Application of GPS Tracking Techniques to Orbit Determination for TDRS

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In this paper, we evaluate two fundamentally different approaches to TDRS orbit determination utilizing Global Positioning System (GPS) technology and GPS-related techniques. In the first, a GPS flight receiver is deployed on the TDRSS spacecraft. The TDRS ephemerides are determined using direct ranging to the GPS spacecraft, and no ground network is required. In the second approach, the TDRSS spacecraft broadcast a suitable beacon signal, permitting the simultaneous tracking of GPS and TDRSS satellites from a small ground network. Both strategies can be designed to meet future operational requirements for TDRS-II orbit determination.

1. INTRODUCTION

The Tracking and Data Relay Satellite System (TDRSS) is used by NASA to support positioning and data relay activities for a wide variety of Earth orbiting spacecraft [1]. The present operational system is composed of two geosynchronous satellites (TDRS-E and TDRS-W at 41° and 171° W longitude respectively), a central ground station located at White Sands, New Mexico, and remote tracking sites at Ascension Island, American Samoa, and Alice Springs, Australia. Accurate real-time positioning of the TDRSS spacecraft is fundamental to the proper operation of the system, and is achieved via the relay of coherent signals broadcast by unmanned transponders at the remote tracking sites. These remote beacons are collectively referred to as the Bilateration Ranging Transponder System (BRTS). Range and Doppler observations from BRTS are routinely scheduled by the central ground processing facility at White Sands, where they are used in conjunction with models of the forces perturbing the spacecraft motion to determine the TDRS positions. Evaluation of the TDRS ephemerides suggests that orbit consistency is maintained to better than 70 m using the operational BRTS method [2]. This level of precision is adequate for current applications; however, the technique requires valuable TDRS antenna time that could otherwise be used for servicing user spacecraft.

In recognition of the need for improved tracking for the next generation TDRS System (TDRSS-II), a number of alternative methods have been explored [3–6]. The demand for improved accuracies provides an important motivation for these efforts. This requirement, however, is balanced by the appeal of a simple, reliable and autonomous system that requires no disruption of TDRSS user services and delivers the ephemerides in near real-time. One technique which promises the potential to meet these sometimes conflicting demands relies on technology from the U. S. Department of Defense Global Positioning System (GPS). Previous efforts addressing this option have produced encouraging results. *Wu* [7] proposed two GPS related-techniques for determining the orbits of high-altitude Earth satellites. He envisioned a wide variety of possible applications; hence the breadth of the study prevented a thorough treatment of TDRSS. Recent efforts have focused directly on TDRSS, but software limitations precluded a complete evaluation [3]. In this paper, we build on these earlier studies by revisiting their assumptions, and revising them to insure they reflect current state-of-the-art. The new assumptions form the basis of a covariance study that exploits software and methodology that have evolved over the past decade as part of a program at the Jet Propulsion Laboratory (JPL) to support GPS-based tracking of Earth orbiters.

Results for two distinct solutions strategies, as prescribed by *Wu* [7], are reported. In the first, a GPS receiver is deployed on the TDRSS spacecraft and the ephemerides are determined using direct measurements from the GPS to TDRSS spacecraft. In the second, the TDRSS spacecraft broadcast wide-beam beacon signals which permit the simultaneous tracking of GPS and TDRSS satellites from a small ground network.

2. GPS-BASED TECHNIQUES FOR ORBIT DETERMINATION

For both military and civilian customers, the principal application of GPS is the precise positioning of ground sites and of moving vehicles near the Earth's surface [8]. The space segment of this system, which is due for completion in mid-1993, will consist of 21 satellites and 3 active spares orbiting in 6 uniformly spaced orbit planes inclined at 55° with respect to the equator. The satellites, which are at an altitude of about 20,200 km, transmit unique navigational signals centered on two L-band carrier frequencies (L1 at 1575.42 MHz and L2 at 1227.60 MHz). Each carrier is modulated with pseudo-random square-wave codes: a coarse acquisition (C/A) code on L1, and a precise (P) code on both L1 and L2. An additional Y-code may be used to encrypt the P-code (anti-spoofing or AS).

A GPS receiver generates a replica of these codes and correlates them with the received signals, from which a

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pseudorange to each visible spacecraft can be inferred. (Pseudorange is simply a range biased by the unknown offset between the spacecraft and receiver clocks.) The receiver uses these pseudorange measurements together with ephemeris and clock information broadcast by the respective GPS spacecraft to determine its location. A minimum of 4 satellites must be in view of the receiver in order for the user to solve for the three components of position and the clock offset. The accuracy with which the user can determine his position is dependent on a number of factors; principal among them is the geometric configuration of the satellites in view. The quality of the broadcast ephemeris and clock information, which can be intentionally degraded as part of Selective Availability (SA), is also an important factor.

The same principles can be applied to the positioning of low-Earth orbiters equipped with GPS receivers. Because the applications in this area are primarily in the field of precise geodesy, a more robust approach is generally required. In particular, multidirectional pseudorange and carrier phase measurements collected simultaneously at ground stations and the user spacecraft can be combined over suitable intervals of time—typically a few hours to several days—in order to determine the ephemerides of the orbiter [9–11]. The simultaneous measurements from the ground stations can be combined to nearly eliminate effects of clock errors SA degradation, while also mitigating the effects of errors in the GPS ephemerides.

