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TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS) SUPPORT OF USER SPACECRAFT WITHOUT TDRSS TRANSPONDERS

James A. Jackson*, Greg C. Marr‡, Michael J. Maher †

NASA GSFC VNS TSG personnel have proposed the use of TDRSS to obtain telemetry and/or S-band one-way return Doppler tracking data for spacecraft which do not have TDRSS-compatible transponders and therefore were never considered candidates for TDRSS support. For spacecraft with less stable local oscillators (LO), one-way return Doppler tracking data is typically of poor quality. It has been demonstrated using UARS, WIND, and NOAA-J tracking data that the simultaneous use of two TDRSS spacecraft can yield differenced one-way return Doppler data of high quality which is usable for orbit determination by differencing away the effects of oscillator instability.

INTRODUCTION

A proposal was made for using TDRSS to support users that do not have TDRSS compatible transponders[1]. Commensurate with this proposal, it was further proposed to use Differenced One-way Doppler (DOWD) to provide metric data usable for orbit determination (OD), for these users who normally will not have a local oscillator (LO) stable enough to be used for OD. This paper will discuss this proposal and the results of tests associated with the proposal, which emphasizes use of the existing user support segment (USS) at the Second TDRSS Ground Terminal (STGT) and the upgraded White Sands Ground Terminal (WSGT). This paper does not cover the ongoing efforts to use the Intermediate Frequency (IF) coupler at STGT, or using the Gamma Ray Observatory (GRO) Remote Terminal System (GRTS).

TDRSS was designed primarily to support low earth orbit (LEO) users that have transponders that radiate and can also demodulate Pseudo-noise (PN) spread spectrum[2]. This not only allows for the use of the multiple access (MA) services, if the user transmits at 2287.5 MHz and receives at 2106.5 MHz, it also keeps the flux densities low. Although this is most common mode of using TDRSS, also referred to as the Space Network (SN), it has been used to support other activities other than spread spectrum users. The evolution of using the SN for such non-standard support leading up to the present demonstrations is depicted in table 1.

* Head, Vehicle and Network Section (VNS), Code 553.3, Flight Dynamics Division (FDD), NASA Goddard Space Flight Center (GSFC), Greenbelt, Maryland, USA 20771.

‡ Aerospace Engineer, VNS, Code 553.3, FDD, GSFC, Greenbelt, Maryland, USA 20771.

† Project Engineer, Allied Signal Technical Services Corporation (ATSC), Tracking Support Group (TSG), Goddard Corporate Park, Lanham-Seabrook, Maryland 20706

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GREG MARR
NASA GSFC 552
(301) 286-7749
GREG.MARR@GSFC.NASA.GOV

Table 1
EVOLUTION OF SN SUPPORT OF USERS WITHOUT COMPATIBLE TRANSPONDERS

Activity	Dates	Achievements
Orbiting VLBI (OVLBI)	May 1986 - March 1988	Used IF Services to collect Wideband phase data from Quasars which was correlated with ground based VLBI observations. Full ellipse SA gimbal exercised.
COBE DG2 Testing	August- September 1986	Demonstrated use of non-spread (DG2) return link at low data rates.
Galileo Perigee 2 TDRSS Support	December 8, 1992	Used OVLBI IF configuration to track transmitted carrier to obtain Doppler. Also tracked carrier using DG2 to obtain Doppler Data. Full ellipse SA gimbal exercised.
TOMS/SN RF SOC Testing	April 1994 - June 1995	Used DG2 to acquire TLM subcarrier and Doppler data. TLM forwarded to POCC. STGT capability demonstrated
UARS Differenced Doppler Tests	May 1994	Demonstrated feasibility of using Differenced Doppler with TDRSS
Centaur/K9	August 27, 1994	Used DG2 to provide TLM modulated on the carrier, and Doppler data.
WIND SN Support	November 1, 1994	Tracked carrier using DG2 to obtain Doppler and Differenced Doppler. Full ellipse SA gimbal exercised
NOAA-J SN Support	December 30, 1994	Tracked carrier using DG2 to obtain Doppler and Differenced Doppler. STGT capability demonstrated. OD using Differenced Doppler comparable to C-band radar OD.
Centaur/K23	May 14, 1995	Used DG2 to provide TLM modulated on the carrier, and Doppler data. Tracked to geosynchronous altitude on opposite side of earth. Performed 20 frequency updates to maintain acquisition.
Centaur/K19	July 10, 1995	Demonstrated 40 kHz expanded frequency uncertainty modification
IUS/TDRS-G	July 13, 1995	Used DG2 to acquire TLM subcarrier and Doppler data. TLM recorded at STGT. 3-way Doppler with the SN also demonstrated.

