1995121371

N95- 27792

A DEMONSTRATION OF UNIFIED TDRS/GPS TRACKING AND ORBIT DETERMINATION

B. Haines, S. Lichten, J. Srinivasan and L. Young
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91109

ABSTRACT

We describe results from an experiment in which TDRS and GPS satellites were tracked simultaneously from a small (3 station) ground network in the western United States. We refer to this technique as "GPS-like tracking" (GLT) since the user satellite—in this case TDRS—is essentially treated as a participant in the GPS constellation. In the experiment, the TDRS K_u-band space-to-ground link (SGL) was tracked together with GPS L-band signals in enhanced geodetic-quality GPS receivers (TurboRogue). The enhanced receivers simultaneously measured and recorded both the TDRS SGL and the GPS carrier phases with sub-mm precision, enabling subsequent precise TDRS orbit determination with differential GPS techniques. A small number of calibrated ranging points from routine operations at the TDRS ground station (White Sands, NM) were used to supplement the GLT measurements in order to improve determination of the TDRS longitude. Various tests performed on TDRS ephemerides derived from data collected during this demonstration—including comparisons with the operational precise orbit generated by NASA Goddard Space Flight Center—provide evidence that the TDRS orbits have been determined to better than 25 m with the GLT technique.

Improvements to enable 10 m accuracy are also discussed. Drawing on these results, as well as experiences with automated Topex/Poseidon and GPS orbit determination at the Jet Propulsion Laboratory (JPL), we discuss prospects for using GLT to operationally collect and process TDRS data for orbit determination, including delivery of solutions within a few hours after maneuvers — all in a very low cost, highly automated system with ground sites close to White Sands. Its high potential for inexpensive, automated high-performance tracking should render the GLT technique attractive to designers of NASA, military and commercial systems used for orbit determination of satellites at geosynchronous as well as other altitudes.

1. INTRODUCTION

The Global Positioning System (GPS) is rapidly emerging as the tracking system of choice for a variety of Earth orbiting spacecraft missions. A conventional approach to GPS-based orbit determination involves a GPS flight receiver on board the user spacecraft. For satellites flying in low-Earth orbit (LEO) well underneath the shell formed by the GPS constellation, a wide range of configurations can be considered. The simplest consists of a minimal GPS flight instrument requiring only a fraction of a watt of power and a few hundred grams mass [*Lichten et al.*, 1995]. Better performance can be achieved with a more conventional flight receiver. For the highest accuracy, data from ground GPS trackers can be combined with the flight data. Using this approach, it has recently been demonstrated that orbits for the Topex/Poseidon oceanographic satellite could be determined to better than 3 cm (RMS) in the radial direction using GPS [*Bertiger et al.*, 1994]. This result can be attributed in large part to the continuous tracking and multi-directional observing geometry afforded by GPS in the 1,340 km altitude orbit occupied by Topex/Poseidon.

An alternative to carrying a GPS flight receiver employs instead a simple beacon on the user spacecraft. The beacon signal is tracked along with signals from the GPS spacecraft in an enhanced GPS ground receiver. This approach, which we call GPS-like tracking (GLT), exploits GPS to precisely determine station coordinates, and media delays and to provide clock synchronization at the ground stations. In contrast to conventional GPS-based orbit determination, a geometric solution for the user orbit is generally not achievable and models of the forces perturbing the spacecraft motion must then be used together with the observations. A limitation for low-Earth orbiters is that the fraction of time during which the beacon illuminates ground sites is typically small. Nonetheless, this alternative remains attractive for certain applications because it can exploit a pre-existing beacon signal (e.g., for telemetry) and requires no additional spacecraft hardware for dedicated orbit determination.

The GLT method is particularly attractive for spacecraft in high altitude orbits (Figure 1): while the practical observability of GPS signals degrades rapidly as a function of altitude above the GPS constellation, the number of ground stations that can be kept in permanent view of a beacon signal increase [e.g., *Wu*, 1985] . At geostationary orbit, a ground network can be designed that is permanently in view of the beacon signal, providing uninterrupted tracking.

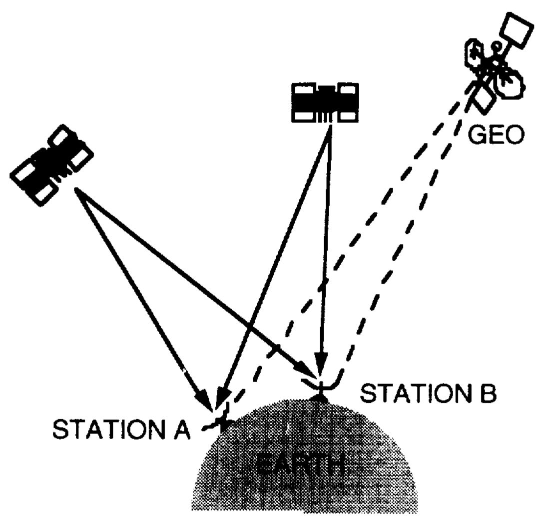

Fig 1. Differential GPS-like tracking (GLT) applied to geosynchronous orbiter. Four simultaneous observations of GPS carrier phase and pseudorange enable removal of transmitter and receiver clock offsets. After tracking for 12–24 hours, the GPS orbits can be determined to a few tens of centimeters. In GLT, the carrier phase of the high-Earth orbiter is also included and its orbit similarly estimated. This relationship is discussed further by *Lichten et al.* [1993].

1.1 TDRS ORBIT DETERMINATION

An attractive candidate for applying the GLT technique is NASA's Tracking and Data Relay Satellite (TDRS) System. The TDRS space segment currently consists of 5 geosynchronous orbiters and is used by NASA to support positioning and data relay activities for a wide variety of Earth orbiting spacecraft. Accurate real-time position knowledge of the TDRSS spacecraft is required to support certain users: though the most stringent current requirement is 200 m (1 σ) for the Space Transportation System (STS), the planned Earth Observing System (EOS) platform calls for 25 m (1 σ) accuracy of the TDRS ephemerides [*Cox and Oza*, 1994].

