Low Earth Orbit Navigation in the Tracking and Data Acquisition System Era

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Several alternatives are addressed for meeting spacecraft orbit and time determination requirements in the 1990s with the proposed follow-on to the Tracking and Data Relay Satellite System. Key objectives are to reduce ground requirements for routine two-way tracking, support onboard navigation, and satisfy projected user accuracy goals down to 10 m (position) and 1 μs (time). This paper focuses primarily on three one-way range and Doppler tracking techniques based on 1) onboard processing of navigation beacon signals broadcast continuously, 2) onboard processing of scheduled tracking signals, and 3) ground-based processing of scheduled, user-generated tracking signals. System configurations and requirements to support each method are compared and preliminary results of navigation performance evaluations are presented as a function of user orbit, relay satellite constellation, and other parameters. Comparison of results with the accuracy requirements in a 1990-2005 mission model indicate that essentially all can be satisfied with beacon tracking based on projected reductions in key error sources. The scheduled tracking alternatives are also applicable except in low-altitude orbits where performance is more sensitive to drag uncertainty, tracking frequency, and/or navigation data upload rates.

Introduction

WITH successful deployment of the first spacecraft in the Tracking and Data Relay Satellite System (TDRSS), a new era is under way for supporting satellite tracking and data communication functions. By the 1990s, however, projected increases in scientific data volume and spacecraft engineering data will require extending TDRSS capabilities. With respect to navigation, NASA missions will require improved tracking and orbit determination in terms of speed, accuracy, and operational efficiency. Requirements are also expected to increase in certain cases for onboard, real-time navigation data (orbit, time, and attitude) to support mission operations (e.g., data annotation, antenna pointing, rendezvous).

Possible options for NASA to meet more stringent requirements in the 1990s range from deploying more Tracking Data Relay Satellites (TDRSs) and upgrading ground support capabilities to developing a new satellite and ground system. The heir to TDRSS for the 1990s and beyond is defined as the Tracking and Data Acquisition System (TDAS).[1,2]

A pre-Phase A TDAS concept definition study[3] covering a 15-year planning period, 1990-2005, has recently been completed. This paper addresses the TDAS-based alternatives identified for supporting user navigation functions: orbit and time determination. The following sections contain a discussion of TDAS navigation architecture goals, a description of the navigation alternatives considered, and some results of preliminary navigation performance evaluations. First, however, an overview is given of TDRSS capabilities, pertinent TDAS architecture options developed in the study, and potential user navigation accuracy requirements.

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TDRSS Overview

To meet expected user needs in the 1980s, NASA will utilize two operational TDRSs spaced 130 deg apart in geosynchronous orbits to relay data between mission spacecraft and the TDRSS ground terminal at White Sands (WSN). Data transfer between WSN and user facilities is provided by terrestrial and/or domestic satellite links. Multiple access (MA) channels are utilized for low data rate users ($\leq$50 Kbps) at S-Band. Single-access (SA) channels provide service for higher data rate users at S-band ($\leq$3 Mbps) or K_u-Band ($\leq$300 Mbps). The baseline TDRSS can accommodate simultaneously two MA forward link users (1 per TDRS), up to twenty MA return link users, and four SA forward and/or return link users (2 per TDRS).

The primary technique for both TDRS and user orbit determination (OD) via TDRSS utilizes ground-derived two-way range and/or Doppler (range-rate) data.[4] Coherent forward and return links are required during each scheduled tracking interval. As indicated in Fig. 1a, user tracking signals originate from and return to the WSN terminal which derives the measurement data. Orbit computations are performed by the Orbit Support Computing Facility (OSCF)† at Goddard which generates both definitive and predictive orbit data for user and network control center support (e.g., TDRS antenna pointing for user acquisition). The two-way technique could also support user time determination (TD) if onboard time tagging and return of signal arrival data is implemented.[5] User clock calibration parameters (bias, drift) may be estimated simultaneously in the OD process or separately once the orbit is determined.

An alternate tracking technique for user OD is available in TDRSS provided the user has a sufficiently stable onboard frequency standard. This is based on one-way Doppler (range-rate) only data acquired at the ground from user transmissions during scheduled return link service (see Fig. 1b). The advantage is that return links are more plentiful and easier to schedule than a coherent two-way link (e.g., 20 vs 2 for MA users). User time determination cannot be performed with this method alone, since range data are required.

†Recently renamed: Flight Dynamics Facility (FDF).

A variation of the one-way technique for user OD based on differenced Doppler data is also of potential interest. Tracking meaurements would be derived from return link transmissions scheduled when two TDRSs are simultaneously in view. Since differencing the received Doppler data effectively cancels user oscillator errors, oscillator stability requirements are not stringent. While demonstration flight tests are anticipated, eventual applications may be limited by high-stability oscillator availability and TDRSS operational considerations.

Another one-way tracking alternative for user OD may eventually be available with TDRSS. This involves onboard OD based on one-way Doppler measurements extracted during scheduled MA forward link service (see Fig. 1c). Ground tests are planned for 1985 to demonstrate the approach and associated user equipment enhancements: Doppler extractor, stable oscillator, and navigation computer (hardware/software).[6] Further developments will depend on test results and user initiatives.