What had prompted these proposals was that there were missions, such as Clementine, that had no communications or tracking for hours after launch. During this early-orbit phase, the spacecraft (S/C) was in view of the SN, but because it carried a Deep Space Network (DSN) compatible transponder, the SN was not considered for use. Although the SN was never used for Clementine, the proposal did get consideration for later missions. After meeting with the RF Systems Branch, GSFC Code 531, it was decided to run several tests, and use the Total Ozone Mapping Spectrometer/Earth Probe (TOMS/EP) for the first demonstration in conjunction with a similar effort to acquire telemetry (TLM) with a special receiver tapping the 370 MHz IF. An existing SN user was to be used to obtain simultaneous Doppler data to demonstrate the capability to process and use DOWD for OD. The RF Simulation Operations Center at

GSFC would be used to conduct feasibility testing of the SN tracking a signal emulating TOMS/EP. Because of the failure of the first Pegasus/XL launch vehicle, the launch of TOMS/EP slipped from the tentative launch in July 1994 to August 1995.

Due to the failure of the second Pegasus/XL, TOMS/EP is on hold, indefinitely. Subsequently, WIND SN support was requested , which, after that successful support, lead to a request for NOAA-J SN support. Although unrelated to this proposal[1] , SN support of expendable launch vehicle (ELV) upper-stages was also being successfully demonstrated, starting with Centaur /K9 on August 27, 1994. The similarity of the ELV support to the proposed support , not only warrants recognition, herein, but as will be explained later, the SN ELV support demonstrated the telemetry subcarrier tracking demodulation technique proposed[1] , and further evolved SN support capabilities for other users without "TDRSS compatible" transponders .

PREREQUISITES FOR CANDIDACY FOR NON-STANDARD SN SUPPORT

In order to determine candidacy for this support, the first prerequisite is that the transmit frequency must be 2200 to 2300 MHz. If the TLM modulation is Phase Shift Keyed (PSK), then it may be possible to get TLM, provided there is sufficient effective isotropic radiated power (EIRP) for the given symbol rate. If the TLM is modulated on a subcarrier, then either the upper and lower subcarrier would be tracked directly, which will mean a relative 2.5 dB loss will result as compared to receivers designed to discriminate and pre-detection combine the subcarriers. Doppler data will also result, if scheduled. The SN Scheduling Orders (SHO) configurations for each TLM modulation case, is outlined in table 2. Note that the "2-way" cases in table 2 are proposed[3], and have not been attempted. If differenced Doppler is desired , then simultaneous return link services (RTN) from 2 non-collocated (East and West) TDRSS's will have to be scheduled. In order to transmit to the 2 TDRS's which will require a large transmit aspect angle, it will usually require an omni antenna, and if 2 omni antennae are available, radiating from both would be optimal. Often, this is the case with early-orbit users and as a result, will cost the user in terms of the EIRP. Because the EIRP is relatively low for SN TLM support, use of lowest available symbol rate available would be desirable for TLM support. Although the signal margin may be too low to consider TLM demodulation, then carrier only Doppler tracking may be still be possible.

The constraints for user support by the Space Network (SN) are outlined[2] for compatible SN Users. Although most of the support elaborated herein is not covered, many of the user constraints[2] still apply. The user should have a good knowledge of the transmit, and if applicable, the receive S-band center frequencies of the S/C communications subsystem. There is a constraint that the user center transmit or SHO return frequency (F_{rtn}) and, if applicable, receive center frequencies should be specified to the SN within 700 Hz, to insure a 0.9 probability of acquisition if the effective isotropic radiated power (EIRP) is adequate to meet the achievable data rate (ADR). For cases that the uncertainty is unknown or exceeds 700 Hz, for 3-way tracking, or for the proposed 2-way tracking of a subcarrier, then an Expanded Frequency Uncertainty Message will need to be sent immediately after each service start . The user must supply the Network Control Center (NCC), usually via or from the Flight Dynamics Facility (FDF), state vectors to an accuracy of within 9 seconds of the propagated state. The user must schedule the desired coverage via the NCC. The user services described herein are all single access (SA), and the return services are Data Group (DG) 2. Although, all of the activities described herein are for S-band SA (SSA), K-band SA (KSA) may also be possible, although no such support using KSA services has ever been tested. The user must establish a data interface with the NASA Communications Division (NASCOM). The SA services are normally constrained to a 14 degree (east-west) x 14 degree (north-south) "box". If requested and approved prior to support, the SA gimbal constraints can be extended up to a 22.5 (east-west) x 31 degree (north-south) ellipse.