The current TDRS orbit determination system is based on the relay of coherent signals through unmanned transponders at globally distributed remote tracking sites. These remote beacons are collectively referred to as the Bilateration Ranging Transponder System (BRTS). Evaluation of the TDRS ephemerides suggests that orbit accuracy is maintained to better than 50 m using the operational BRTS method [*Cox and Oza*, 1994]. This level of accuracy does not meet the future EOS requirement; moreover, the scheduling of BRTS observations consumes TDRS antenna time that could otherwise be used for servicing user spacecraft. In recognition of this, a number of studies aimed at identifying alternative methods for TDRS orbit determination have been undertaken [see also *Marshall et al.*, 1995; *Oza et al.*, these proceedings].

1.2 GPS-LIKE TRACKING OF TDRS

Under the direction of NASA, JPL has investigated a number of potential new strategies for determining the TDRS orbits [*Nandi et al.*, 1992; *Haines et al.*, 1992]. Judged the most promising among them was a hybrid approach which combined elements of GLT with a specialized form of interferometric tracking over very short baselines (Connected Element Interferometry or CEI; see *Edwards et al.*, 1991).

The short baseline scenario is necessitated by the nature of the existing TDRS space-to-ground link (SGL). The TDRS SGLs illuminate only a limited area of the southwestern U.S. surrounding the TDRS Earth station in White Sands, New Mexico (Figure 2). This precludes the use of globally dispersed stations for tracking the SGL. However, if a GLT network fitting within the SGL footprints could be designed to deliver the desired accuracy, significant benefits could be gained: 1) The SGL is always on when the TDRS is servicing users. Thus the signal can be passively monitored and no TDRS services need be scheduled for orbit determination. 2) The SGL is broadcast at K_u-band (13.731 GHz). At this frequency, the delay caused by the presence of charged particles along the signal path (i.e., ionosphere delay) rarely exceeds a few cm in equivalent range. This contrasts with the BRTS tracking, which is based on the lower frequency S-band transmissions which are significantly delayed by the ionosphere. (Several meters of delay is typical.) 3) A small ground network in the vicinity of the White Sands complex (WSC) has many operational advantages: all the sites can be readily accessed for maintenance, and communications links to the Earth station can be made reliable and short.

Following the direction of NASA, JPL designed an experiment to demonstrate the feasibility of this technique. The foundation of the experiment is simultaneous tracking of GPS and TDRS signals over short baselines to determine the TDRS orbit [*Lichten et al.*, 1993]. Coincident observation of GPS and TDRS signals in the same ground receiver enables calibrations of clock errors [*Dunn et al.*, 1991, 1993] and tropospheric delays [*Lichten*, 1990], supplanting the fiber optic links and expensive calibration devices that are needed in a connected element network. An added benefit is the ability of GPS to provide very precisely (sub cm) the positions of the tracking stations relative to one another, and the network orientation in the terrestrial reference frame [*Blewitt et al.*, 1992].

We note that the GLT method described herein uses a measurement type known in the GPS community as "differential carrier phase". It is instructive to think of the phase measurement as a range observation that is biased by an amount corresponding to an unknown integer number of cycles along the transmission path. Each modified TurboRogue station tracks the phase of the TDRS SGL with great precision (enabled by GPS). Contained in the station-differenced phase data is very precise information on the velocity of the TDRS spacecraft in the plane-of-sky. Using the information in a standard dynamical orbit determination strategy determines very precisely five of the six osculating (classical) elements that describe the geosynchronous TDRS orbit. In order to determine the last component—the longitude of the satellite orbit or its down track position in inertial space—some knowledge of the range to the spacecraft is needed. To provide this information, we used data from routine ranging done at WSC.

Additional information on the heritage of the technique, and initial results are given by *Haines et al.* [1994]. Herein we summarize the experiment configuration and initial findings and report on some extended results intended to address the operational potential of the method.

2. JANUARY 1994 DEMONSTRATION

The TDRS/GPS tracking demonstration took place from January 16–22, 1994. GPS and TDRS satellites were tracked simultaneously from three sites: El Paso, TX, Socorro, NM, and Pasadena, CA (Figure 2). This configuration permitted us to test the performance of side-lobe tracking, as JPL is in a fortuitous location that placed it in the first side lobe of the SGLs from both TDRS-5 (175° W) and TDRS-3 (62° W). The other two stations, operated from motel rooms in El Paso and Socorro, were within the main beam of the SGL of both TDRS-3 and 5.

The cornerstone of each tracking station was an enhanced TurboRogue GPS receiver. The TurboRogue, developed at JPL [*Meehan et al.*, 1992] and currently globally distributed in a 50+ receiver network used for precise GPS orbit determination and a variety of geodetic and tectonic studies [*Zumberge et al.*, 1994], was augmented for this experiment with a small, K_u-band horn antenna (opening dimensions 17 X 14 cm) and a K_u- to L-band downconverter. In addition, the TurboRogue software was modified to measure and record the phase of the TDRS SGL with the same sub-mm precision and receiver time-stamp as GPS carrier phase measurements. This system architecture produces data products that significantly simplify subsequent orbit determination processing.

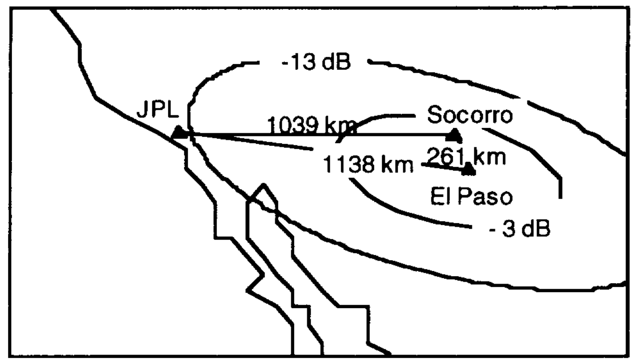

Fig 2. Configuration of TDRS/GPS tracking network. The footprint of the TDRS-3 space-to-ground link (SGL) during the January 1994 experiment is shown.

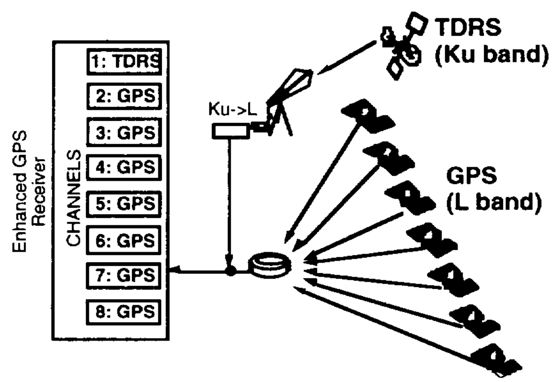

Fig 3. Schematic for the GPS ground receiver enhanced to simultaneously track TDRS along with GPS satellites. For the TDRS SGL, which is at 13.731 GHz, a small separate antenna with down converter was added.