What makes this approach especially attractive is that the robust observation geometry permits orbit solutions without dynamic model constraints on the spacecraft motion [12]. (Errors in dynamic models are the principal limitations in traditional approaches to satellite orbit determination.) Where advantageous, however, dynamic models can still be exploited to improve the accuracy [13]. Although a state-of-the-art GPS receiver capable of providing proof-of-concept has not flown at this writing, covariance analyses suggest that positioning at the sub-decimeter level should be achievable. Plans for a number of U. S. and international missions include flight-hardened, high performance GPS receivers. Two such missions, the joint U. S.–French Topex/Poseidon satellite [14] and NASA's Extreme Ultraviolet Explorer, are to be launched in 1992.

While the application of GPS for the positioning of low-Earth orbiters has received considerable attention, this is not the case for high-Earth orbiters such as the geosynchronous TDRSS spacecraft. The GPS constellation illuminates the Earth from an altitude of 20,200 km and as such, is better suited for low-Earth users. Since the TDRSS spacecraft are located above the GPS constellation, they must look down to receive GPS signals spilled over the limb of the Earth from satellites on the other side of the planet. The configuration, hereinafter referred to as "down-looking GPS" in keeping with Wu [7], is shown in Figure 1.

Although an observer traveling with TDRS would be able to establish a direct line of sight to many GPS satellites, the number of useful GPS spacecraft is limited to those that fall within an annular region delineated on the inside by the Earth

blockage and on the outside by the beamwidth of the GPS signals. The half-width of the mainbeams are 22° and 27° respectively at L1 and L2 frequencies, while the angle subtended by the Earth at GPS altitude is 27°. Together these constraints imply that, on average, the signals from only 1 GPS satellite can be seen from geosynchronous altitude at any given time [7]. Of course this entirely precludes the possibility of kinematic positioning, and the orbits must be determined dynamically. For a spacecraft at geosynchronous altitude, however, the perturbative accelerations due to the non-spherical Earth are highly attenuated and the effects of atmospheric drag are negligible. As a result, the proper modeling of the forces acting on a spacecraft is much less problematic than it is for a low-Earth orbiter.
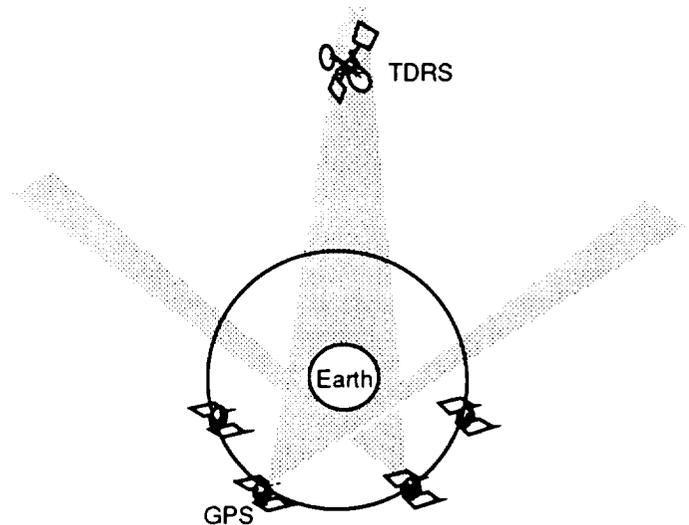
Figure 1. 2-d view of down-looking GPS tracking configuration: Geosynchronous TDRSS satellite with GPS receiver sees GPS signals spilled over limb of Earth.

Aside from these special limitations, the overall strategy for down-looking GPS is not unlike that for the up-looking variation used by low-Earth orbiters. In particular, the determination of the orbit can be made using simultaneous observations formed with data collected at ground stations, or directly, without the aid of a ground network. The benefit gained from the use of simultaneous observations, however, is somewhat limited owing to visibility constraints. Simultaneous observations of the same 2 GPS spacecraft from geosynchronous orbit and the ground are possible less than half the time even with the most optimistic scenarios [3,7]. Implicit in both approaches therefore is a greater vulnerability to clock errors, and to the effects of SA if the

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flight receiver is not equipped with a decryption module. Despite these problems, the down-looking GPS approach is quite attractive for TDRS orbit determination because of the high level of autonomy and the greater potential for achieving real-time results.

An alternative strategy requires that the high-Earth orbiter transmit a suitable signal which can be monitored at the same ground stations observing GPS [7, 15]. This method is referred to as "inverted GPS" because the major factor affecting the orbit accuracy is the number of ground stations, rather than GPS satellites, in common view of the user spacecraft (Figure 2). Inverted GPS promises the highest accuracies for geosynchronous tracking because any number of ground sites may be visible from the TDRSS spacecraft [7]. Coincident observations of the GPS satellites from the ground are desired in order to enable estimation of clock biases. As is the case for down-looking GPS, dynamic models of the forces governing the orbital motion are used to supplement the geometric content of the measurements.
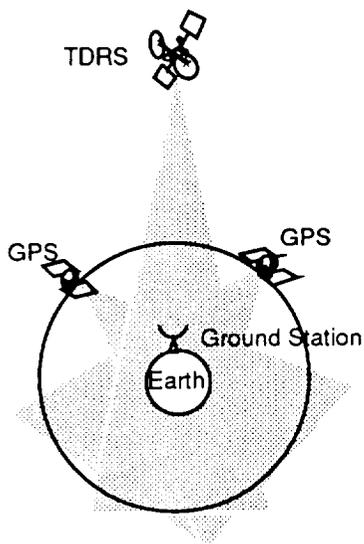
Figure 2. Inverted GPS tracking configuration: TDRSS and GPS beacon signals tracked simultaneously from ground.

