frequency drift are more easily discerned from the residuals than from the tracking measurements. The frequency bias and drift were considered reflections of USO performance. The residuals used for the data evaluation were obtained from 24-hour GTDS solutions generated over the course of the period starting with COBE's launch and ending at the end of November 1990 (tracking data evaluation was unaffected by venting effects). Each 24-hour solution provided a mean residual for each batch of data occurring within it's solution arc.

The first parameter evaluated was the USO frequency bias. A least-squares quadratic curve was fit to all the Doppler residual mean values that had accumulated during the period under study (from September 27, 1990, through October 1990). The equation for this fit was as follows:

$$b(T) = -226.178 - 0.1583T + 0.000127T^2 \pm 0.1086$$

where T is the number of days from December 31, 1989, and b(T) is in hertz.

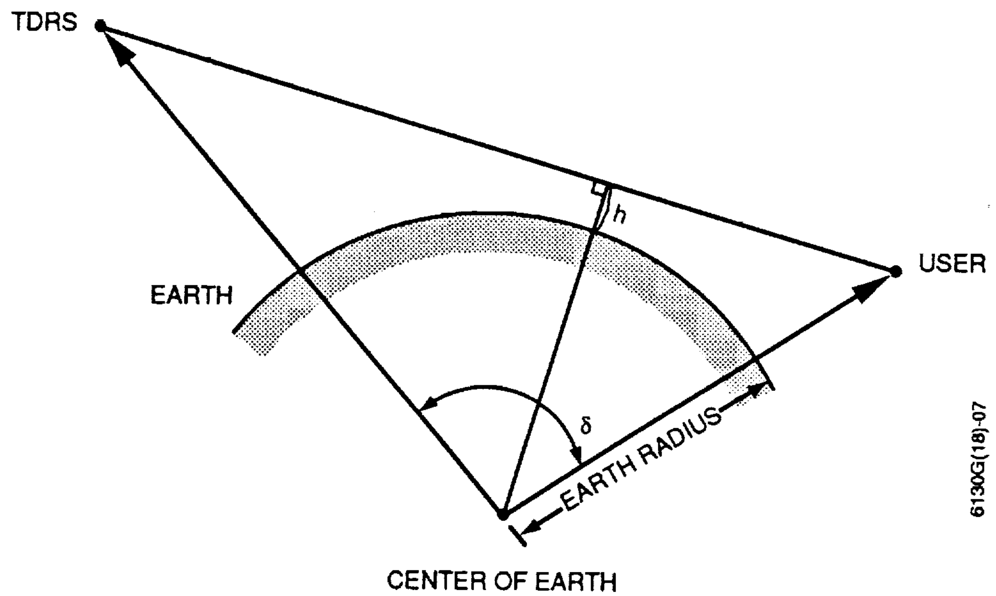

Figure 2. **Illustration of the Atmospheric Editing Geometry Showing the Height of Ray Path (h) and the Central Angle (δ)**

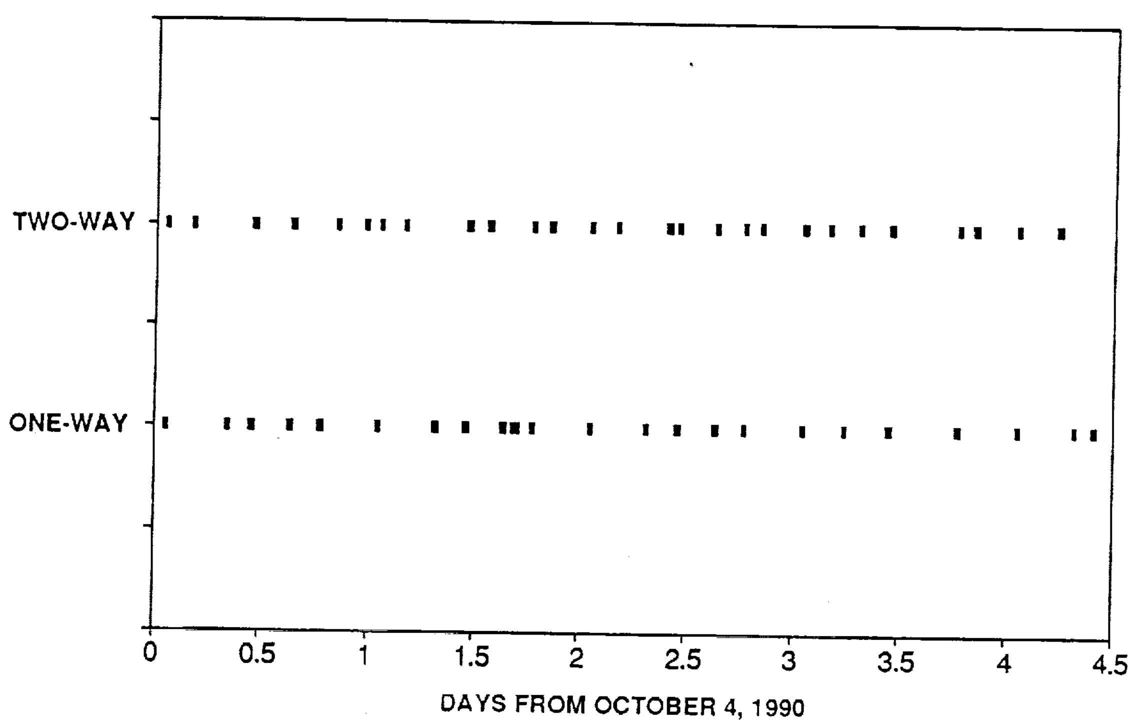

Figure 3. **Passes Accepted by the Differential Correction Process for a Typical Solution Arc**