2.1 DATA

Data collection commenced on January 16 with tracking of TDRS-3. Also known as TDRS-Central, this spacecraft was seen at an elevation of approximately 30° when viewed from White Sands. TDRS-3 was tracked for nearly 5 days before the stations were reconfigured to track TDRS-5 (January 21). This spacecraft presently occupies the western slot and is seen at an elevation of only 10° from White Sands. Although the TDRS-5 track spanned only 18 hours, this session was useful for understanding the effects of tracking at lower elevations. A time line showing the data coverage for the experiment is given in Figure 4. Depending on the station, 85–95% tracking coverage was achieved over the course of the experiment. The largest data outage occurred on Jan. 18 when the TDRS-3 SGL was switched off for approximately 7 hours to support an antenna maintenance activity at WSC. All three sites did experience a significant number of phase interruptions over the duration of the experiment: the longest period of time during which all three stations tracked without a single loss of lock was about 20 hr. We believe that the number of phase breaks can be greatly reduced in future demonstrations with changes to the receiver configuration.

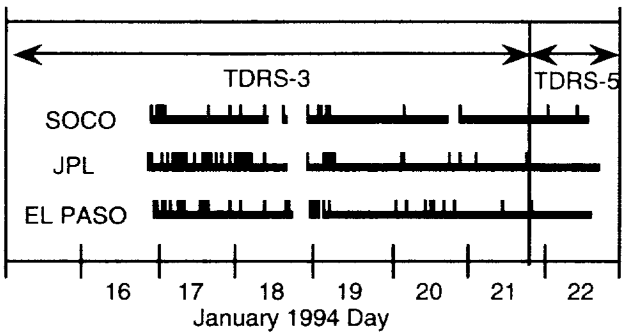

Fig 4. Time line showing data coverage at each of the three GPS stations over the course of the TDRS tracking experiment. Solid horizontal bars indicate the receiver was tracking. Vertical bars indicate that a loss of lock occurred.

Figure 5 depicts a sample of the raw TDRS-3 data from each of the three sites. The top panel gives the raw phase measurement converted to a biased 3-way range (White Sands to TDRS-3 to GPS terminal) and the bottom panel gives the signal-to-noise ratio. The range data show the expected diurnal signature from the geosynchronous TDRS orbits. For TDRS-3, the peak to peak variation of the 3-way range was ~200 km, while for TDRS-5 (not shown) the variation was only ~30 km. This disparity is attributable primarily to the different orbits occupied by the spacecraft: TDRS-3 was inclined by 0.7° relative to the equator, while the TDRS-5 inclination was only 0.07°. The TDRS-3 orbit was also slightly more eccentric. Also worthy of note in Figure 5 is the lower characteristic SNR for the JPL station. This reflects the decrease in signal strength associated with observing the SGL in the side lobe of the antenna pattern.

As explained previously, ranging information to TDRS is needed to fix the longitude of the spacecraft. To satisfy this requirement, we used range observations from routine Tracking Telemetry and Control (TT&C) activities at White Sands. These observations are based on tracking of the K_u-band SGL with 18-m antennae located at the central ground terminal. The range data are not intended for precise orbit determination (a service which is presently provided by the BRTS system). As such, the observations can contain large systematic biases that, without calibration, preclude achievement of high accuracy in determining the longitude of the TDRS orbits.

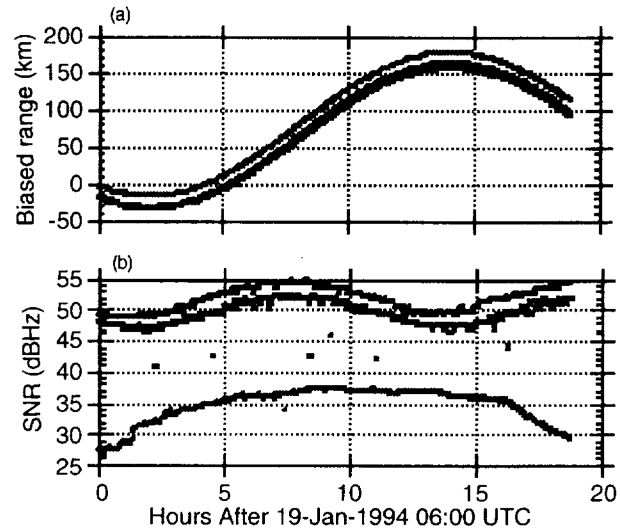

Fig 5. Biased range (Panel A) and signal-to-noise ratio (Panel B) from TDRS-3 carrier phase tracked at JPL, El Paso, and Socorro on January 19, 1994. The station with the low SNR is at JPL, which tracked TDRS-3 from within the first sidelobe.

In order to estimate the range biases, we calibrated the TT&C range data against the precise TDRS orbits generated at GSFC using the BRTS system. Shown in Fig. 6 are the residuals of the TT&C range with respect to the BRTS orbits for TDRS-3 over the course of the experiment. Biases as large as 50 m (one-way) can be seen. (Note the bias estimates also reflect uncertainty in station coordinates, errors in the BRTS orbits, and potential inconsistencies in the processing of the data.)

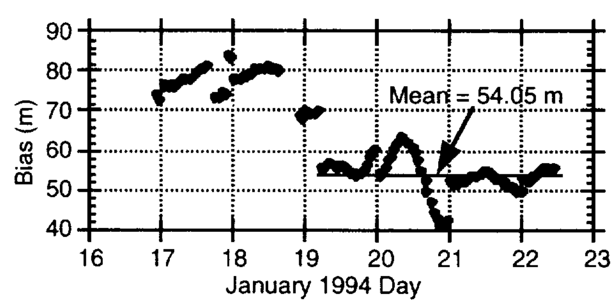

Fig 6. Residuals of White Sands TDRS-3 range data with respect to BRTS-derived orbit from Goddard Space Flight Center. A 1-way bias of 54.1 m was used in this study to calibrate the TDRS-3 range data for periods after 06:00 UTC on January 19, 1994.

For TDRS-5, which was observed from an elevation of 10° from WSC, the partial derivative of the range bias with respect to the spacecraft longitudinal position is about 1/8. This implies that a 10 m one-way (20 m two-way) range bias could translate into an 80-m error in the longitude component of the TDRS, underscoring the proper calibration of the ranging system.