3. COMMON STRATEGY

The assumptions forming the foundation of this study are governed by guidelines that have been advanced by NASA for future TDRS-II orbit determination [e.g. 3,4]. These guidelines reflect a balance between the demands for increased accuracy and system autonomy. For this effort, the figure of merit for the accuracy is 50 m in total position (1-σ). We assumed that this level of accuracy should be met in nominal operations with 24-hours of tracking, although we also examined the feasibility of achieving 50 m after only 2 hours of tracking (for the cases where the trajectory is to be

recovered rapidly after a station-keeping maneuver). For system autonomy, the primary drivers include: minimized impact on TDRSS user services, minimized human intervention during normal operations, and for the inverted technique, a simple ground network. We began with the premise that the inverted-technique would provide the best accuracy, and focused on identifying compromises that would ensure greater autonomy. Conversely, for the down-looking approach, we devoted our efforts to determining ways to improve the accuracy.

The Orbit Analysis and SImulation Software (OASIS) package developed at JPL served as the primary evaluation tool. The OASIS system is designed to provide a flexible,versatile and efficient covariance analysis tool for Earth satellite navigation and GPS-based geodetic studies [16]. It has been used extensively for spacecraft orbit error analysis, and its factorized Kalman filter strategies [17] also form the basis for the GPS Inferred Positioning SYstem (GIPSY) software used in the reduction of actual GPS data for recovering geodetic baselines and improving satellite orbits.

For both strategies, a full 24-satellite GPS constellation was assumed. The TDRSS-II satellites were assumed to be at the same locations as the present TDRS-W and TDRS-E. The actual TDRSS-II constellation will contain additional satellites, but they should be clustered in the same vicinities as the current spacecraft. The results therefore should not be significantly different for these additional satellites. The next sections detail specific error models applied in the two solution strategies, along with the results. Covariance analysis results portray the actual expected errors only to the extent that the a priori models are authentic. In order to address the possibility of unanticipated errors, we therefore adopted a set of a priori assumptions that were somewhat conservative.

4. INVERTED GPS

Assumptions

As a starting point, we propose some small ground networks suitable for the simultaneous tracking of GPS and TDRSS spacecraft. An initial stated goal for TDRSS-II orbit determination was to confine all stations to the continental U.S [3]. This constraint was subsequently relaxed [4]; it nonetheless remains essential to identify a minimum network that will deliver the desired orbit accuracy. For this effort, we selected various station configurations from the 6-site global GPS network that has been established to support the Topex/Poseidon mission. Three of the 6 sites are collocated with NASA Deep Space Network (DSN) stations at Goldstone, California; Madrid, Spain; and Canberra, Australia. The remaining three are at Santiago, Chile; Usuda, Japan; and Hartebeesthoek, South Africa. An additional receiver at the TDRSS ground control station at White Sands was assumed for some of the variations. The visibilities of these sites from the TDRS-E and TDRS-W respectively are shown in Figure 3.

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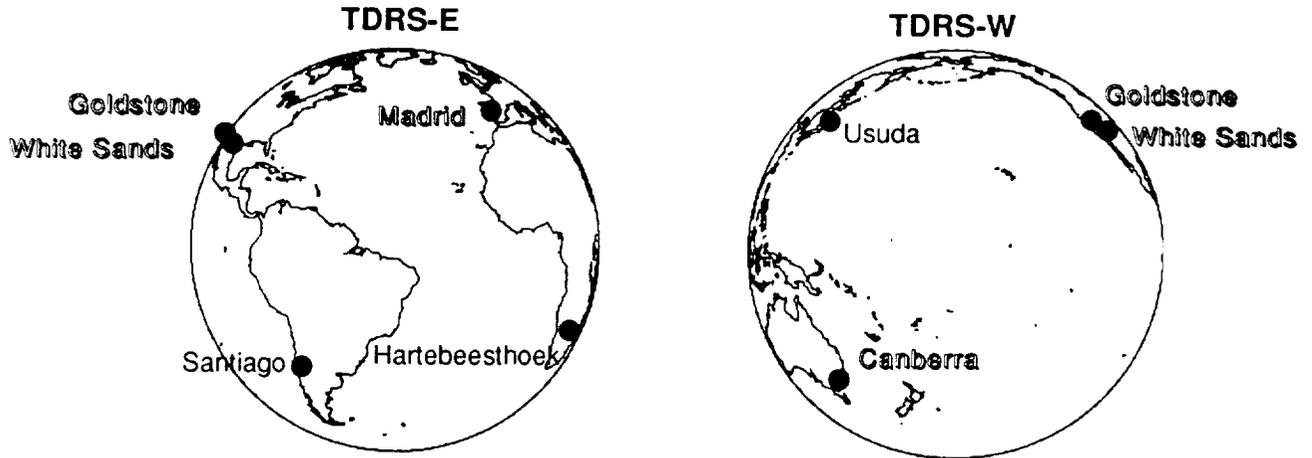
TDRS-E   **TDRS-W**

Figure 3. Visibility of proposed GPS ground network for TDRS tracking. The views show the perspectives of the Earth from the TDRS-E and TDRS-W geosynchronous orbit positions respectively. The minimum network considered, consisting of stations at the DSN sites and the White Sands TDRSS ground control center is shown in shadowed text.

It is instructive to note that these sites are presently used to support well-established NASA programs. Each is equipped with a JPL Rogue digital receiver capable of tracking pseudorange and carrier phase from 8 GPS spacecraft simultaneously [18]. Although the receivers are designed to operate unattended, staff are always on call at these sites should any problems develop. For this study, we assumed that the Rogue receivers at each of the tracking sites were retrofitted so that a TDRSS beacon signal could be tracked continuously on 1 of the 8 channels (Figure 4). We note that GPS receivers have already been used in demonstrations to track Pioneer Venus and Magellan at X and S bands [19].