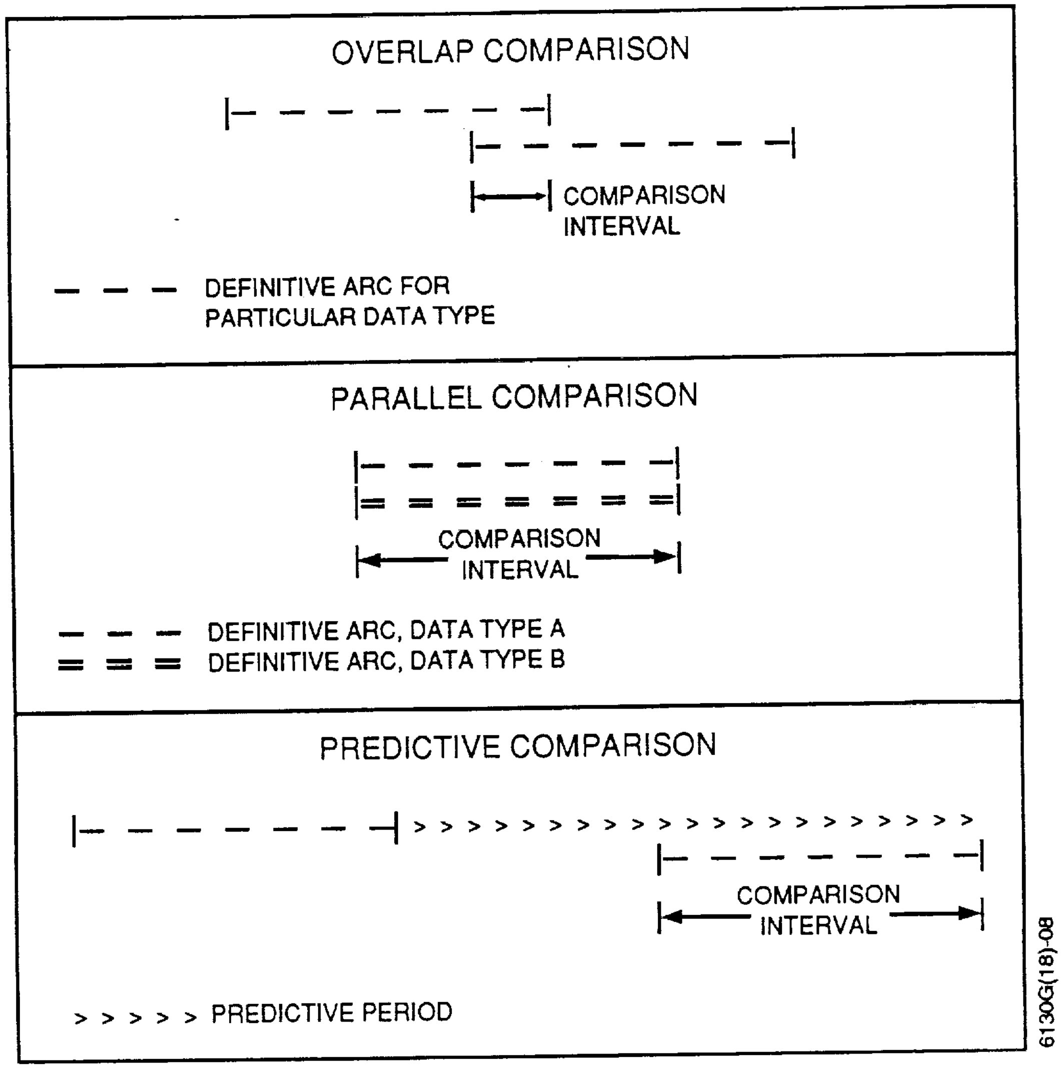

Figure 4. Illustration of Ephemeris Comparison Schemes

Figure 5 shows the fitted parabola along with the mean residual data. The figure also displays the estimated values of the USO frequency bias obtained from the 4-day solutions generated for this study. The curve can be interpreted as the offset from the nominal S-band return-link frequency of 2287.5 megahertz. Spikes in the curve are likely attributable to exceptionally high levels of ionospheric disturbance. It was confirmed that most of the tracking data which produced these spikes were rejected from the orbit determination process either with atmospheric editing or 3σ editing.

The second parameter evaluated was the frequency drift. A least-squares linear curve was fit to the mean residuals over sliding 24-hour intervals. Table 3 lists the drift values obtained from these 24-hour curve fits, from differentiation of the frequency offset equation above, and from the 4-day orbit solutions. The drift is expressed as fractional parts of 2287.5 megahertz per day. Table 3 shows good agreement between the 4-week evaluated drift values and the estimated drift values. The 24-hour evaluated drift values displayed wider fluctuation. All