2.2 SOLUTION STRATEGY

The unified TDRS/GPS orbit solutions were computed using the GIPSY/OASIS II software [*Webb and Zumberge*, 1993]. Table 1 outlines the solution strategy. With the exception of a few elements that are not consistent with a real-time solution, the strategy for processing the 3-station TDRS data mirrors that presently used at JPL in the routine, highly automated processing of GPS data from the much larger (80+ station) global Intl. GPS Service for Geodynamics (IGS) network [*Zumberge et al.*, 1994]. In particular, zenith wet troposphere delays were estimated as stochastic random-walk parameters, and clock offsets were estimated as stochastic white noise processes at each measurement batch.

We note that satellite states for the TDRS and all GPS spacecraft were estimated, with *a priori* for the latter coming from the broadcast ephemerides. Inasmuch as the GPS data are collected at only three ground stations, and they are quite close, the GPS orbit errors are undoubtedly nonuniform over the globe. In this study, GPS provides clock synchronization and media calibration for our network in the southwestern U.S. In this context, regional improvement of the GPS orbits is adequate. Additional details on the solution strategy are provided by *Haines et al.* [1994].

The TDRS phase data were modeled as three-way measurements (i.e., 2 legs and 3 participants). Although it is instructive to think of TDRS as the originator of the signal (in the manner of GPS), this is not strictly correct. The signal originates at White Sands, and is transmitted to TDRS which serves as a "bent-pipe" transponder, redirecting the signal to the ground. It follows that we do not solve for the TDRS clock offset in our orbit determination procedure, but rather the offset of the master frequency generator on the ground at WSC. This modeling ensures that the Doppler signature from the uplink is handled properly, i.e. it is not incorrectly absorbed in the TDRS clock solution. The range data from WSC were modeled as simple 2-way measurements.

Station coordinates for the TDRS/GPS terminals in El Paso, Socorro and Pasadena were fixed at precise values determined *a priori* using the GPS data collected at the sites. Details on this procedure are discussed by *Haines et al.* [1994]. Their results suggest that the station coordinates have been determined at the cm level relative to the geocenter. For the 18-m WSC antennae that collect the range data, we used coordinates provided by NASA in the WGS-84 system. We did not have a GPS receiver at WSC and therefore were unable to estimate improved coordinates. Any error in this station coordinate will manifest itself as a range bias, which we estimated via external calibration (as described in the previous section).

TABLE 1. ESTIMATION STRATEGY FOR GPS/TDRS ANALYSIS

Data Noise (150 s observations)	
GPS carrier phase	1 cm
TDRS carrier phase	1 cm
GPS pseudorange	1 m
TDRS two-way range (1/hr)	5 m
A-priori for estimated parameters	
TDRS position (X, Y, Z)	100 km
TDRS velocity (X, Y, Z)	1 m/s
TDRS solar radiation pressure coeff.	100 %
TDRS carrier phase biases	1 s
WSC range bias (1 way)	1 m
GPS position (X, Y, Z)	100 km
GPS velocity (X, Y, Z)	1 m/s
GPS carrier phase biases	1 s
GPS spacecraft clock offset	1 s white
GPS gnd. station clock offset[1]	1 s white
White Sands station clock offset	1 s white
GPS gnd. station zenith wet trop.	40 cm +5 cm/$\sqrt{}$day random walk
1 El Paso clock fixed	
Models and constants	
TDRS solar rad. pressure model	Bus
TDRS area	40 m^2
TDRS mass	1807 kg
GPS solar rad. pressure model	T10/T20
Polar motion (X, Y)	IERS-B
Earth rotation (UT1 – UTC)	IERS-B
GPS Station locations	ITRF'91
White Sands station location	WGS-84
Luni-solar perturbations	DE-200
Earth gravity field	JGM-3 (12X12)

2.3 ORBIT DETERMINATION RESULTS

We consider first 4 separate orbit arcs: three for TDRS-3 and one for TDRS-5. The arc lengths vary from 18 to 21 hours and span the period from January 19 06:00 UTC to January 22 13:00 UTC. For TDRS-3, the calibration correction of 54.1 m was applied *a priori* to all the range data. For TDRS-5, which was tracked from a separate antenna at WSC, range data were not available at this writing. For range observations to TDRS-5, we simulated measurements from WSC using the BRTS orbit from GSFC.

2.3.1 Postfit Residuals

Table 2 gives the statistics of fit for the four precise TDRS orbit solutions. The root-mean-square (RMS) postfit observation residuals for the TDRS and GPS phase measurements were 2.6–5.8 mm and 2.8–3.0 mm respectively. That the TDRS phase data can be fit nearly as well as the GPS phase is encouraging, and suggests that the TDRS data quality is excellent (Figure 7). The GPS pseudorange, which is important for determining the clocks offsets, was fit to 0.3 m (RMS). In the cases where the TDRS 2-way range were included, these observations were fit to between 1 and 3 m (RMS). While these numbers are instructive for estimating bounds on the measurement noise, they reveal little about the orbit accuracy. For this, we examine the formal errors and overlap statistics of the TDRS orbit solution, and compute differences with respect to the BRTS-derived orbit from GSFC.

TABLE 2. ROOT-MEAN-SQUARE POSTFIT TRACKING DATA RESIDUALS FOR TDRS.

S/C	Arc Epoch (UTC)	TDRS Phase (mm)	TDRS Range (m)	GPS Phase (mm)	GPS Range (m)
TDRS-3	19-JAN 06:00	2.6	2.8	2.8	0.3
	19-JAN 21:00	5.8	1.9	3.0	0.3
	20-JAN 21:45	3.2	1.0	2.9	0.3
TDRS-5	21-JAN 19:48	2.0	NA	2.7	0.3

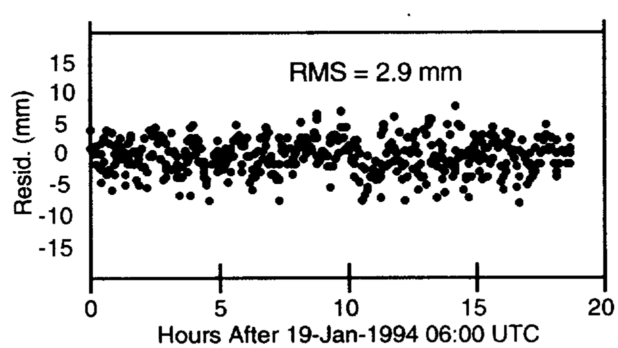

Fig 7. Postfit residuals for carrier phase from TDRS-3 as tracked by TurboRogue GPS receiver in Socorro, NM.