A critical design parameter for the inverted GPS technique is the measurement characteristic of the TDRS beacon signal. Several options for the design of an advanced beacon signal have been considered [3, 4]. For the present study, ranging tones broadcast by the TDRSS spacecraft at Ku band served as the nominal configuration for the transmission. A major advantage of exploiting the high-frequency Ku band is the relatively small signal delay due to ionospheric refraction. Equivalent range delays at Ku band vary from less than 1 cm to 20 cm depending on the level of solar activity. Ionospheric calibration based on the GPS dual frequency L-band data collected at the various tracking sites can then be applied in modeling the delay to better than 1 cm in range. A similar activity is already underway at the DSN sites, where the GPS data is used to calibrate ionospheric delays for deep-space tracking [20].

The proposed Ku-band signal could, in theory, provide pseudorange measurements with a random noise component of 1 cm averaged over 30 minutes, assuming a 100 MHz bandwidth (L. Young, private communication, 1992). In practice, the implementation of new Rogue hardware to down-convert the Ku-band signal to GPS frequencies (L band) would introduce an additional error because separate signal paths would be used for the TDRS and GPS signals.

This instrumental error would manifest itself as a slowly varying delay offset in the TDRS pseudorange residuals. Preliminary analysis indicates the effect would be bounded by about 1 nsec (amounting to 30 cm in range delay) and would modulate with a period of about one-half day. Because of the long period, the error appears as a constant bias over a typical measurement interval, permitting us to model it as a stochastic process in OASIS. Several variations from these nominal characteristics were explored in order to assess how deviations from these assumptions would impact the TDRS orbit accuracies. Results and additional details are presented in the next section.

Modified GPS
Ground Receiver
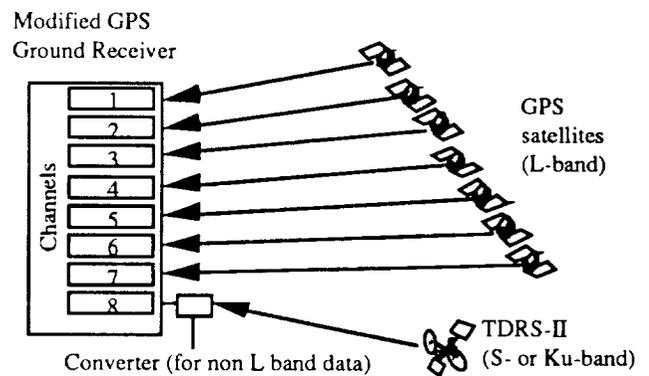
Figure 4. Schematic showing 8-channel GPS receiver modified for TDRS tracking on one channel.

The noise of the ionosphere-corrected GPS P-code pseudorange and carrier phases measurements was set at 25 and 1 cm respectively for 30 minute measurement intervals.

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Carrier Phase rms = 2.9 mm

Pseudorange rms = 0.26 m
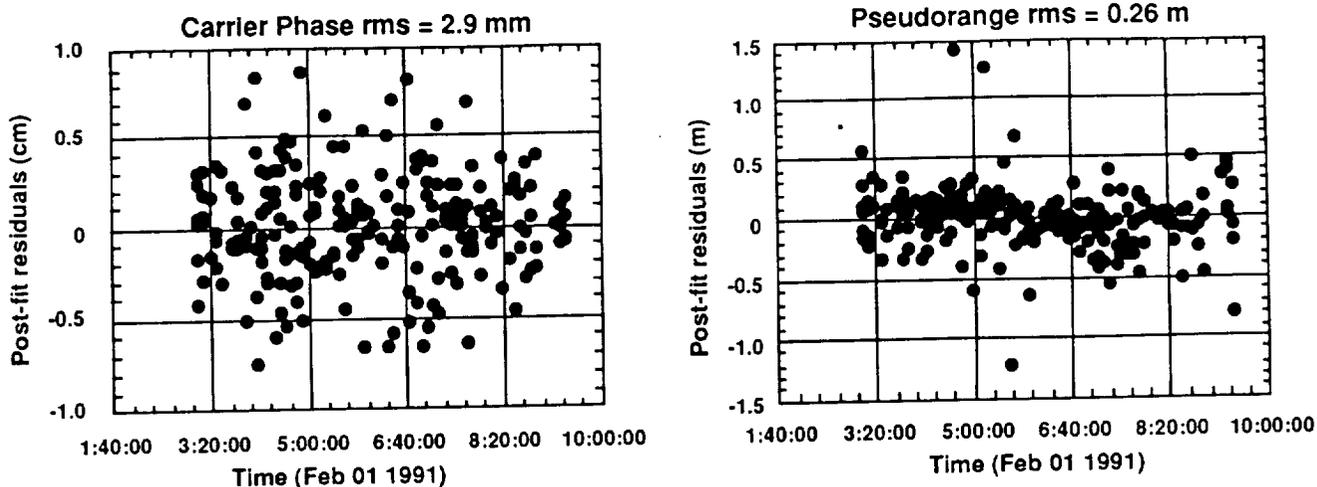
Figure 5. Actual post-fit GPS data residuals from Rogue receiver at Goldstone for carrier phase (left) and pseudorange (right). The GPS measurements are at a 6-minute rate.