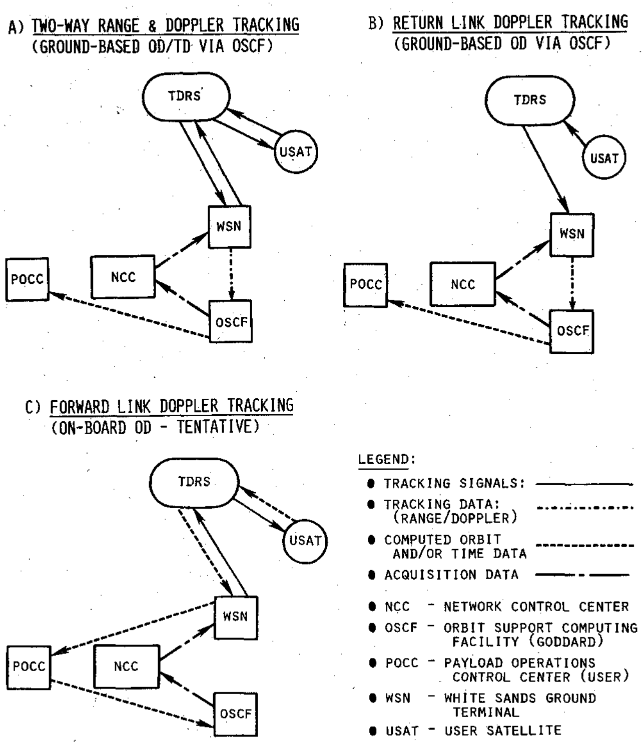


Fig. 1 TDRSS options for user navigation.

TDAS Architecture Aspects

Like TDRSS, TDAS is planned to support user communications, tracking, telemetry and control (TT&C), and navigation services. Design guidelines assume existing TDRSS services will continue, so that any transition to TDAS is transparent to users. At the same time, however, new or improved capabilities will be needed to support increased demands beyond 1990. This section reviews TDAS space segment and networking aspects pertinent to subsequent discussion of the navigation alternatives.

TDAS Spacecraft Enhancements

Candidate TDAS architectures were investigated for supporting user communications functions based on the following goals: 1) improve S-band MA service (number of channels/link margin), 2) provide user TT&C data directly to mission centers, 3) provide experiment control and mission data reception at user facilities (5 or more CONUS locations), 4) increase number of high rate accesses, 5) provide ultra-high rate access capability (>300 Mbps), and 6) 100% coverage. Achieving each goal would add a capability beyond that available with TDRSS. Study findings[3] indicate that all goals (excluding coverage) are realizable by including the following enhancements to TDRS capabilities on each TDAS spacecraft (see Fig. 2): 1) another forward link S-band MA channel, 2) onboard beamforming of the MA antenna, 3) multiple beam space/ground antenna and switch to serve five fixed and four selectable sites in the Contiguous United States (CONUS), 4) five SA channels at 60 GHz for ≤50 Mbps users, 5) one laser SA channel for >300 Mbps users, and 6) a TDAS-TDAS crosslink channel (laser or 60 GHz).

It was also determined that two TDAS spacecraft suitably deployed and with the above enhancements could meet communication requirements of NASA missions in the 1990-2005 period. Three satellites could meet potential communications requirements of NASA and applicable military missions.

TDAS Constellation and Networking Options

The TDAS constellation and supporting ground network are intricately related to user coverage and space/ground connectivity considerations. Three of the more important options are depicted in Fig. 3 with fixed ground sites indicated at Goddard, Houston, White Sands, Colorado Springs, and Sunnyvale for illustration.

Option I utilizes two operational spacecraft deployed as in TDRSS. This provides user coverage ≥85% down to 200-km altitudes and connectivity to both east and west CONUS terminals via a bilateral crosslink.

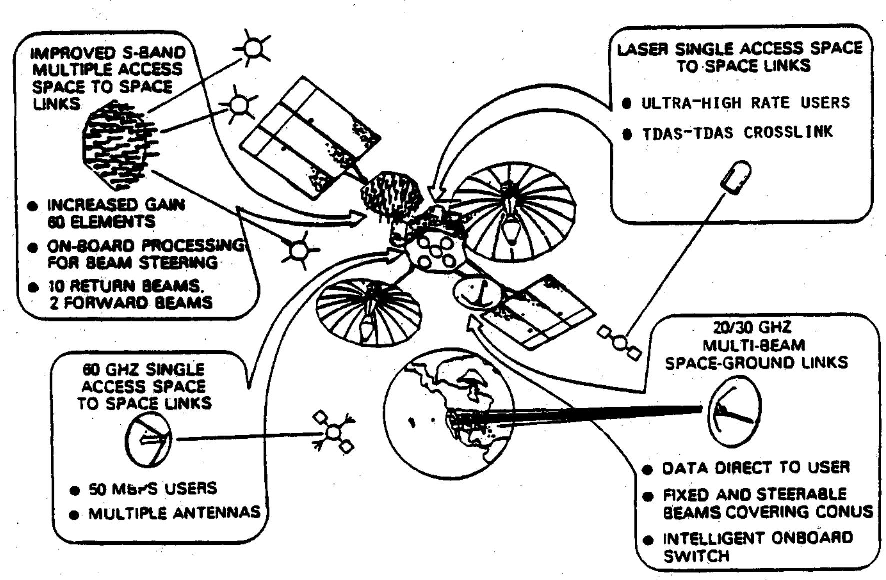


Fig. 2 Potential TDAS spacecraft configuration with laser crosslink.