Table 2
SN SUPPORT CONFIGURATIONS AND POTENTIAL DATA

TLM Modulation	SHO Setup	Possible Data	Comments
PSK on carrier	RTN:SSA DG2, Mode 2, F_{rtn} at carrier, Data rate, format and coding per user TLM configuration. TRK:1 way Doppler	TLM, 1-way Doppler	TDRSS DG2 compatible. Contact NASA Code 531.1 to determine link margin.
PSK on subcarrier	RTN:SSA DG2, Mode 2, F_{rtn} at either subcarrier, Data rate, format and coding per user TLM configuration. . TRK:1 way Doppler.	TLM, 1-way Doppler	Relative 3 dB loss(no combining). Contact NASA Code 531.1 to determine link margin.
Other modulation on subcarrier , or PSK with insufficient link margin	RTN:SSA DG2, Mode 2, F_{rtn} at carrier, Data rate 1 kb/s, single channel, no coding, NRZ-L format. TRK:1 way Doppler.	1-way Doppler	Return service set up for carrier Doppler tracking only. Contact NASA Code 531.1 to determine link margin.
PSK on carrier	FWD: SSA, PN Off, No Mod(CW), Doppler Comp On* RTN:SSA DG2, Mode 1, F_{rtn} at carrier, Data rate, format and coding per user TLM. configuration. TRK:2 way Doppler	TLM, 2-way Doppler*	*Proposed: not demonstrated. TDRSS DG2 compatible. Contact NASA Code 531.1 to determine link margin.
PSK on subcarrier	FWD: SSA, PN Off, No Mod(CW), Doppler Comp On* RTN:SSA DG2, Mode 2, F_{rtn} at either subcarrier, Data rate, format and coding per user TLM. configuration. TRK:2 way Doppler.	TLM, 2-way Doppler*	*Proposed: not demonstrated. Relative 3 dB loss(no combining). Must use RTN frequency sweep. Contact NASA Code 531.1 to determine link margin.
Other modulation on subcarrier , or PSK with insufficient link margin	FWD: SSA, PN Off, No Mod(CW), Doppler Comp On* RTN:SSA DG2, Mode 1, F_{rtn} at carrier, Data rate 1 kb/s, single channel, no coding, NRZ-L format . TRK:2 way Doppler.	2-way Doppler*	*Proposed: not demonstrated. Return service set up for carrier Doppler tracking only. Contact NASA Code 531.1 to determine link margin
Other modulation on carrier	N/A	N/A	Not a candidate for normal RTN acquisition Must use IF for TLM

SUMMARY OF TEST RESULTS

Galileo Tracked by TDRSS

On December 8, 1992, Galileo had its second earth encounter for its final gravity assist to provide the trajectory to Jupiter. The Galileo Radio Science Team had successfully acquired the carrier for Doppler tracking using TDRSS Intermediate Frequency (IF) SSA Return Services to monitor the Doppler during this phase[5] . The technique used was derived from a proven method used to conduct Orbiting Very Long Baseline Interferometry (OVLBI) using TDRSS, which was successfully performed from 1986 through 1988 [6,7,8] . Additionally, SSA DG2, mode 2, return link services with a 1 kb/s data rate in conjunction with one-way Doppler tracking services were scheduled using TDRS-4 (East)[1]. Carrier acquisition was obtained providing good Doppler data. Carrier-to-Noise Density (C/N_0) was estimated to be from 51.7 dB-Hz to 53.2 dB-Hz using the measurements from the concurrent IF service[5]. This Doppler data was used to perform Differential Correction (DC) used to determine the heliocentric trajectory of the Galileo Spacecraft, in addition to solving for the Galileo transponder ultra-stable oscillator (USO) bias.