As Rogue receivers are presently providing this level of precision for 6 minute measurement intervals (cf. Figure 5), these estimates are quite conservative. The higher levels of data noise, however, are intended to accommodate periods when the receivers must track using codeless techniques because AS is turned on. Additional assumptions applied in OASIS for evaluating the inverted GPS technique are listed in Table 1. We assumed the a priori knowledge of the GPS ephemerides was very poor, and solved for the 24 GPS and 2 TDRSS epoch states together. Additional estimated parameters included a single solar radiation pressure coefficient for each TDRS, and GPS solar radiation pressure coefficients and carrier phase biases. Clock errors were estimated as stochastic white noise processes with a reference frequency standard at Goldstone, an approach which is analogous to (but more general than) using doubly differenced measurements. A random-walk process noise parameter was used to model the zenith troposphere delay at each of the stations [21].

The sensitivities of the TDRS orbit to errors in several important unestimated parameters were also computed. These unestimated or "consider" parameters, can be included in covariance studies in order to yield more realistic error estimates. The additional error contributions from the consider parameters are added to formal errors from the filter, which contain only the effects of data noise. The consider parameters and their associated errors (1-σ) are also shown in Table 1. Note that these errors for consider parameters represent fixed systematic errors [17]. Most important among them are the tracking station coordinates and Earth orientation parameters. For individual components of the DSN station positions, errors of 3 cm were assumed. Recent analyses suggest that cm-level accuracies are already being achieved for the locations of GPS antennae at the 2 DSN sites in the Northern Hemisphere [22]. Coordinates for non-DSN sites were assigned conservative errors of 10 cm. Uncertainties in the X and Y pole positions were set at 25

cm, while the error in the variation of Earth rotation as manifest in UT1 − UTC was set at 6.0 X 10 $^{-4}$ s. In a unified GPS/TDRSS solution strategy at JPL, these Earth orientation parameters could be adjusted to reduce these errors by at least an order of magnitude. By using higher errors, we allow for a real-time system where accuracy may be degraded.

The lumped effects of errors in the Earth's gravity model were represented by 25 % of the difference between the Goddard Earth Models (GEM) −10 and −L2 [23,24]. Our own analysis suggest that for many applications this representation is comparable to the errors in the GEM-T3 gravity field [25], a state-of-the-art model developed in support of the Topex/Poseidon mission. Owing to the extremely high altitude of a geosynchronous orbiter, the gravity model errors have only a minor effect on the TDRS orbit determination in comparison with other sources.

Table 1: Error models for inverted-GPS

A PRIORI FOR ESTIMATED PARAMETERS				
TDRS Position, Vel. (X, Y, Z)	5	km,	50	m/s
TDRS Solar Radiation Pressure	5	%		
GPS Position, Vel. (X, Y, Z)	100	m,	1	m/s
GPS Solar Radiation Pressure	25	%		
GPS Y Bias	10^{-12}	m/s^2		
GPS Carrier Phase Biases	1000	km		
GPS/TDRS/Station Clocks	1000	μsec	white noise	
Zenith Troposphere	40	cm	+12 cm/day	

CONSIDERED PARAMETERS			
DSN Station Coordinates	3	cm	
Non-DSN Station Coordinates	10	cm	
GM Earth	2	ppb	
Lumped Earth Gravity Field	25	%	GEM-10 − L2
X, Y Pole Motion	25	cm	
UT1 − UTC	6 X 10^{-4}	s	

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Results for Routine Orbit Determination

We consider first a nominal case which is characterized by the TDRS Ku-band beacon design outlined in the previous section and a minimal ground network consisting of the 3 DSN sites and White Sands. Figure 6 depicts the mapped orbit error (1-σ) for TDRS-W as a function of time past the epoch of the arc. The formal (computed) error reflecting the effects of data noise is shown along with the systematic error from unestimated (consider) parameters. We adopt the maximum RSS total error as the basis for comparing various strategies in relation to the TDRSS requirement. For the 24-hour period in question, the total position error for TDRS-W never exceeds 15 m, well under the 50 m requirement.
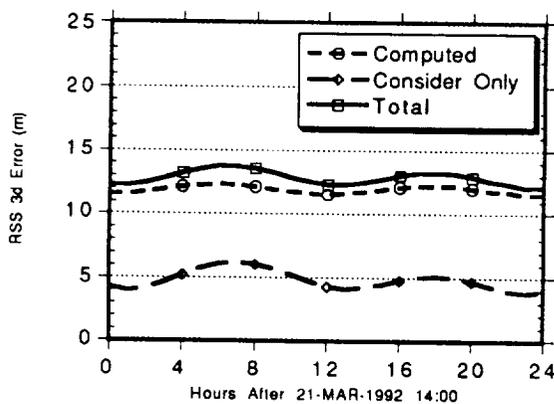
Figure 6. TDRS-W position error for 24-hour arc. Orbit determined using inverted technique with tracking from 2 DSN sites and White Sands. TDRS-W carries nominal Ku-band beacon.
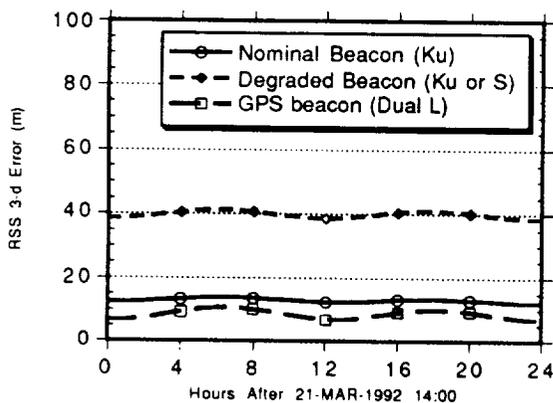
Figure 7. TDRS-W position error over 24-hour arc for hypothetical beacon signals. Orbit determined using inverted technique with tracking from 2 DSN sites and White Sands.