2.3.2 Internal Assessments of Orbit Error

Formal "noise-only" errors for the 4 orbit solutions were mapped over the respective arcs, and the results are summarized in Figure 8. Errors are decomposed into the height, cross- and down-track components of the orbit position. The largest errors are in the down-track component, for which the RMS values are typically 15 m. We note that the down-track errors are due in large part to the range bias, which is being estimated with an *a priori* standard deviation of 1 m (one-way). There is essentially no information for the estimation of the bias; it serves only to inflate the formal errors so that they are more realistic.

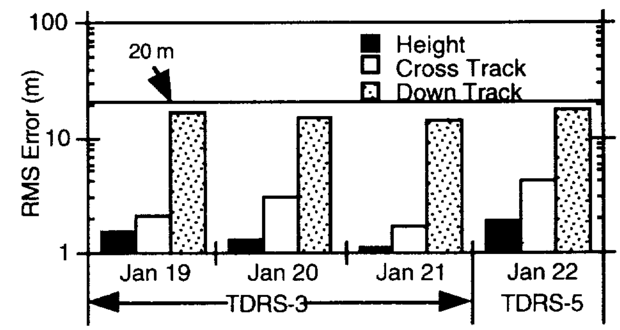

Fig 8. Bar graph showing RMS formal errors of TDRS orbit solutions computed as part of this study. The first three solutions correspond to TDRS-3 and the last to TDRS-5. The arcs vary between 18 and 20 hours in length.

Two of the TDRS-3 orbit solutions overlap by ~4 hr (Figure 9). The RMS differences of the two solutions during the overlap is 2, 11, and 12 m in height, cross track and down track respectively. These differences suggest that the orbit precision is better than 25 m (RMS).

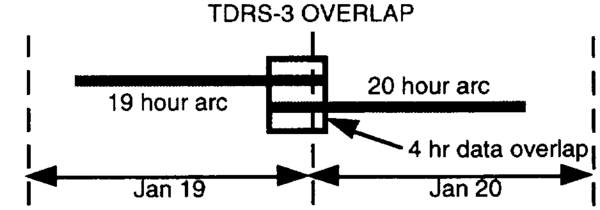

Fig 9. Schematic of orbit overlap for TDRS-3 orbit comparison. The RMS differences in height, cross track and down track during the overlap are 2, 12 and 11 m respectively.

2.3.3 External Assessments of Orbit Error

While the formal errors and overlap statistics from the solutions are instructive for characterizing the general behavior of the orbit errors, it is important to note that they may represent underestimates of the actual orbit error, and thus should be interpreted with caution. Systematic error sources, such as those due to unmodeled solar radiation pressure effects, non-random variations in the tracking observations, and errors in Earth rotation and orientation parameters can augment considerably the actual orbit error. A better measure of the orbit accuracy is thus gained from external comparisons. To this end, we compared our TDRS orbit solutions against the precise BRTS-derived orbits. These orbits are thought to be accurate to 50 m or better in total position (1-σ). The comparisons were performed in the inertial (J2000) reference frame.

Figure 10 shows the difference of our solution for TDRS-3 and the BRTS orbit for the first orbit solution (epoch of 19-JAN-1994 06:00 UTC). The RMS differences in height, cross and down track are 2, 22, and 14 m respectively. This level of agreement is considered quite encouraging, and was somewhat unexpected given published estimates of the errors in the BRTS orbits. It should be remembered, however, that the down track component of our orbit (i.e. longitude) is constrained to match the BRTS orbits in the bias term via the range calibration.

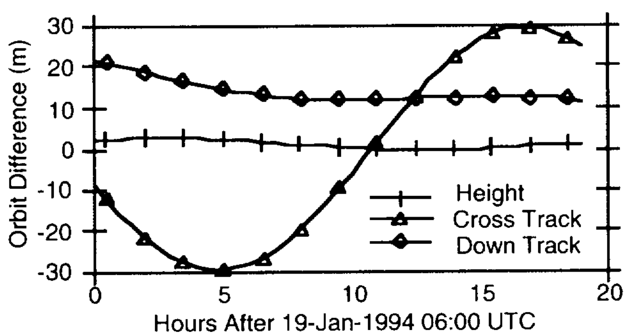

Fig 10. Time series of TDRS-3 inertial orbit differences (this study vs. BRTS orbit from Goddard Space Flight Center) for January 19, 1994. The RMS differences in height, cross track, and down track are 1.6 m, 22.4 m and 14.2 m respectively.

Figure 11 summarizes the differences with respect to the BRTS orbits for all four solutions. The RMS differences range from 1 to 9 m in height, 13 to 30 m in cross track, and 14 to 30 m in down-track, and the maximum difference over the entire ~3 day span is 52 m. Especially encouraging are the results for TDRS-5, which was tracked at a very low elevation (10°). Moreover, the signature that TDRS-5 traced in the plane of sky was very compact compared to the one for TDRS-3. Despite these important differences, the TDRS-5 orbit accuracy appears only slightly degraded.

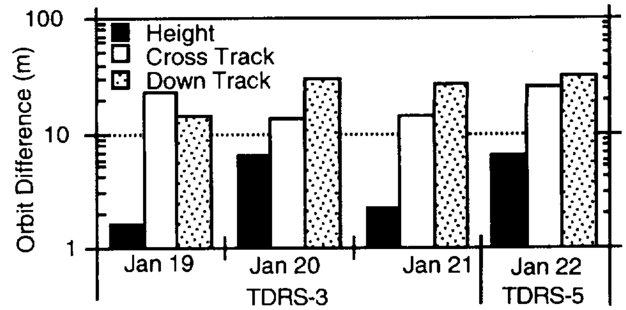

Fig 11. Bar graph summarizing RMS TDRS orbit differences (this study vs. BRTS). he first three solutions correspond to TDRS-3 and the last to TDRS-5. The arc lengths vary between 18 and 20 hours in length. The largest excursion over the entire set of comparisons is 52 m.