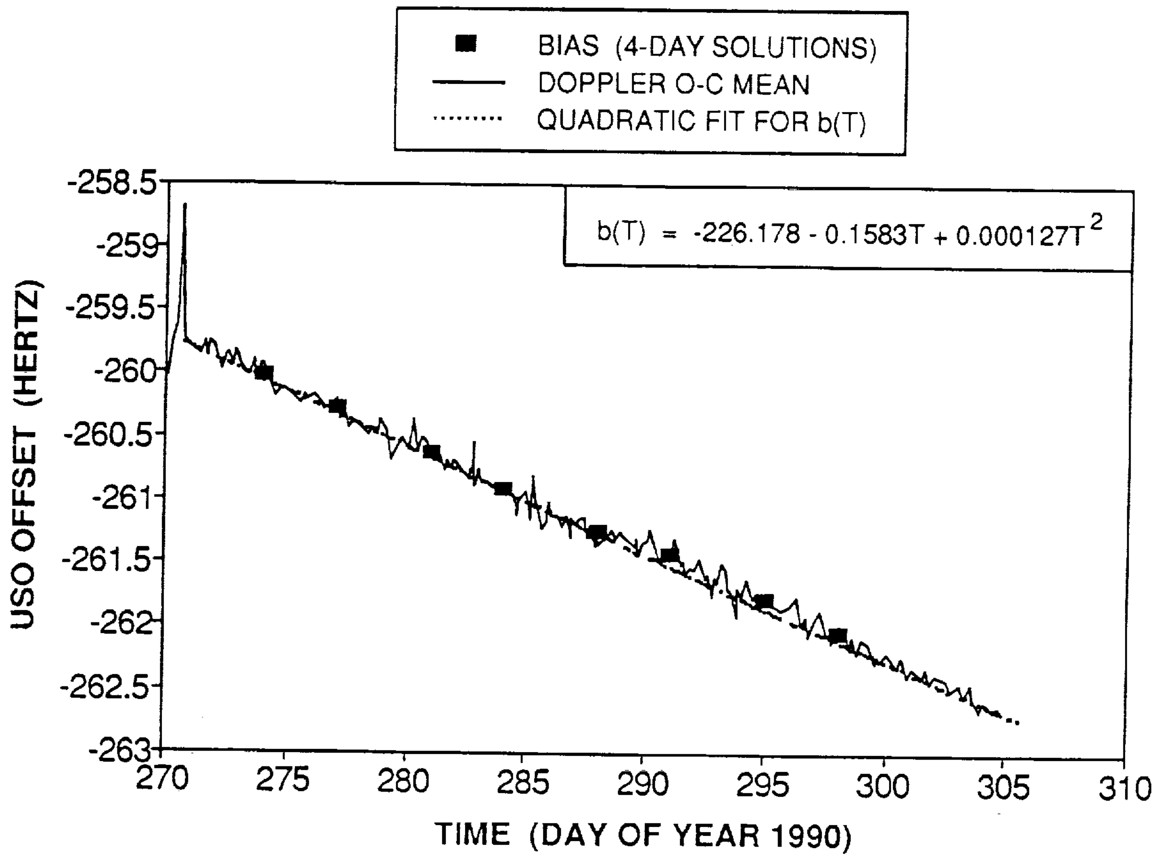

Figure 5. One-Way Doppler Residual Mean Values Used to Estimate the USO Frequency Bias

Table 3. Estimated and Evaluated S-Band Frequency Bias and Drift

A. BIAS

SOLUTION EPOCH (0 HOURS)	ESTIMATED BIAS (HERTZ)		EVALUATED BIAS (HERTZ)
	FROM ONE-WAY SOLUTION	FROM COMBINED ONE- AND TWO-WAY SOLUTIONS	FROM 4-WEEK QUADRATIC FIT
10/01/90	-260.0260	-260.0374	-260.0252
10/04/90	-260.2743	-260.3117	-260.2902
10/08/90	-260.6440	-260.6466	-260.6400
10/11/90	-260.9246	-260.9133	-260.8997
10/15/90	-261.2572	-261.2529	-261.2424
10/18/90	-261.4292	-261.4084	-261.4967
10/22/90	-261.7965	-261.8137	-261.8323
10/25/90	-262.0560	-262.0480	-262.0813

B. DRIFT

SOLUTION EPOCH (0 HOURS)	ESTIMATED DRIFT (PARTS/DAY)		EVALUATED DRIFT (PARTS/DAY)	
	FROM ONE-WAY SOLUTION	FROM COMBINED ONE- AND TWO-WAY SOLUTIONS	FROM 4-WEEK QUADRATIC FIT	FROM 24-HOUR QUADRATIC FIT
10/01/90	-3.9723×10^{-11}	-4.1034×10^{-11}	-3.8785×10^{-11}	-2.9290×10^{-11}
10/04/90	-3.6917×10^{-11}	-3.8953×10^{-11}	-3.8452×10^{-11}	-2.2295×10^{-11}
10/08/90	-3.7234×10^{-11}	-3.6762×10^{-11}	-3.8008×10^{-11}	-6.0328×10^{-11}
10/11/90	-4.3104×10^{-11}	-3.9550×10^{-11}	-3.7675×10^{-11}	-1.6175×10^{-11}
10/15/90	-2.8505×10^{-11}	-3.1803×10^{-11}	-3.7230×10^{-11}	$+5.6831 \times 10^{-11}$
10/18/90	-2.4158×10^{-11}	-2.4320×10^{-11}	-3.6897×10^{-11}	-2.7541×10^{-11}
10/22/90	-3.8783×10^{-11}	-4.1310×10^{-11}	-3.6453×10^{-11}	-19.8470×10^{-11}
10/25/90	-4.2898×10^{-11}	-3.7718×10^{-11}	-3.6119×10^{-11}	$+11.3224 \times 10^{-11}$

three sources of drift values indicate good USO stability. Furthermore, the USO characteristics have so far remained essentially unchanged during the course of COBE's in-flight life.

Finally, an evaluation of the random noise level on the one-way Doppler data was performed. Again, the statistical properties of the mean observation residuals were used to infer characteristics of the raw Doppler data. The 24-hour solutions provided residual data for noise analysis. A technique called Variate Differenced Noise Analysis (VDNA) was applied to the selected set of measurement residuals. A pth-order variate difference, δ_p, is given by

$$\delta_p = \sqrt{\frac{\sum_{i=1}^{n-p} (\Delta_i^p)^2 \; n! \; n!}{(n-p)\,(2n)!}}$$

where n = number of data points

Δ_i^p = ith pth-order difference computed from the data points

Since the differencing operation tends to eliminate nonrandom trends in data, the VDNA computation provides a measure of randomness. As the order of the variate difference grows, the elimination of deterministic variation becomes more thorough. On the other hand, fewer terms in the variate summation become available. The third-order variate difference was computed for this study. A discussion of VDNA is provided in Reference 9.