In interpreting Figure 6, it is instructive to note that the total error is dominated by the formal (computed) error contribution, indicating the results may be highly sensitive to our assumptions for the TDRS beacon signal. To address this concern, we examined two limiting cases. In the first, the TDRS signal was degraded by increasing the magnitude of the systematic contribution from 30 cm to 100 cm. Introducing this increase allows the partial accommodation of unmodeled ionospheric refraction errors, in addition to aggravated instrumental effects. For instance, if the TDRS beacon broadcast at S band instead of Ku band, the calibration of the ionospheric delay would yield accuracies of only a few decimeters. For the case of this degraded beacon, the maximum total error grew to 41 m (Figure 7), a value which is still lower than the 50-m requirement.

In the second case, the systematic contribution was removed entirely, but the noise was increased by a factor of 25 (from 1 cm to 25 cm for 30 minute averaging). Inasmuch as the GPS pseudorange signals were also assigned a data noise of 25 cm, this approach is analogous to the situation in which the TDRSS spacecraft are equipped with actual GPS beacons. The maximum total RSS error was 10 m, an improvement over the nominal case, showing that the 25-fold increase in the noise contribution was more than balanced by the elimination of the slowly varying bias (cf. Figure 7). Taken together, these results indicate that the greatest concern for the TDRS beacon signal lies in the minimization of the systematic, slowly varying bias introduced by the different path lengths for the GPS and TDRS signals.

It is also instructive to investigate how the period of these systematic errors in the TDRS beacon signal affect the orbit determination. To answer this question, we assigned different values to the time constant for the 30 cm bias and computed the formal position error for TDRS-W at epoch. (Recall that the nominal 1/e folding time constant, τ, was one-half day.) The results, depicted in Figure 8, indicate that the worst accuracies are experienced when the period of the systematic error is about 5 hours. As the time constant of the systematic error decreases below 5 hours, the orbit error also decreases until the limiting case of white noise is reached. This phenomenon is evidently a consequence of increased decoupling with other parameter errors, even though smaller τ represents higher process noise. Likewise, as the period approaches 1-day, the orbit error decreases as the systematic error appears more like a single constant bias over the entire 24 hour arc.

We examine now the effects of various different tracking network configurations. While it is adequate for observing TDRS-W at 171° W, the minimum network consisting of stations at the 3 DSN sites and White Sands is not well-suited for tracking TDRS-E at 41° W. The situation is best illustrated in Figure 3. TDRS-W is viewed by 2 DSN sites (Goldstone and Canberra) plus White Sands. Although the distance between the two American stations is rather short, the overall baseline orientation is adequate enough to provide the necessary geometric diversity in the observations. In contrast, TDRS-E is viewed by only Madrid and White Sands. (The elevation of TDRS-E above the horizon at

Goldstone is about 2°, rendering any observations collected there unreliable.) The network consists of a single, long baseline which can provide TDRS-E orbit accuracies no better than 300 m. Even in a best-case scenario, in which we assume that useful observations can be made from Goldstone, the maximum orbit error for TDRS-E cannot be brought below the 50 m level without tuning of Earth orientation parameters. For tracking TDRS-E, it is therefore necessary to consider an augmented tracking network.

is observed by Madrid, Hartebeesthoek, and Santiago, while TDRS-W is viewed by Canberra, Goldstone, and Usuda. It is noteworthy that no tracking from White Sands is involved, a scenario which is attractive because: 1) Among all the sites discussed, White Sands is the only location not presently part of the operational NASA GPS network. 2) In many of the strategies, tracking of both TDRS-W and TDRS-E is required from White Sands, implying that the single TDRS channel in the reconfigured GPS receiver would have to be shared. Figure 9 shows the orbit accuracies for TDRS-W and -E throughout a 24-hour simulated arc with tracking from the full Topex network. The accuracies achieved are better than 5-m for both spacecraft, an order of magnitude better than the the 50-m requirement.

Figure 8. TDRS-W epoch position error for various systematic signal errors in TDRS beacon. The time constant refers to the period of the systematic error. The error is bound by 1 nsec (about 30 cm in range).

The simplest augmented network is a 5-station configuration consisting of the 3 DSN sites, White Sands, and the Topex site in Santiago, Chile. While the tracking geometry for TDRS-W remains identical to the nominal case, the situation for TDRS-E is dramatically improved. The introduction of the Santiago site implies that TDRS-E is observed by 3 well-distributed stations. Indeed, Table 2 reveals that with this 5-station network the TDRS-E orbit can be determined to the sub-5 m level, a factor of three better than the TDRS-W orbit.

Table 2: TDRSS orbit error for various tracking strategies

TRACKING NETWORK	TDRS-W max error	TDRS-E max error
3 DSN + White Sands	14	>300
3 DSN + White Sands + Santiago	14	4
3 DSN + 3 Topex	4	4

As a final case, we considered the 6-station Topex network. This configuration supplies the most robust and consistent geometry for observing both spacecraft – TDRS-E

Figure 9. TDRS-E and -W position error for 24-hour arc. Orbit determined using inverted technique with tracking from 6 Topex sites. Both satellites carry nominal Ku-band beacon.

Results for Trajectory Recovery and Prediction

The TDRSS spacecraft are actively maneuvered as part of routine station-keeping activities. In order that minimum disruption to user services occurs, it is desirable to recover the trajectory as quickly as possible after the thrust maneuvers. In this section, we explore the capability of the inverted technique for determining the TDRS positions to better than 50 m within 2 hours of a thrust event. Two different approaches are adopted: In the first, a complete recovery of the TDRS epoch state immediately after the maneuver is performed. No a priori information on the TDRS trajectory is assumed. In contrast to the nominal approach outlined in the previous section, however, the GPS orbits are well determined from routine tracking for 12 hours prior to the maneuver. In the second approach, a 3-component velocity increment at the maneuver time is used to augment the TDRS state vector; thus the thrust maneuver is determined as part of the orbit determination process.