2.3.4 Covariance Analysis

Building on the results of the evaluation of the tracking data from the January 1994 experiment, we performed a covariance analysis to further assess the orbit accuracy. In this study, the sensitivities of the TDRS orbit to certain unestimated parameters were also computed and used to augment the formal "noise-only" error contribution. These unestimated or "consider" parameters are included in covariance analyses to yield more realistic error estimates. The consider parameters and their associated errors (1σ) are given in Table 3.

TABLE 3. CONSIDER PARAMETERS AND UNCERTAINTIES FOR COVARIANCE ANALYSIS.

Consider Parameters	
TDRS solar radiation pressure coeff.	2 %
WSC one-way range bias	1 m
WSC zenith wet troposphere (range)	10 cm
Ionosphere delay (K_u-band)	100 % Bent
Gravity model error	50 % JGM-3 – WGS-84
Tracking station baselines	1 cm East 1 cm North 2 cm Vertical
X, Y Pole Motion	10 cm
UT1–UTC	3 msec

With the exception of the solar radiation pressure coefficient and WSC range bias, all other parameters were treated in accordance with the estimation strategy shown in Table 1. In keeping with a conservative approach, the solar radiation pressure coefficient and WSC range bias were not estimated, rather they were treated as consider parameters. In order to account for the possibility of anomalies in tracking the SGL (as experienced in the actual experiment; compare Figure 4), the phase biases were occasionally reset according to the assumption that at least one of the three stations (El Paso, Socorro, or JPL) would lose lock every 8 hours on average. Also noteworthy is the absence of consider parameters for the location of the WSC range station. Any error in this position would be reflected in the range bias computed from the BRTS orbit. (In practice, the range station could be surveyed in with the remote TurboRogue stations at the cm level using a GPS survey. Any residual error would be negligible in comparison with the uncalibrated portion of the range bias.)

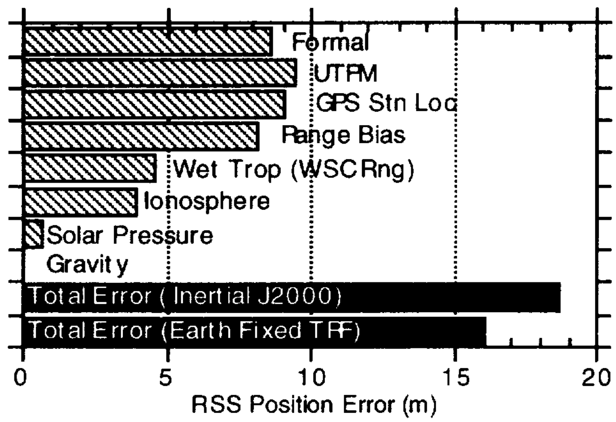

Fig 12. Relative contributions of various error sources for TDRS-5 orbit determination based on covariance analysis. These results apply to TDRS-5 data collected during the January, 1994 experiment (18 hour arc). Note that errors in the Earth rotation and orientation parameters (UTPM) lead to significant errors in orbit positions referred to the inertial (J2000) frame but not to the terrestrial reference frame (TRF).

Shown in Figure 12 are the errors for the TDRS-5 orbit solution (epoch 21-JAN-1994 19:48 UTC) separated by source. The TDRS-5 case was selected because this spacecraft occupies the western orbit slot, and the results are of greater operational consequence than the corresponding results for TDRS-3. Evidenced in the Figure are the dominant contributions of the formal "noise- only" errors and the station location errors for the GPS/TDRS tracking terminals. These error sources are particularly important in shorter arcs, i.e. spanning less than a full diurnal revolution of the spacecraft, as the solution will have enhanced sensitivity to errors associated with the measurement models. Errors in the parameters describing the Earth orientation and rotation (UT1–UTC and X, Y Polar Motion or "UTPM") are also large contributors, but have very little effect on orbit positions referred to the Earth-fixed terrestrial reference frame (TRF). The next largest error source is the range bias. As the range bias has been calibrated using the BRTS orbit, it was assigned an a priori standard deviation of 1 m (1 way). A more realistic estimate of the range bias from the WSC would augment the orbit error significantly. (This will be discussed further in Section 3.1.2.) The total RSS 3-d orbit error is < 20 m for this ~18-hr solution. This result corroborates the findings of the internal and external orbit tests described earlier, and suggests that the TDRS orbit accuracies achieved for the experiment are better than 25 m (1 σ).

2.3.5 Special Arc Length Studies

A critical requirement for TDRS orbit determination is the prompt recovery of the trajectory estimates after a station-keeping maneuver. In recognition of this, we have examined the effects of reducing the arc length on the error in the recovered orbit. Our nominal orbit solution for this comparison is a 34-hr arc for TDRS-3. Gradually shorter tracking data arcs were used in computing orbit solutions for comparison with this nominal ephemeris. Depicted in Figure 13 are the differences with respect to the nominal 34-hr solution; these results suggest that 75 m orbit precision is being approached with only 4 hours of tracking. (The current requirement for STS is 200 m (1 σ) within 4 hours after a maneuver [*Cox and Oza*, 1994].) Differences of the 12-hr arc with respect to the nominal are less than 20 m in all components.

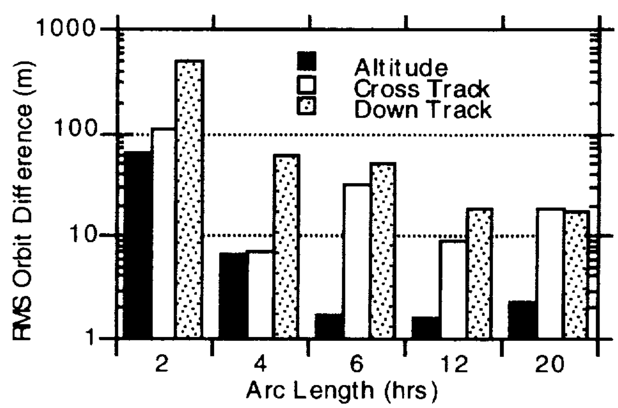

Fig 13. Effect of solution arc length on precision of recovered TDRS-3 orbit. The orbit differences shown are taken with respect to a nominal 34-hr solution.

The results in Figure 13 are instructive, but show only internal consistency of a single set of test solutions for TDRS-3. Clearly, additional work is warranted on the issue of rapid trajectory recovery. This is discussed at greater length in Section 3.2.