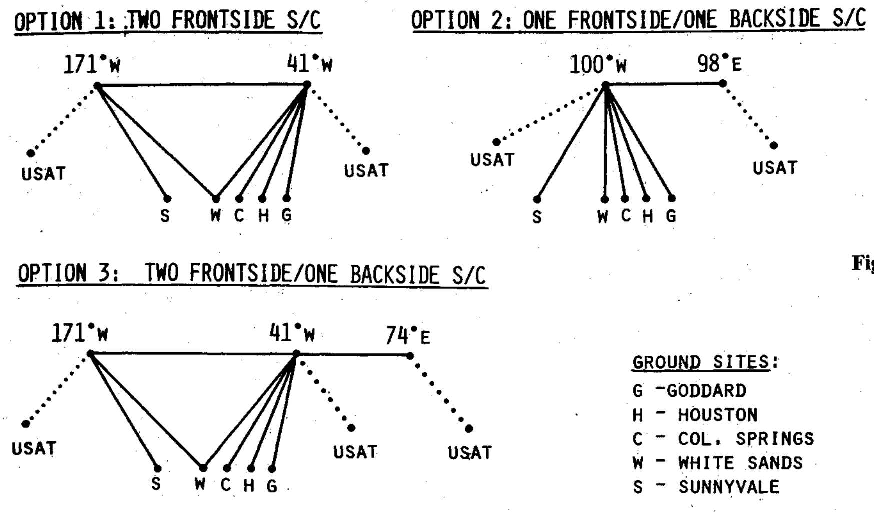


Fig. 3 Some TDAS constellation/network options.

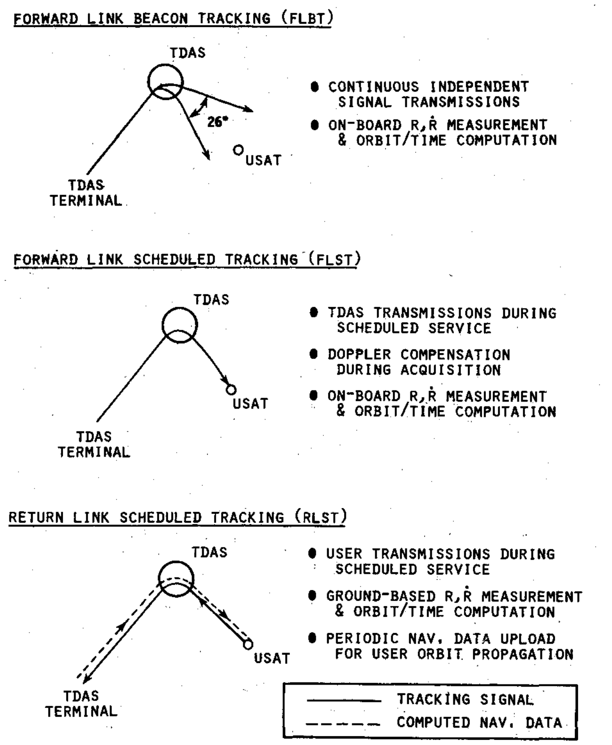


Fig. 4 TDAS one-way tracking alternatives—tracking signal and data handling interfaces.

Option II also utilizes two operational spacecraft but one is centrally located at 100 deg W and the other on the back side with the maximum possible spacing (162 deg) to support a crosslink. This provides better coverage (≥98%), connectivity through the front-side satellite to all CONUS sites and favorable elevation angles to mitigate rain attenuation effects. Crosslink traffic loading is asymmetric, since the heavier (return link) flow is from back side to front side.

Option III utilizes three operational spacecraft, two deployed as in Option I and one on the back side. This provides 100% coverage and better geometrical deployment for user tracking. Balanced loading of back-side return traffic is possible at the expense of maintaining crosslinks to both front-side satellites.

All three options will be compared below with regard to supporting user navigation as well as implications for TDAS satellite tracking.

User Navigation Accuracy Requirements for TDAS

To identify potential user types, a TDAS mission model was developed for the 1990-2005 time frame. Scenarios of experiments and missions were generated from a screened baseline of NASA plans. A flight schedule was established by assigning *planned* missions first, then *candidate* missions, and finally *opportunity* missions. Where planning information was unavailable, generic experimental missions were added based on trends established in the 1980s planning data and a comparable level of mission activity beyond 1990. Table 1 indicates the type and number of missions included in the model.

Corresponding navigation accuracy requirements for the model were developed from user community survey data, conservations with NASA contacts and/or independent estimates. Table 1 summarizes the position accuracy data by orbit class and mission type. Except for TOPEX-type missions the most stringent requirement is 10 m at altitudes at or above 400 km and 30 m below 400 km. For time accuracy the most stringent requirement was found to be 1 μs.

TDAS Navigation System Goals

Two goals were adopted for use in defining a TDAS navigation system architecture. These pertain to the user navigation techniques employed and the accuracy objectives:

1) Develop one-way techniques for user navigation: support onboard and ground-based options; reduce dependence on two-way tracking for *routine* support.

2) Meet accuracy requirements of TDAS mission model: user position accuracy—down to 10 m (1σ); user time accuracy—1 μs (1σ).

The TDRSS two-way tracking technique is still an option for the TDAS era; as a minimum in an orbit verification role since tracking signal generation, data measurement, and OD processing are all totally under ground control. Motivation for other alternatives to two-way tracking for routine support stems from the need for and complexity of acquiring and maintaining coherent forward and return links during each scheduled tracking interval.

Non-TDAS-based methods for spacecraft navigation (e.g., via the NAVSTAR Global Positioning System) are possible options which planners of future missions may certainly consider. The objective here, however, is to assess techniques which capitalize on the significant communications package investment which TDAS users would have, i.e., by utilizing or augmenting this capability with other elements to also support navigation functions.

User Navigation Alternatives Description

Three one-way tracking alternatives are identified for potentially supporting user navigation with TDAS. These are defined as (see Fig. 4): 1) Forward Link Beacon Tracking (FLBT)—independent navigation signal transmissions broadcast continuously by TDAS satellites provide tracking data for onboard OD/TD processing; 2) Forward Link Scheduled Tracking (FLST)—TDAS transmissions during scheduled contacts provide tracking data for onboard OD/TD processing; and 3) Return Link Scheduled Tracking (RLST)—user spacecraft transmissions during scheduled contacts provide tracking data for ground-based OD/TD processing.