In the current application, the measurement noise levels provided by VDNA can reveal periods of large ionospheric scintillation of the tracking signal. A scatter plot of 10-second one-way Doppler noise from VDNA is provided in Figure 6. The greatest noise levels apparent in Figure 6 coincide with transits of COBE through the Earth's polar regions where tracking measurements are particularly susceptible to ionospheric disturbance.

ORBIT DETERMINATION ANALYSIS RESULTS

Figure 7 shows the maximum total position differences for the one-way, two-way, and combined one-way and two-way overlap comparisons. Figure 8 shows how the comparison varied over time for a typical case. The maximum total position differences for the overlap comparisons fell within similar ranges for the three solution types (10 meters to 73 meters, 20 meters to 75 meters, and 15 meters to 72 meters for the one-way, combined, and two-way cases, respectively). The largest disparity between comparison results for a given comparison interval was 30 meters. An overlap comparison is essentially a consistency measure. While it is true that a poor solution can be self-consistent, a good solution *must* be self-consistent. In fact, overlap comparison results can justifiably be used as a lower bound on definitive orbit accuracy.

Figure 9 summarizes the results of parallel comparisons between solution types, giving the maximum total position differences. The comparison interval corresponds to the 4-day,

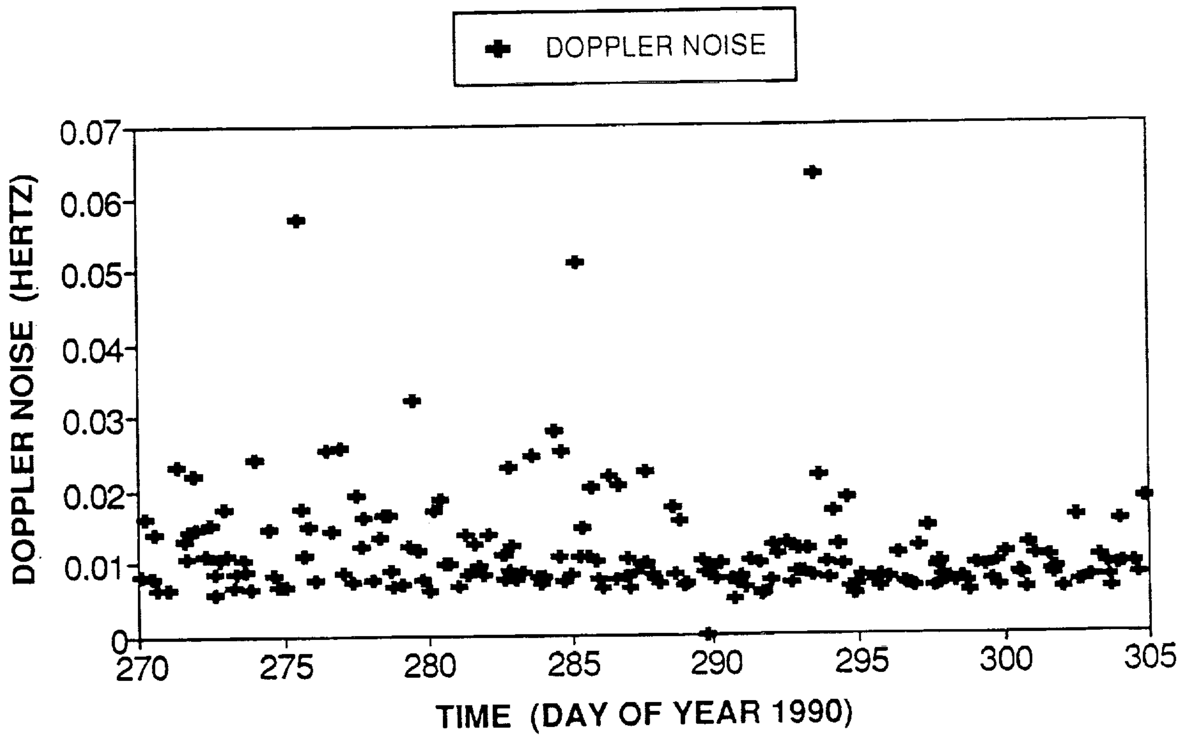

Figure 6. One-Way Doppler Noise for 10-Second Data

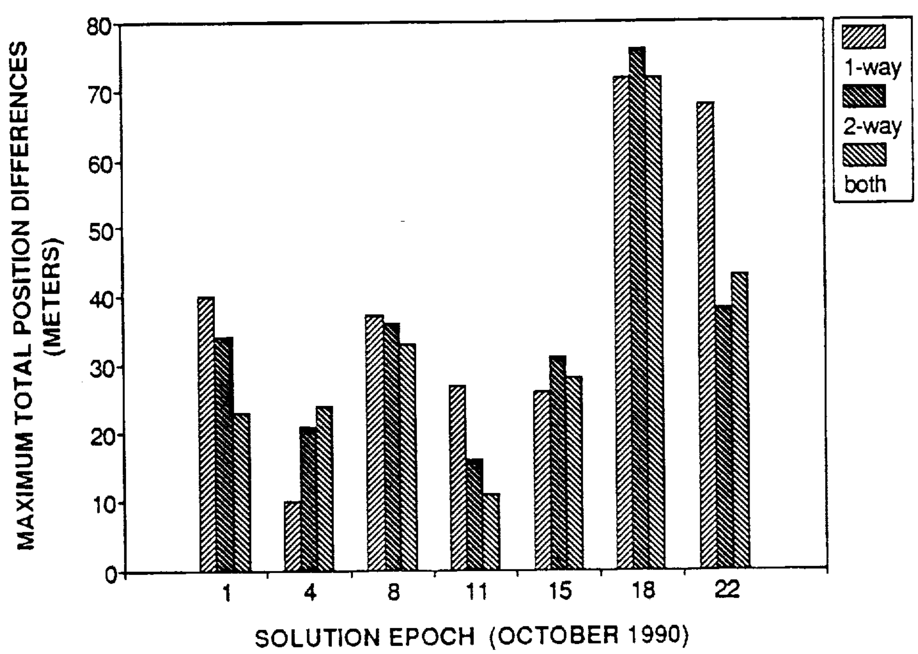

Figure 7. Maximum Position Difference Overlap Comparisons

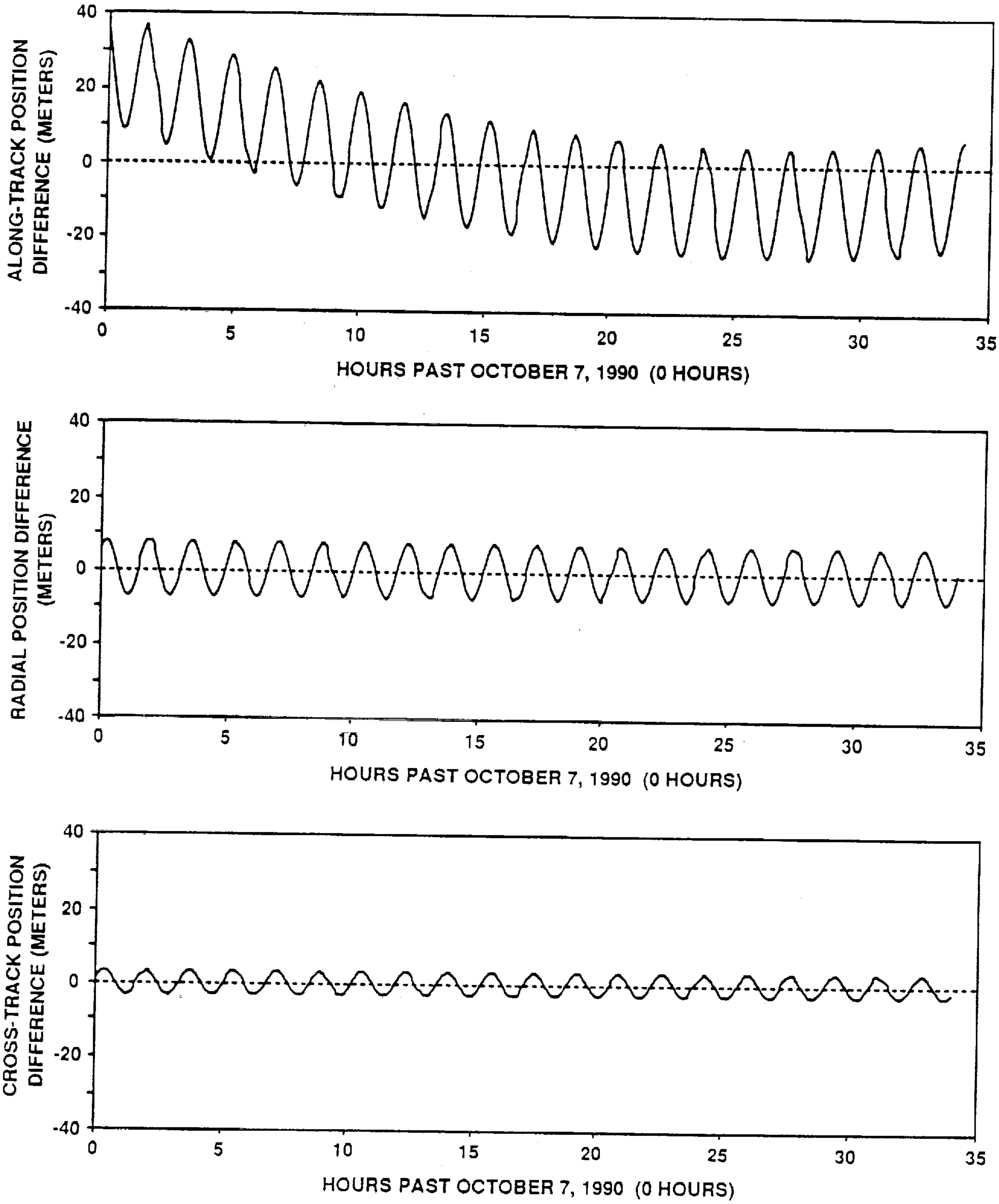

Figure 8. One-Way Overlap Ephemeris Comparison

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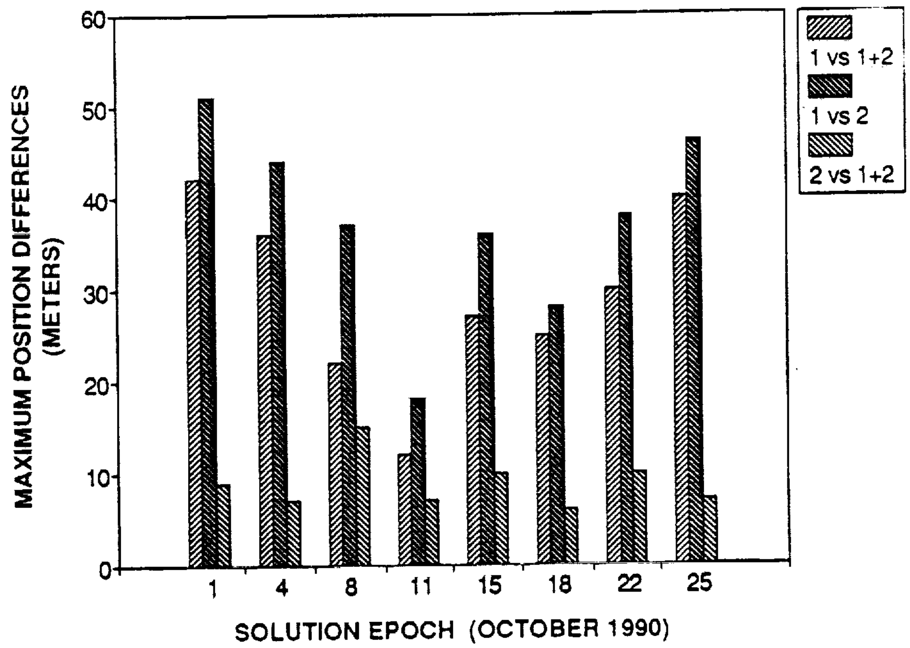

Figure 9. Maximum Position Difference Parallel Comparisons