3. FUTURE DEMONSTRATIONS

For the TDRS study, there are a number of outstanding issues that should be addressed in examining the operational viability of the GLT approach. We plan to perform another demonstration of the system in which all stations are deployed in the immediate vicinity of White Sands within the main beam of the SGLs. A smaller network (~100 km baselines) will be used and the duration of the demonstration will be extended so that some maneuvers can be tracked. A new ground station is in place at White Sands (Second TDRS Ground Terminal or STGT), and a close examination of the new TT&C range data is also warranted. In anticipation of this demonstration, some covariance analyses have been performed to assist in the design of the experiment.

3.1 COVARIANCE ANALYSES

For the covariance study, the towns of Las Cruces, Truth or Consequences and Tularosa, New Mexico were selected for the tracking sites. These towns all lie within the main beam and baselines among them form a triangle with ~100 km legs surrounding the TDRS White Sands station. With the exception of the tracking stations, the assumptions for the covariance study are identical to those comprising the estimation strategies outlined in Tables 1 and 3. TDRS-5 was chosen for the subject of this covariance study owing to the greater operational interest.

3.1.1. Nominal TDRS Orbit Determination

For nominal orbit determination, we assumed that the same arc length (42 hours) currently applied in the processing of the BRTS data would be used. With this nominal approach, the covariance analyses suggest that the 25 m orbit accuracy requirement for TDRS can be readily met with a properly designed system (Figure 14). The largest contributor to the TDRS-5 orbit error is mismodeling of the UTPM parameters. As noted earlier, the UTPM errors have negligible impact on the accuracy of the orbit in the Earth-fixed TRF.

3.1.2 WSC Range Bias

The next largest error source from the covariance result (Figure 14) is the bias of the range measurements from WSC. Recall that an *a priori* value of 1 m (one-way, equivalent to 2 m two-way) was assigned to this parameter in the covariance analysis. One meter is optimistic, being considerably smaller than the design specification of the ranging system at the STGT [*Cox and Oza*, 1994]. This prompted us to perform an analysis to determine the maximum range bias that could be tolerated before the future TDRS orbit determination requirement of 25 m is exceeded. *Nandi et al.* [1992] performed a similar evaluation for a connected element network near WSC, but the assumptions were somewhat different. Most notable among the differences, the noise figure of the differenced phase observables in their study was due mostly to unmodeled tropospheric fluctuations. Since we are using GPS to estimate the zenith troposphere [*Lichten*, 1990], the errors should be significantly smaller.

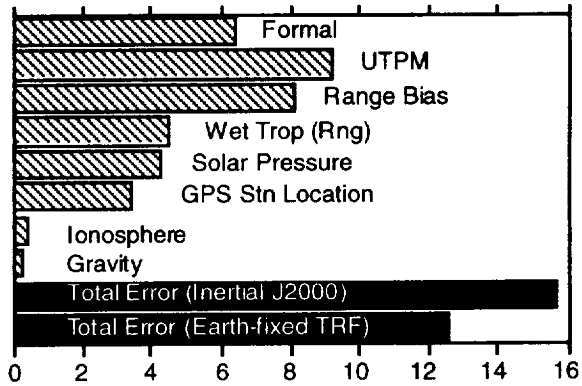

Fig 14. Relative contributions of various errors sources on future TDRS-5 orbit determination (3-d) based on covariance analysis. This exercise assumes baselines of ~100 km for the GPS/TDRS stations, and a 42 hr arc. The total 3-d orbit error is 12–16 m, depending on the reference frame.

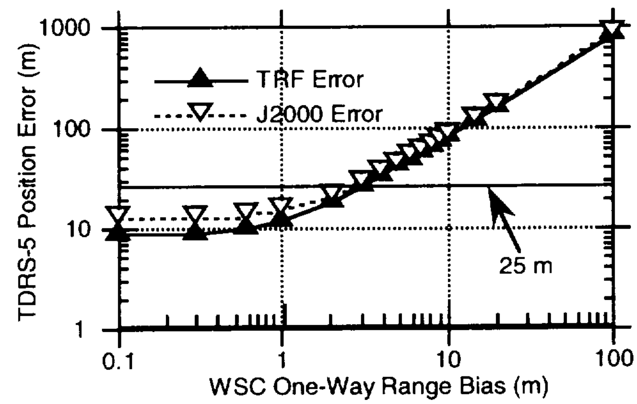

Fig 15. Expected Position Error for TDRS-5 (RSS) as a function of the WSC one-way range bias for 100 km network from covariance analysis. The one-way bias must be known to better than 3 m in order to support 25 m orbit determination for TDRS. (Equivalently, the two-way bias must be known to 6 m or better.) The orbit error is given in both the inertial (J2000) and terrestrial reference frames (TRF).

Figure 15 gives the expected 3-d orbit accuracy (RSS) for TDRS-5 as a function of the one-way range bias. The plot indicates that the one-way range bias must be kept under 3 m in order to maintain the orbit error below 25 m (1 σ). (The fundamental observation is a two-way range from WSC to TDRS and back to WSC. Strictly speaking, therefore, the only requirement is that the total observation bias accumulated over both the uplink and downlink must be kept below 6 m. The distribution of the bias errors on the uplink and downlink is not important, as long as the total bias is less than 6 m.) Keeping in mind that orbit errors attributable to the "consider" parameters in our covariance analyses scale in a linear fashion, it can be seen (compare Figure 14) that the range bias emerges as the leading contributor to the orbit error once its one-way value exceeds ~1 m. This behavior is further illustrated in Figure 15, which shows the total 3-d orbit error increasing in an approximate linear fashion once the bias exceeds 3 m. For these regimes, the expected RSS position error can be approximated using the partial derivative of the range bias with respect to the satellite longitude. As noted earlier, for observing TDRS-5 at 10° elevation from WSC, the value of this partial is about 1/8. Hence a 1-way bias of 10 m will result in an orbit with a 3-d accuracy of about 80 m. The error will be manifest almost entirely as a simple bias in the longitude of the satellite position. In order to meet the EOS requirement for TDRS-5 (TDRS-West) orbit determination, the one-way range bias should thus be kept below 3 m. This result applies in an approximate sense to operational TDRS satellites in the eastern slot as well (e.g., TDRS-4), since the elevation as seen from WSC is nearly the same.