Beacon Tracking (FLBT)

The beacon signal is assumed to be generated by a TDAS ground terminal for broadcast by each TDAS satellite using a single element of its 61 element S-band MA antenna array. The signal is modulated with a unique PN code (per satellite) from which users estimate range (R) data. Doppler tracking of the signal provides range-rate ($\dot{R}$) data. Signals are also modulated with ancillary data that provides, as a minimum, TDAS orbit and timing information (PN epoch, etc.) for synchronization purposes.

Typical link performance calculations were made assuming TDAS EIRP = 23 dBW (10-W output power and 13-dB gain/element) and user G/T = −22 dB/K (e.g., 0 dB antenna and 2 dB noise figure). Results show that the beacon signal could support ancillary data at 125 bps with a 10^{-5} bit error rate and a tracking measurement precision for R and $\dot{R}$ of 5 m and 5 mm/s, respectively.[3]

Users would receive continuous tracking signals while within a beacon antenna's ±13-deg field of view. The corresponding upper limit on user altitude for 100% coverage exceeds 3100 km for all TDAS constellations considered. Lower altitude coverage is governed by the zone of exclusion (ZOE) size, if any, for a given constellation.

In supporting multiple users simultaneously, adjustment of the transmit frequency during signal acquisition to compensate for Doppler shifting is not feasible. Doppler-aiding for signal acquisition/reacquisition would rely on orbit predictions from prior tracking periods and/or coordination with other tracking modes.

To perform OD/TD computations, the user would provide an onboard processor and appropriate software, most likely a sequential-type algorithm. Estimated parameters would include spacecraft position and velocity states, clock bias and drift, and possibly others (e.g., drag model terms). Parameter estimates are updated after each measurement or measurement set and propagated forward between measurements or during signal outages (such as a ZOE interval). The accuracy of an update will depend on the geometric quality of measurements and the validity of software models used to propagate prior estimates forward. In low-altitude (high-drag) orbits where modeling is sensitive, the availability of more frequent tracking data is precisely the potential benefit of beacon tracking over the scheduled techniques.

Scheduled Tracking (FLST, RLST)

In the scheduled modes, tracking signals are available only during an allocated contact period as part of normal MA or SA service. Each TDAS spacecraft can support 2 forward and 10 return MA channels at S-band and 8 (forward and return) SA channels: 2 at Ku or S-band, 5 at W-band (60 GHz) and 1 laser. Theoretically, with a two-satellite TDAS constellation up to 20 users with FLST and 36 users with RLST could be accommodated simultaneously depending on ground support capabilities and channel scheduling policy.

With FLST the tracking data is assumed to be derived from normal forward link transmissions. For example, using a TDRSS signal format for MA users[4] would provide PN modulated command and range channel (SQPSK) signals suitable for Doppler tracking and range estimation. Required ancillary data (TDAS orbit and timing information) are included on the command channel signal and decoded by the user. Signal acquisition is aided by the ground with Doppler compensation to limit received carrier frequency uncertainty. OD/TD computations are performed onboard in a manner similar to beacon tracking. In this case, however, intervals between estimated parameter updates tend to be significantly longer, so estimates propagated forward will be more sensitive to dynamic modeling uncertainties than with beacon tracking.

With RLST the tracking data are derived from ground-based processing of signals originated onboard the user spacecraft during scheduled return link contacts. PN signals, as used in TDRSS (e.g., DG1 Mode 2)[4] would be suitable, if appropriate ancillary data (user PN epoch, time reference, and a synchronization word for range ambiguity resolution) are included. A stable oscillator is required to provide an onboard frequency and time standard. Results of ground-based OD/TD computations can be arranged for direct use in supporting: state vector updates to user spacecraft for onboard orbit/time predictions between contacts, TDAS and mission control functions (e.g., antenna/beam steering, event scheduling, etc.), and orbit/time data archiving for subsequent experiment/mission analysis and data reduction.

Space/Ground System Interfaces

The multiple beam antenna and switch enhancements for TDAS spacecraft provide the capability for simultaneous, direct transmissions between the space segment and several ground stations. This provides possibilities for *direct* control of user spacecraft by a Mission Control Center (MCC) instead of interfacing through the Network Control Center (NCC) and White Sands (WSN) terminal as in TDRSS (see Fig. 1).

Table 1 Summary of TDAS mission model and position accuracy requirements

NASA mission types (1990-2005)	Position accuracy: Inc 28-70 deg	Position accuracy: Inc>70 deg	Alt, km
□ Astrophysics (12)[a]		30 M ■	
○ Solar			<400
terrestrial (4)	≥100 M □ ▲	≥100 M ▲	
△ Global			
environment (8)			
■ Resource	10-30 M ●	10-50 M ■ △	400
observation (7)	>100 M ○ □ ▲	≥100 M □ ▲	−800
● Meteorology (2)			
▲ Space			
transportation (6)	3 M (0.1 Alt) △[b]	≥100 M □ ● ▲	>800
■ Space station (1)	≥100 M ▲		

[a]( ) indicates number of missions in model. [b]Topographical experiment mission (TOPEX).

The NCC would retain sole responsibility for TDAS resource scheduling and coordination, e.g., user channel assignments and antenna pointing commands to WSN.

Figure 5 illustrates potential options for tracking signal and navigation data flow with each of the one-way alternatives. Since the beacon signal for FLBT is a general resource, it is assumed to originate at WSN, the assumed control point for TDAS spacecraft (see Fig. 5a). Navigation data computed onboard can be received by a TDAS ground terminal at the NCC directly and by MCCs with direct space/ground access. Additional interfacility transfer of data can occur to support MCCs without direct space/ground access or for system resource coordination and/or verification functions. The latter includes WSN which has control of TDAS spacecraft functions (e.g., antenna pointing for scheduled service support).