10-hour definitive arc. Although a parallel comparison can demonstrate concurrent orbit solution quality for two different solutions, it is perhaps more a reflection of the correlation of the two solutions. Thus, Figure 9 reveals best agreement when the two solutions were based on many common tracking measurements (i.e., two-way and combined) and poorest agreement when there were no tracking measurements in common (i.e., one-way and two-way). Furthermore, the poorest parallel comparisons occurred when one-way measurements were the fewest and the best when they were most abundant.

Figures 10 through 12 represents predictive comparison results for 1-week, 2-week, and 3-week predictions, respectively. The prediction interval is measured between the end points of the solution arcs. The maximum position differences within the definitive period occurred usually (but not always) at the end of the later definitive arc. Since the error in the definitive orbit becomes less significant relative to the prediction error as the prediction interval grows, this technique for determining prediction errors works best for long-term predictions. Large variations are seen in the position differences for different solution arcs. This would be explained by the wide fluctuation in atmospheric density during the period under study. An examination of the estimated values of the atmospheric drag variation coefficient, ϱ_1, given in Table 4, shows excellent agreement among estimates for a given 4-day period but dissimilarity among estimates for distinct 4-day periods. Since the ϱ_1 estimates were used in the propagation, some randomness in the prediction results might be expected (most of the predictive error is in the along-track direction). The important observation is the good consistency in the comparison results among the one-way, two-way, and combined cases for given prediction intervals; this suggests that the one-way and two-way tracking measurements allowed for similar prediction capability.