Figure 10 depicts the TDRS-W orbit accuracy as a function of time after the thrust event for these two

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approaches. Two different tracking configurations are also considered. For complete orbit state recovery with the nominal tracking network, the 50-m requirement is nearly met after 2 hours. Using the full Topex network, sub 40-m accuracy can be achieved after only 2 hours of tracking. Assuming that the 3-component velocity increments can adequately model the thrust event, and moreover that the time of the maneuver is known, the 50-m requirement can be easily met with minimal tracking.

Finally, we consider how long the quality of the TDRS trajectories can be maintained after cessation of tracking. To examine this, we predicted the TDRS-W orbit state forward for 3 days following the end of the 24-hour definitive orbit determination interval. The results, shown in Figure 11, suggest that the 50-m requirement would continue to be satisfied, even with a total loss of tracking for three days.
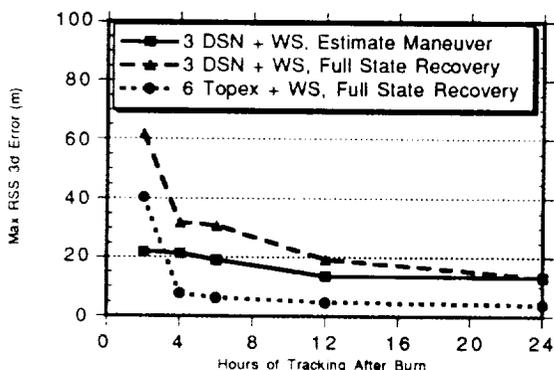
Figure 10. TDRS-W position error after station-keeping maneuver for inverted technique. Orbit after maneuver is determined either using full TDRS-W state recovery or via the solution of 3-component velocity increments.
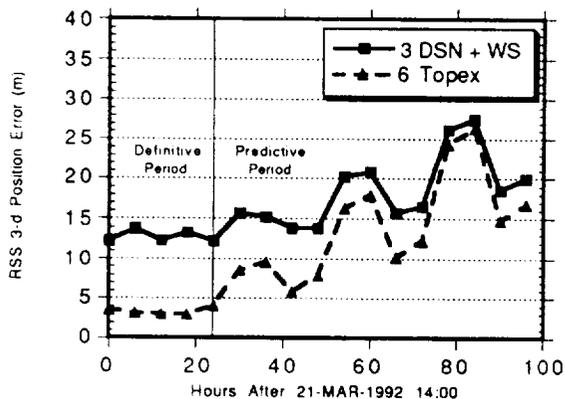
Figure 11. TDRS-W position error as a function of time for definitive and predictive orbit determination. Actual observations are reduced only for the first day.

5. DOWN-LOOKING GPS

Assumptions

For the down-looking GPS tracking option, we elected not to introduce any NASA tracking from the ground. The enhancement in accuracy that might be achieved with only a very limited number of differential observations is outweighed by the benefit of the increased autonomy associated with no ground sites. The estimation strategy for nondifferential down-looking GPS is quite different from that for the inverted option, owing in large part to the weak observability. Many of the parameters, such as the solar radiation pressure coefficient and the GPS orbit states, cannot be recovered reliably with the limited set of observations. Moreover, tracking in nondifferential mode implies that the GPS measurements are sensitive to the effects of the intentional dithering of the GPS clocks and ephemerides (SA). For our nominal case, then, we assumed that the on-board flight receiver would be a military-class instrument with a decryption module. We note that the introduction of this type of flight instrument on TDRSS-II spacecraft should not pose a problem since considerable military data are already processed through TDRSS. We assumed additionally that the receiver would represent an advanced design capable of 35 cm pseudorange measurements with averaging over 15 minutes.

Table 3: Error models for down-looking GPS

A PRIORI FOR ESTIMATED PARAMETERS		
TDRS Position (X, Y, Z)	10	km
TDRS Velocity (X, Y, Z)	1	m/s
TDRS Clock Bias	33	μsec
TDRS Clock Drift	3	nsec/s

CONSIDERED PARAMETERS				
	w/ decrypt.		w/o decrypt.	
TDRS Solar Radiation Pressure	5	%	5	%
GPS Position (RSS 3-d)	7	m	30	m
GPS Clock Error	6	nsec	60	nsec
Earth GM	2	ppb	2	ppb

Table 3 lists the nominal set of a priori assumptions for the down-looking approach. The TDRSS spacecraft epoch positions and clock errors (bias and linear drift) served as the only estimated parameters. Solar radiation pressure was considered at 5 %, a value which is conservative in comparison with the 2 % value that is representative of current modeling efforts [26]. GPS satellite epoch states and clock errors were also considered. For the nominal case, in which it was assumed that the flight receiver was equipped with a decryption module, the GPS ephemeris and clock

errors were set at the few-m level. For the degraded case, these values were increased by a factor of 4 or more to account for the effects of SA [27].

Results for Routine Orbit Determination

Figure 12 shows the position error for TDRS-W as a function of time for nominal 24-hour tracking. Because the down-looking technique considered herein does not rely on ground tracking, the overall results are invariant to the position of the satellite and should not be much different for TDRS-E. The results suggest that with the decryption module on the TDRS satellites, the down-looking technique yields orbit accuracies at the sub-10 m level. In contrast, without the module, the position error reaches 80 m, and the 50-m requirement is not met. Longer data spans are not expected to provide appreciably higher accuracies – after 24 hours the TDRS position errors approach the limiting values governed by the GPS ephemeris and clock errors.