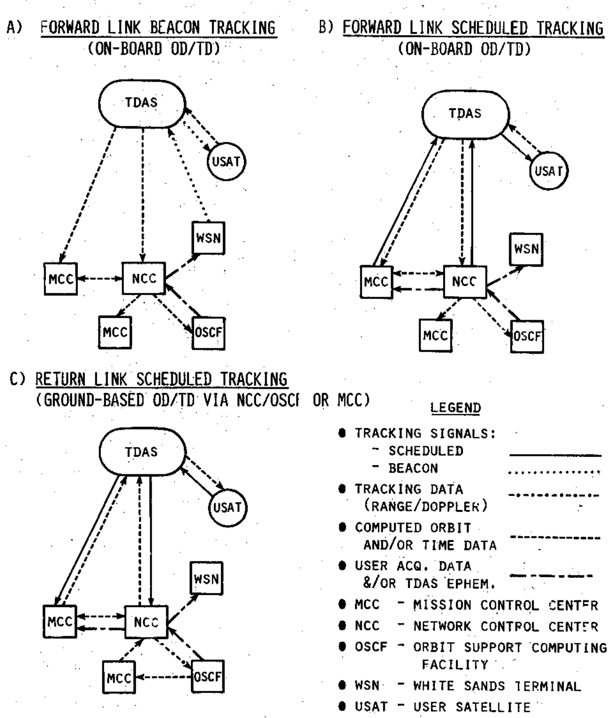


Fig. 5 One-way tracking alternatives for user navigation.

With FLST (see Fig. 5b) the user tracking signal is embedded in the normal uplink data communication traffic so it can emanate from a TDAS ground terminal at either the NCC or cognizant MCC site. Navigation data computed onboard can be distributed in the same manner discussed above for FLBT.

With RLST (see Fig. 5c) the user tracking signal is embedded in the normal downlink data communication traffic, so it can be received by a TDAS ground terminal at either the NCC or cognizant MCC site. Ground processing for user OD/TD can occur at the Orbit Support Computing Facility (OSCF) or at the MCC with subsequent interfacility data transfer as noted above. However, more study is needed to assess potential benefits and resource impacts, before allocation of any orbit computation functions between the OSCF and direct access MCCs can be recommended.

System Requirements

Table 2 lists pertinent requirements for both TDAS and user elements to support the one-way tracking alternatives. Corresponding requirements for two-way scheduled tracking (TWST) are also given for comparison.

Users need to augment the basic communications package (antenna/transponder) with the elements indicated in Table 2, either to derive and process the tracking data onboard (FLBT, FLST), or generate the tracking signals for ground-based tracking and updating (RLST).

Figure 6 shows the various elements and interfaces for a potential S-Band user configuration, not all of which are necessary, depending on the techniques employed.

Compared to the system enhancements for user communications support (see Fig. 2), requirements indicated in Table 2 for the tracking alternatives have a relatively minor hardware impact on TDAS. Only beacon tracking would require additional satellite hardware and power (<40 W raw dc). On the other hand, operational requirements to provide TDAS satellite tracking also need to be considered, particularly if a back-side satellite is involved. This is addressed in the next section on user navigation performance.

User Navigation Performance

To assess the potential navigation performance with each of the one-way alternatives, user OD/TD accuracy was evaluated as a function of various parameters and compared with requirements in the TDAS mission model.

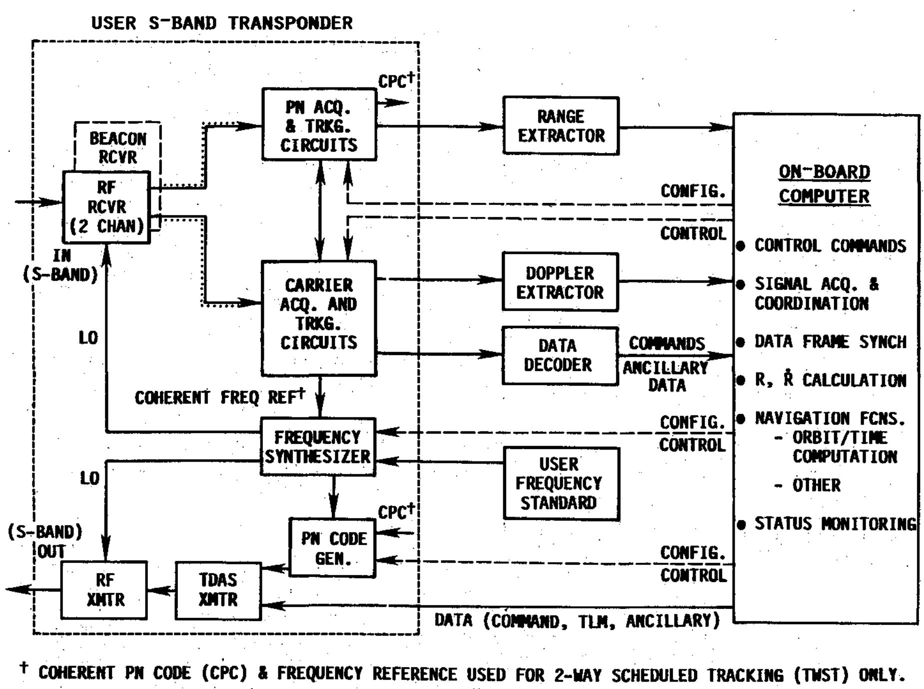


Fig. 6 Potential user equipment and interfaces for TDAS-based navigation support (S-Band example).