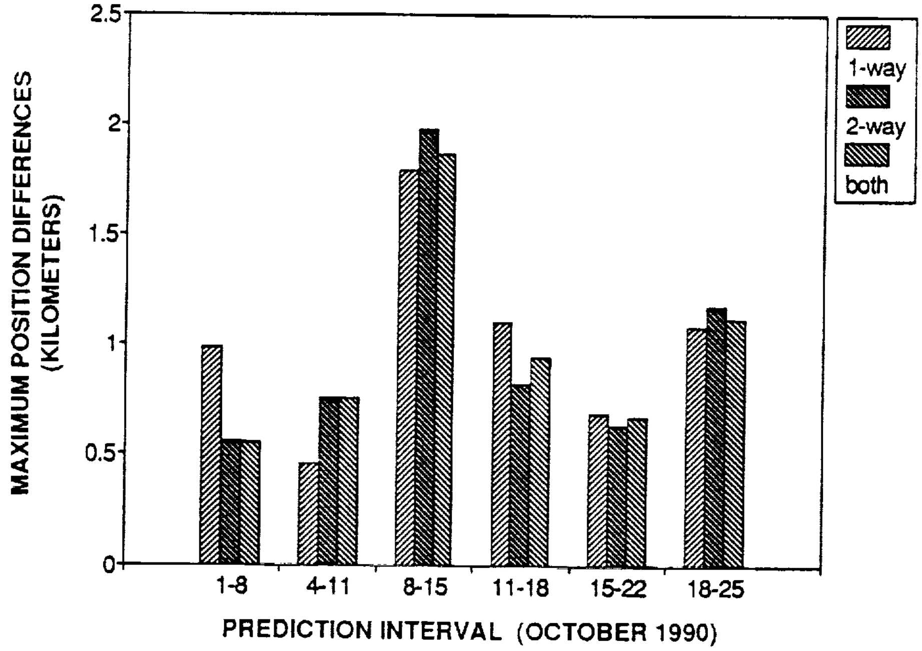

Figure 10. Maximum Position Difference 1-Week Predictions

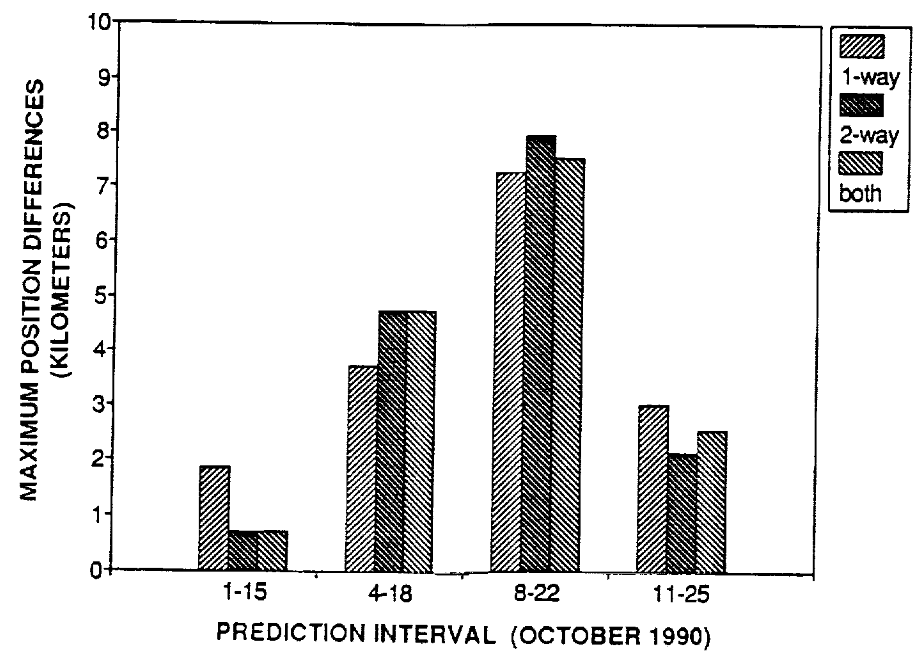

Figure 11. Maximum Position Difference 2-Week Predictions

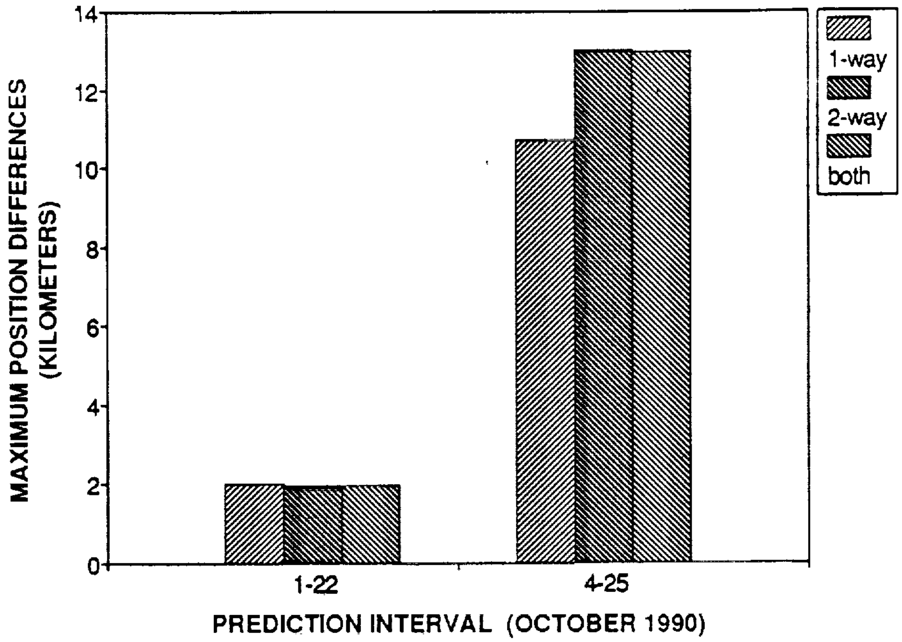

Figure 12. Maximum Position Difference 3-Week Predictions

Table 4. Atmospheric Drag Variation Coefficients (ϱ_1) Estimated by One-Way, Two-Way, and Combined Solutions

SOLUTION EPOCH (0 HOURS)	ONE-WAY SOLUTION	TWO-WAY SOLUTION	COMBINED SOLUTION
10/01/90	0.18	0.12	0.12
10/04/90	0.03	-0.004	-0.004
10/08/90	0.03	0.008	0.02
10/11/90	0.34	0.33	0.33
10/15/90	0.21	0.22	0.21
10/18/90	0.20	0.19	0.20
10/22/90	0.36	0.32	0.34
10/25/90	0.18	0.15	0.16

Since the ionosphere tends to increase tracking measurement noise levels, long tracking signal paths through the ionosphere are preferably avoided. Figure 13 shows the accumulated locations of COBE (from the TDRS perspective) at the times TDRS tracking of COBE was occurring for the period under study. The figure shows that most of the tracking (both one-way and two-way) occurred when COBE was outside the Earth's "disk", as viewed from TDRSS. This limited tracking geometry, which resulted largely from the restricted antenna pattern of the TDRSS antenna on COBE (visibility was limited between 65 degrees and 105 degrees of the antenna boresight), allowed little opportunity to avoid long signal path lengths through the ionosphere. Thus, the antenna restriction was a barrier to orbit determination accuracy, whether one-way or two-way data were used. In an attempt to eliminate tracking measurements plagued by heavy ionospheric disturbances, the atmospheric editing criterion discussed earlier was employed. On average, this editing scheme eliminated approximately 30 percent of the available tracking data.

The COBE tracking geometry contributed to accuracy degradation in a second manner. Since COBE is in a near-polar orbit (99-degree inclination), the TDRSs each view the COBE orbit-plane perpendicularly twice a day. For TDRS-East, this occurs at approximately 0300 Greenwich Mean Time (GMT) and 1500 GMT; for TDRS-West, it occurs at approximately 1200 GMT and 0000 GMT. Such a COBE-TDRS orientation permits little Doppler measurement variation. Consequently, the along-track motion of COBE (the largest component of the overall motion) cannot be well determined using only Doppler measurements. Thus, a polar orbit is more favorable to two-way tracking (which involves range measurements) than to one-way Doppler tracking. The deleterious effects of a polar orbit are still further compounded by the exposure of the spacecraft to the electrically stormy polar regions.