Because the TDRS orbit errors for the down-looking approach are dominated by errors in unadjusted parameters, it is instructive to examine a simple error budget. Figure 13 shows the breakdown of the TDRS-W orbit error for the 24-hour arc. For the nominal case (with decryption), the limiting error sources are the GPS clocks and ephemerides. The data noise contribution from the filter estimation is negligible, owing to the high quality of the pseudorange measurements. For the case in which the receiver is not equipped to handle SA degradation, the GPS errors increase several-fold. In addition, the data noise contribution from the filter estimation becomes quite significant. This increase reflects the dithering of the GPS clocks, which can introduce apparent range errors as high as 60 m into the pseudorange observables [27].

Results for Trajectory Recovery and Prediction

The figure of merit for evaluating the trajectory recovery capability of down-looking GPS is simply the shortest interval of tracking that can provide sub-50 m position error for TDRS. In this context, rapid recovery of the trajectory after station keeping can be achieved only if the flight receiver is equipped with a decryption module. Without the module, the TDRS position error after 2 hours of tracking is in excess of 4 km; approaching the 50-m requirement requires at least 24 hours of tracking. With the module, the 50-m requirement can be met with tracking as short as 4 hours (Figure 14).

Figure 12: TDRS-W Position Error for 24-hour arc. Orbit determined using down-looking technique.
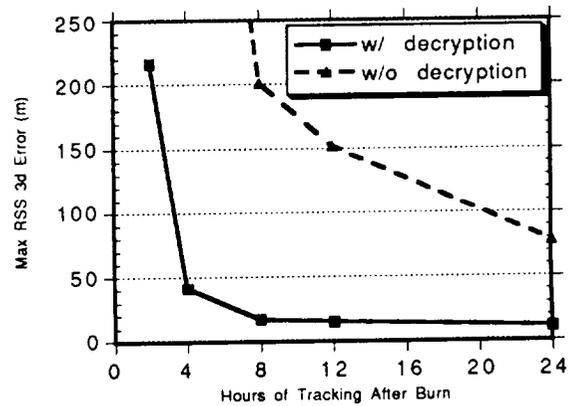
Figure 14. TDRS-W maximum position error after station-keeping maneuver for down-looking technique. Orbit after maneuver is determined using full TDRS-W orbit state recovery.

Figure 13: TDRS-W orbit error for 24-hr arc. Orbit determined using down-looking technique.

The nature of the predicted orbit error for TDRS-W was not explicitly examined for the down-looking case. We note that predicted orbit error is a function of: 1) the error in the satellite state at the beginning of the predictive interval (also called the initial condition error); and 2) the errors in the

dynamic models used to integrate the satellite position. To the extent that the initial condition errors for the down-looking and inverted approaches are roughly equivalent in magnitude, the predictive errors should also be similar. In this context, we conclude that the 50-m requirement cannot be met during the predictive interval unless the flight receiver is equipped with a decryption module. Without the module, the errors in the initial conditions estimated with 24-hours of tracking prior to the predictive interval would exceed the 50-m threshold. With the module, sub-15 m initial condition error is achieved after 24-hours of tracking, and the pattern of the predicted error would likely be similar to that shown in Figure 11.

6. CONCLUSIONS

We have explored two GPS-based strategies for tracking the geosynchronous TDRSS spacecraft. Direct tracking of the TDRSS spacecraft from the GPS constellation promises the greatest autonomy since no ground network is required. For this strategy, the primary impairment is the poor geometry—the TDRSS spacecraft must look down to find signals broadcast from GPS satellites on the other side of the Earth. The situation is exacerbated by sensitivity of the TDRS orbit accuracy to Selective Availability (SA), because measurements from the ground cannot be exploited to form differential observations which are free from these effects. In order to circumvent this difficulty, the TDRS-II satellites can carry military qualified GPS flight receivers which are designed to decrypt the degraded signals. Our results suggest that, equipped in this manner, a GPS receiver should be able to provide the TDRS positions autonomously to better than 15 m for routine 24-hour tracking. Implicit in this result is the assumption that nominal Department of Defense operations are maintained. Moreover, if this technique is adopted, the effects of the long GPS to TDRS transmission paths and near-Earth grazing need to be further examined.

An alternative approach relies on simultaneous tracking of TDRSS and GPS beacon signals from the ground. If accuracy is the prime concern, then this inverted technique is the best suited for tracking geosynchronous orbiters. However, the introduction of a ground network makes it less autonomous than its down-looking counterpart. For this study, we relied on a small number of current NASA GPS tracking sites and assumed that the receivers operating at those sites would be retrofitted to track TDRSS-II on 1 of the 8 channels that are normally reserved for GPS. Moreover, we assumed that the TDRSS-II spacecraft would be configured to broadcast continuously a suitable wide-beam beacon signal, preferably at Ku band to mitigate the effects of ionospheric refraction. Our results suggest that data collected at the ground sites introduces a robust differential observation geometry that promises to deliver few-m accuracies for TDRS with as few as 6 global stations. Smaller networks could still meet the 50-m TDRSS

accuracy requirement, but each satellite must be observed by a minimum of 3 stations that are moderately well distributed. The TDRSS-II orbit determination activities could be incorporated into routine GPS data processing that is currently done at JPL to support ongoing NASA programs. The mechanisms for near real-time operations are already in place, as the GPS data from these remote sites are transmitted to JPL on a daily basis for automated processing.

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