Table 2 Comparison of system requirements for alternate tracking techniques

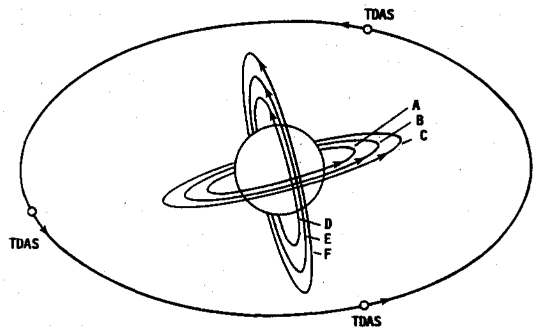
System element	System requirement	Tracking techniques FLBT	FLST	RLST	TWST
Ground	Scheduled tracking signal generation		✓		✓
	Beacon signal generation	✓			
	Ancillary data generation and transmission	✓	✓		
	R, Ṙ measurements			✓	✓
	User OD/TD[a] computation			✓	✓
	and NAV data upload			✓	
Space	Dedicated hardware:				
	K to S-Band repeater channel				
	and power amplifier	✓			
	MA antenna element	✓			
User	TDAS transponder		✓	✓	✓
	Additional receive-only channel	✓			
	Stable frequency standard	✓	✓	✓	
	R, Ṙ extractor	✓	✓		
	NAV data decoder	✓	✓	✓	
	Tracking signal and ancillary data generation			✓	
	Onboard computing facility:				
	Full OD/TD[a] computation	✓	✓		
	Orbit/time propagation only			✓	

[a]OD/TD = orbit determination and time determination.

User Orbits and TDAS Constellations

User orbit options considered are shown in Fig. 7. The low-altitude (high-drag) user orbit types are of interest to determine whether more frequent tracking data, available with FLBT, are of significant benefit. The high- and low-inclination orbit types are of interest since their coverage and geometrical properties can differ significantly.

TDAS constellations considered were those identified previously in Fig. 3. Option I is analogous to TDRSS with two satellites spaced 130 deg apart for 85-100% coverage at altitudes down to 200 km. Option II also uses two satellites, but with the maximum allowable spacing, 162 deg, for 98-100% coverage. Option III has three satellites, two deployed as in Option I and a third on the back side, which together provide 100% coverage.



USER ORBITS

TYPE	INCLINATION	ALTITUDE
A	28°	200 KM
B	"	600
C	"	1000
D	97°	200
E	98°	600
F	"	1000

Fig. 7 User orbits considered.

Tracking Schedules/Processing Algorithm

For the FLBT mode, metric tracking data $(R,\dot{R})$ were assumed to be measured whenever a selected TDAS was in view. For the FLST and RLST modes the schedule impact was assessed based on tracking measurements *every* orbit and *every other* orbit during a 10-min pass for each TDAS satellite. Navigation performance was evaluated assuming a sequential filter is used for processing the tracking data.

Error Modeling

User OD/TD errors were computed via covariance analysis programs given nominal TDAS and user orbits, a tracking schedule, processing algorithm, and appropriate models of the tracking error sources. The latter comprised measurement errors and various systematic errors, e.g., gravitational constant and harmonic modeling errors, drag modeling error, TDAS ephemeris error, and user oscillator drift effects. In the RLST mode, errors arising in the navigation data upload were assumed to result solely from ephemeris/time prediction errors. Possible additional errors due to data truncation or approximations to reduce upload requirements were not addressed.

Navigation Performance Results

Figures 8 and 9 summarize the user position and time accuracy characteristics in terms of the maximum error over 24 h for each tracking alternative and TDAS constellation option. Relevant user requirements identified in the TDAS mission model (see Table 1) are also indicated for comparison.

User *position accuracy* results in Fig. 8 illustrate that in low-altitude orbits where drag is a factor, performance depends heavily on frequent data availability. Beacon tracking is clearly superior in this respect. At higher altitudes this is not the case and all three tracking alternatives can give comparable performance.

With respect to the various TDAS constellations, Option III gives typically better performance due to better geometric distribution of the tracking data available with three satellites. In the two satellite constellations, Option I with (130-deg spacing) is better in the high-inclination orbits, while Option II (with 162-deg spacing) is better in the low-inclination orbits. Although Option II provides nearly full coverage (≥98%), the performance for high-inclination users is sensitive to poor geometry conditions for Doppler tracking. This occurs twice a

Table 3 Error contributor summary for beacon tracking (sequential data processing)

Error contributor	Modeling assumptions for analysis	Orbit determination impact for 40 m accuracy	Projected requirements for 10 m accuracy[a] 30 m accuracy[b]	Comments
Gravitational harmonics model	100% Gem-9[c] error (12×12)	Major	20% Gem-9[c] error	≥10:1 improvement anticipated by early 1990s
Drag coefficient (C_D) (<600 km orbits)	2.5% of nominal C_D (residual error)	Secondary	Same as model	Optimize processor tuning parameters
TDAS orbit error	50 m position 5 mm/s velocity	Secondary	25 m position 2.5 mm/s velocity	Minimal BRTS[c] configuration cannot meet projected requirement VLBI[c] tracking meets projected requirement
User oscillator drift	10^{-10}/day	Negligible	Same as model	Currently available capability

[a]98 deg, 600 km orbit; [b]98 deg, 200 km orbit; [c]GEM-9 = Goddard Earth Model 9 (1979), BRTS = Bilateration Ranging Transponder System; VLBI = Very Long Baseline Interferometry

Table 4 Summary of proposed TDAS navigation functions

User support function		Proposed technique	Rationale
	Routine	Beacon tracking	Maximum availability Meets requirements
Onboard navigation	Initial acquisition	Scheduled tracking (forward link)	Doppler compensation available
Onboard navigation	Backup	Scheduled tracking (forward link or 2-way)	Provide redundancy via communication channels
Onboard navigation	Verification	Scheduled tracking (2-way)	Ground-based operations Quality control
Ground-based navigation	Routine	Scheduled tracking (return link)	Scheduling flexibility
Ground-based navigation	Backup	Scheduled tracking (2-way)	Provide redundancy via communication channels
COMM/NAV	TDAS antenna pointing	Scheduled tracking (return link) or beacon tracking	Ground-based operations Accuracy sufficient Direct downlink to NCC

day when the user orbit normal points in the general direction of each TDAS. Consequently a tradeoff may exist between maximum TDAS spacing (162 deg) for best coverage and lower spacing to achieve better OD performance.