SUMMARY AND CONCLUSIONS

The study has shown that, given a USO drift which can be compensated to 10^{-11} parts per day and given equivalent one-way and two-way tracking schedules, TDRSS one-way return-link Doppler tracking of a user spacecraft enables orbit determination accuracy comparable to two-way orbit determination accuracy. Similar ephemeris comparison results were observed for one-way and two-way solutions. Overlap comparisons of 4-day arcs resulted in maximum total position differences of at most 75 meters for both one-way and two-way cases. Parallel 4-day definitive comparisons between one-way and two-way solutions were at most 50 meters. The 1-week through 3-week predictive comparisons produced nearly identical results for the one-way and two-way cases. Post-helium-venting ephemeris comparison results for both the one-way and two-way cases are an order of magnitude improved from the corresponding venting-phase ephemeris comparison results.

Based on the postventing phase analysis, one-way return-link USO frequency-stabilized Doppler tracking is a feasible alternative to two-way range and Doppler tracking for GSFC FDF mission support. Furthermore, a mixture of one-way and two-way tracking measurements is likely to be beneficial because of the improved tracking coverage. Thus, the conclusions reached from the venting phase analysis are affirmed by the postventing phase analysis.

The one-way orbit solution accuracy achieved in this study is not at the limit of one-way accuracy capability, primarily because of poor COBE tracking geometry. Additional analysis

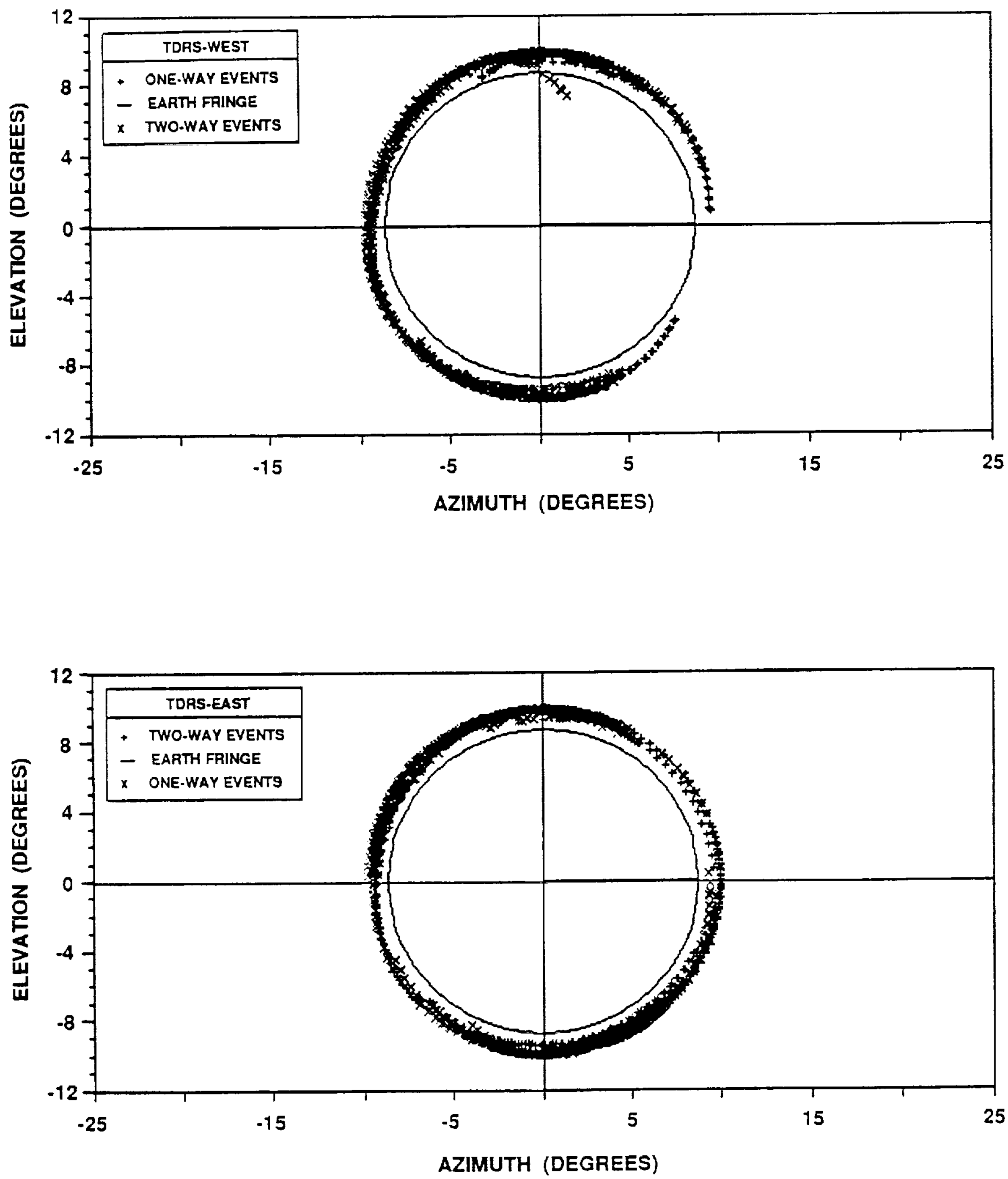

Figure 13. TDRS-East and TDRS-West Views of COBE Based on Radio Frequency (RF) Beam Angles (9/27/90 Through 10/31/90)

involving a more favorable orbit geometry and less restricted TDRS visibility is needed before substantial one-way accuracy improvement can be demonstrated. Such analysis should reexamine the USO frequency stability, since USO limitations to orbit determination accuracy may become more important.

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