The STGT ranging system is undergoing testing at WSC, and the ranging data from there should be improved. If the new system cannot routinely deliver the required accuracy in nominal operations, a calibrated measurement might be obtained by tapping into the uplink and downlink at White Sands with additional enhanced TurboRogue receivers. The TT&C ranging tones would be tracked directly in the TurboRogues, which would be placed in the system as close to the respective STGT antennae as possible in order to mitigate cable and other hardware delays.

Another alternative for obtaining range data from WSC is to use the observations from the BRTS beacon. The BRTS range observations are derived from a TDRS service. The transmissions are made at S band, so the ionosphere delay is of some concern. Fortunately, this can be calibrated quite effectively with a colocated GPS receiver. Even with the unmodeled ionospheric delays, the BRTS range is considered more accurate than the TT&C range. We note that in this scenario, only the BRTS beacon at WSC would be used. None of the remote BRTS sites would be required. Though this option will be investigated, we will focus first on using the TT&C data.

3.1.3 Limiting Orbit Accuracy

Figure 15 also suggests that, with unbiased range measurements (< 1 m), the 3-d orbit accuracy (1 σ) for TDRS-5 can be brought below 10 m using the GLT technique. Though this remains to be demonstrated with actual data, it nonetheless underscores the remarkable precision of the differenced phase observables. That these measurements taken over very short baselines (~100 km) have the potential to support 10 m orbit accuracy for a geosynchronous spacecraft is a testimony to the powerful ability of the GPS data to enable ultra-precise time transfer and reliable calibrations of atmospheric delays.

3.2 TRAJECTORY RECOVERY

An additional important requirement for TDRS orbit determination is the trajectory can be recovered rapidly after a station-keeping maneuver. Results from the January 1994 demonstration (Figure 13) provide evidence that the current STS requirement of 200 m TDRS orbit accuracy within 4 hours of a maneuver can be met. Additional data should be collected under a variety of conditions to make a more compelling case; this will be one of the primary goals of our next demonstration.

For improved accuracies in post-maneuver trajectory recovery, additional options can be explored. Since the short-baseline differenced phase data is not strong enough to recover the trajectory at the 25–50 m level from a cold start in a few hours, we would attempt to include the maneuvers(s) in the orbit solution arc [e.g., *Nandi et al.*, 1992]. In the simplest approach, a velocity impulse could be estimated at the burn time. (Even if the time of the burn could not be supplied *a priori*, or it could be detected by interrogating the continuous phase observations in a preprocessor. In recent analysis of similar GLT data from the Inmarsat geosynchronous spacecraft [*Kelecy et al.*, 1994], we readily detected a station-keeping maneuver in prefit tracking data residuals.) Estimating a velocity impulse at the burn time has been applied effectively for recovering the GPS orbits after a maneuver [*Lichten and Bertiger*, 1989]. Since the station-keeping maneuvers of a geosynchronous satellite are generally long in duration, more advanced approaches might prove necessary (e.g., estimating of stochastic accelerations in the presence of higher-resolution ground tracking.)

4. DISCUSSION

The results from the January 1994 TDRS/GPS tracking demonstration suggest that the short-baseline GLT method can be used to deliver TDRS orbits with accuracies better than 25 m in total position. Achievement of this level of accuracy is contingent on the availability of a small number of calibrated range observations from WSC with one-way biases known to about 3 m or better. Covariance studies provide evidence that, with a properly designed system, 10 m TDRS orbit accuracies can be approached using this method. In an actual operational scenario, it would be necessary to obtain these results in real time. In this context, we note that entire orbit determination procedures were run on HP work stations, and that the sequence of programs required to generate an ephemeris file consume a cumulative CPU time of only a few minutes. These program sequences can be automated, as has been done for computing Topex/Poseidon orbits [*Wu et al.*, 1993]. In a recent demonstration of the Topex/Poseidon automated system, orbit estimates were delivered within 24 hours of the receipt of the flight data. For this exercise, a combination of orbit fits and predictions permitted achievement of 3D accuracies better than 1 m (better than 15 cm radially) in real time.

Although the tracking station equipment was operated and monitored by JPL scientists and engineers during the January 1994 demonstration, it is straightforward to adapt the current setup for unattended, continuous operation. The enhanced GPS receiver and antennae can be combined with a modem and phone line to permit automatic monitoring and data offloading by remote computer. Expected tracking station maintenance and repair is minimized due to the high level of autonomy and low system component count. This feature has in fact already been demonstrated with the performance of the continuously operating global network of Rogue and TurboRogue GPS receivers. The maturity of GPS technology, flexibility of the TurboRogue architecture, and simplicity of the demonstrated tracking station all contribute to low expected system costs.

If some of the issues addressed in Section 3 can be addressed in the next demonstration, then the short-baseline GLT method offers some distinct advantages for future TDRS tracking. Among them are: 1) low-cost of the small antennae and enhanced GPS receivers in comparison with larger systems typically used for geosynchronous tracking; 2) accuracy rivaling connected element networks for the calibration of media, Earth platform and timing errors from the simultaneous observation of TDRS and GPS; 3) operational convenience and maintainability afforded by a small, simple tracking stations in the vicinity of White Sands (as opposed to the present global network); and 4) processing system that lends itself to a high-level of automation, even on a desktop work station.

Similar benefits could be shared by other future missions adopting the GLT technique. In the case of the NASA Deep Space Network, which supports high-Earth orbiters in addition to deep space probes, valuable large antenna time could be freed up for more dedicated interplanetary tracking sessions. The high potential for inexpensive tracking should also be attractive to designers of NASA, military and commercial systems used for orbit determination of geosynchronous satellites.

ACKNOWLEDGMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We are grateful to Dennis Sweeney of Virginia Tech, Scott Stephens of TRW and Don Spitzmesser of JPL for their invaluable contributions to the January 1994 Demonstration. Sumita Nandi, Charles Dunn, Sien Wu and Willy Bertiger of JPL are thanked for their valuable consultations. We would also like to acknowledge a number of individuals at both White Sands and GSFC who provided assistance in supporting this experiment. They include: Wilson Lundy and Candelario Gallegos at WSC, and Leslie Ambrose, Mark Beckman, Osvaldo Cuevas, Roger Flaherty, Phil Liebrecht and Andy Marshall at GSFC. We also thank Charles and Betty Strange of the Motel 6 in El Paso, and Coy and Seretta Heard from the Motel 6 in Socorro for leaving the lights on for us, and cheerfully granting us permission to track from the roofs of their motels.

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