User *time accuracy* results in Fig. 9 indicate that TD performance is uniformly better with beacon tracking (≤ 0.25 μs) than with scheduled tracking in all four orbits. Nevertheless, performance with the scheduled alternatives is sufficient to meet the most stringent user time requirement (1 μs) identified in the TDAS mission model.

Analysis of error sources affecting OD accuracy indicates that in the high-inclination, high-altitude orbits (98 deg, 600/1000 km) gravitational harmonic modeling uncertainty is typically the dominant error contributor. This is also the case at low altitudes with beacon tracking since filter tuning (adjusting filter gains to deweigh prior estimates, i.e., filter memory control) acts more to suppress the drag contribution. At low altitudes with scheduled tracking, drag is the dominant contributor in all cases. TDAS ephemeris error is typically a secondary contributor.

Table 3 lists the baseline modeling assumptions made for some particular error sources and their relative impact on achieving a 40-m OD accuracy with beacon tracking in the user orbits considered. Analysis of user accuracy requirements in the TDAS mission model indicate that most would be met with beacon tracking and in many cases with scheduled tracking based on error analysis results using the assumed models. Meeting the more stringent requirements would imply some improvement in key error sources. In Table 3, the projected requirements indicate the gravitational model improvement required (in terms of GEM-9 errors) to achieve 10-m and 30-m accuracies in the noted orbits. (Significant improvements (≥10:1) over GEM-9 are anticipated from the Gravitational Research Mission (GRM) planned originally for a late 1980s launch.[7]) At this level the modeled TDAS ephemeris error would also become significant so a reduction of ~2:1 is indicated.

Observations

Analysis of the above results leads to the following key findings.

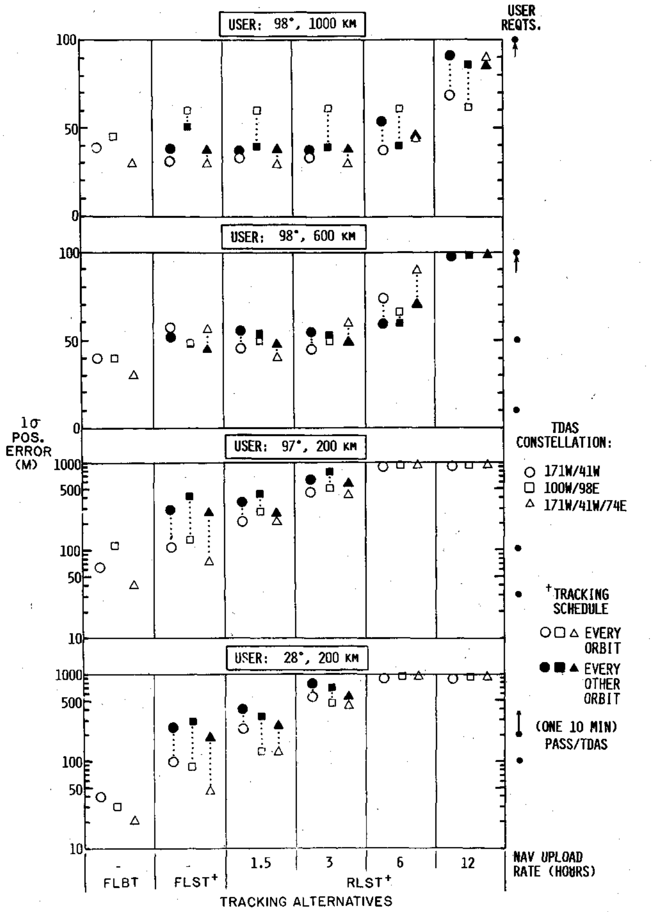


Fig. 8 User position accuracy vs TDAS one-way tracking alternatives.

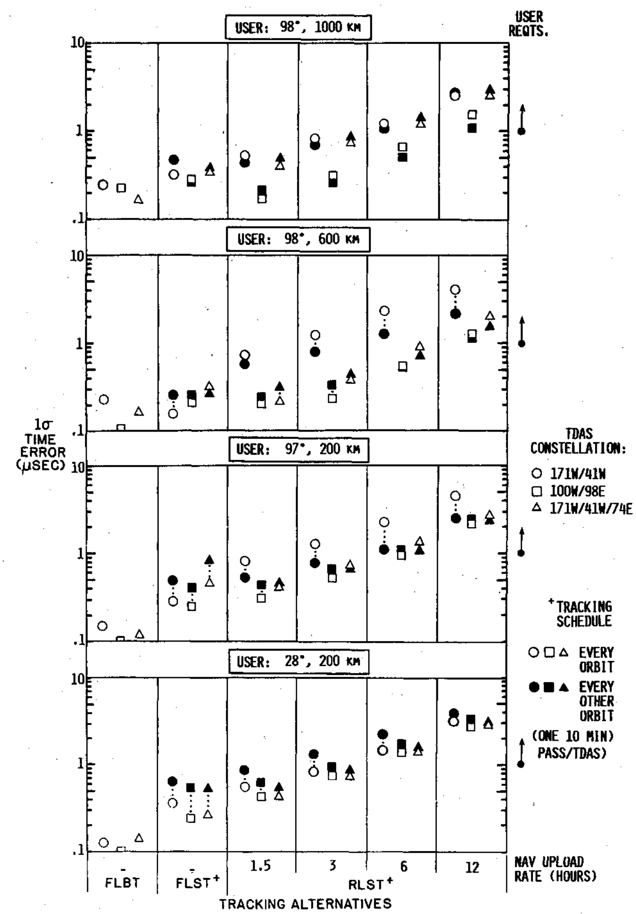


Fig. 9 User time accuracy vs TDAS one-way tracking alternatives.

Performance projections indicate that TDAS beacon tracking (FLBT) can satisfy all users in the TDAS mission model (see Fig. 2) with position accuracy requirements down to 10-m.

Scheduled tracking alternatives (FLST, RLST) can also meet the accuracy requirements except at low altitudes where performance is highly sensitive to: drag uncertainty, frequency of tracking passes, and/or frequency of navigation data uploads (RLST/only).

A two- or three-satellite TDAS constellation impacts performance as follows: 1) Selecting two satellites leads to a tradeoff between coverage and accuracy. Increased satellite spacing beyond 130 deg improves coverage, but a point is reached where performance in high-inclination orbits begins to degrade. 2) Selecting three satellites provides full coverage and up to a 2:1 advantage in navigation accuracy over two satellites.

Projected tracking accuracy requirements for TDAS spacecraft (25-m position and 2.5-mm/s velocity) are significantly more stringent than present TDRS tracking capabilities using the Bilateration Ranging Transponder System (BRTS).

TDAS Satellite Tracking Considerations

TDAS orbit data are needed to support user OD/TD operations on a recurring basis. Navigation performance is a function of TDAS orbit uncertainties in the interval between updates, i.e., prediction errors resulting from the tracking process.

For TDRS OD, automated transponders at surveyed sites (two per TDRS) are interrogated during regularly scheduled MA service intervals to obtain two-way range and Doppler measurements at WSN. Error analysis studies indicate that TDRS position uncertainty over a 24-hour prediction interval is at the 100-m level or above depending on the data span and other tracking parameters.

As observed above, the projected accuracy requirement for TDAS tracking is more stringent (~4:1). Furthermore, both front-side and back-side satellites may be involved depending on the constellation configuration. With BRTS, two-way ranging to a back-side station involves signals relayed via the crosslink. This impacts tracking accuracy, since measurements are affected by uncertainties in the front-side satellite orbit as well.

Very Long Baseline Interferometry (VLBI) techniques have been suggested as a possible BRTS enhancement or eventual replacement. With this approach the basic tracking data type is equivalent to the difference in range (ΔR) between a signal source (TDAS satellite) and two receivers displaced along a known baseline. Tracking signals received by at least three stations (≥ 2 baselines/satellite) are collected and cross-correlated to generate VLBI observation data (ΔRs). For a back-side satellite, crosslink uncertainties are not a factor due to the inherent differencing of common path components.

Results of a covariance analysis of TDAS tracking indicate that[3]: 1) OD errors for back-side satellite tracking via BRTS are significantly higher (~2-3:1) than for front-side satellite tracking (≥ 100 m) based on the minimum configuration (two sites/satellite); and 2) VLBI tracking offers the potential for significantly improved TDAS orbit accuracy (< 10 m) for both front- and back-side satellites.

Realization of the VLBI capability is contingent upon achieving subnanosecond time synchronization between stations, and ΔR measurement precision and baseline calibrations at the centimeter level.

Concluding Remarks

TDAS-based alternatives for supporting user navigation in the 1990s have been discussed in terms of system requirements for both TDAS and users (see Table 2). The hardware impact on TDAS is relatively minor; only beacon tracking adds slightly to satellite hardware and power requirements. Users may augment their basic communications package with other elements identified in Table 2 depending on the technique(s) employed. Figure 6 shows a possible integrated comm/nav configuration applicable to S-Band users.

Results of preliminary navigation performance evaluations were presented for representative user orbits and TDAS constellation options and compared with accuracy requirements in the TDAS mission model. Performance projections based on reductions in key error sources indicate that all can be satisfied with beacon tracking except for TOPEX-class mission requirements. The scheduled tracking alternatives are also applicable except in low-altitude orbits where performance is more sensitive to drag uncertainty, since tracking contacts and/or navigation data updates are less frequent.

Based on the study results, beacon tracking is recommended as the prime approach to pursue for routine onboard navigation support. Scheduled tracking alternatives, one, and two-way, should also be considered for supporting user navigation functions, as proposed in Table 4. In summary, the TDAS navigation system architecture should accommodate all of the one- and two-way tracking techniques.

Various technical considerations emerged from this initial TDAS study that warrant further investigation. Three significant areas, each with some major objectives, are:

1) TDAS tracking alternatives evaluation. Assess techniques that may support front-side and back-side satellites, meet projected 25-m accuracy requirements, and minimize/avoid foreign tracking stations.

2) Gravitational harmonic modeling. Define orbit determination software requirements to support a projected 10-m accuracy capability and identify potential improvements without a Gravitational Research Mission (GRM) by the 1990s.

3) Beacon signal specification. Define baseline signal format and identify any utility for other applications (e.g., TDAS tracking, emergency data link).

Analysis of these and other issues is part of a continuing effort to identify and assess the technical impacts and requirements to support the proposed TDAS-based navigation services.

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