UARS DOWD Demonstration

At the request by the Vehicle Network Section (VNS), GSFC Code 553.3, the UARS project scheduled simultaneous return-link and 1-way Doppler Tracking services from TDRS-4 (East) and TDRS-5 (West) on May 3, 5, 7, 9, 11, 13, and 15, 1994. The simultaneous Doppler data was then processed as DOWD. The OD capability of the DOWD was then assessed. The Doppler data collected for each event was only 5 to 7 minutes long. These short spans were not sufficient for reliable orbit determination (OD) using only a single pass. Longer arc's of 48 hours or multiples of 48 hours, were accomplished by using combinations of the DOWD events. These longer arcs provided more reliable OD, than the single event solutions, which will be explained in more detail later.

TOMS/SN RFSOC Testing

In preparation to support TOMS/EP with the SN, the Radio Frequency Simulation Operations Center (RFSOC) at GSFC was used to test the techniques proposed for SN support. The RFSOC had radiated to TDRS-4 (East) , a signal emulating TOMS/EP in both modulation and expected EIRP of 2.1 dBW. The SN obtained subcarrier lock, directly demodulating the PM/PSK subcarrier, obtaining good symbol synchronization, and obtaining valid Doppler tracking data. This was first tested using the WSGT Wide Dynamic Demodulators (WDD) in March and September 1994. Successful subcarrier tracking using the STGT Integrated Receiver (IR) was performed using the RFSCOC on April 11 and 13 and on June 1, 1995. Symbol synchronization and good Doppler data were obtained from all testing. Carrier-to-Noise Density (C/N_0) estimates from the IR in the Operational Data Messages (ODM) were 44.5 to 44.8 dB-Hz, and then measured to be 49.6 dB-Hz on April 11, 1995 for the EIRP of 2.1 dBW. Threshold was then obtained by attenuating the signal down to an estimated C/N_0 of 39.6 dB-Hz, and exhibiting a bit-error rate (BER) of 10^{-4}. Furthermore, during the testing in September 1994 and June 1995, simulated TLM data modulated through the RFSOC was forwarded to the TOMS/EP Payload Operations Control Center (POCC).

WIND SN Support

On November 1, 1994 the SN supported WIND shortly after the transfer trajectory insertion (TTI) maneuver to a Highly Elliptical Orbit (HEO). SSA DG2, mode 2, return link services with a 1 kb/s data-rate in conjunction with one-way Doppler tracking services were scheduled simultaneously for carrier Doppler tracking using TDRS-4 (East) and TDRS-5 (West), which were supported through WSGT. Additionally, similar services were scheduled using TDRS-6 to test out the capabilities using STGT. Carrier acquisition with valid Doppler data was obtained by TDRS-5 at 10:59:16 GMT, and then by TDRS-4 at 10:59:44 GMT. Carrier lock and valid Doppler tracking via both TDRS's were maintained until 11:16:33 GMT, when the spacecraft went to coherent mode with an uplink from DSS-16, the 26 meter Deep Space Network (DSN) station at Goldstone, CA. Because the Doppler correction required for the WDD at WSGT could not model the translated uplink from any ground station, the unmodeled Doppler caused these receivers to drop lock, and was never re-acquired. The EIRP was estimated to be -5.0 dBW. The analytical estimate of the C/N_0 was 39.6 dB-Hz. The TDRS-6/STGT support failed because the SA antenna elevation limits were expanded to +22.5 through +22.5, thus restricting it to a linear track at that elevation and not obtaining the signal in the SA boresight.

NOAA-J SN Support

On December 30, 1994, the SN supported NOAA-J shortly after ELV separation. The SN was scheduled for carrier only Doppler tracking similar to that of the WIND support, except for the frequency and the TLM format. TDRS-3 (Spare/West) and TDRS-4 (East) were supported through WSGT and STGT, respectively. The EIRP for NOAA-J was estimated to be +0.1 dBW. The RTN link format was specified to be Bi-Phase level, commensurate with the TLM format. Carrier acquisition with valid Doppler data was obtained by TDRS-3 at 10:17:07 GMT, 7 seconds after service start, and maintained lock until 10:51:20 GMT, when occultation occurred. However , the TDRS-4 support did not acquire until the TLM format was reconfigured from Bi-phase level to non-return-zero level (NRZ-L). Subsequently, TDRS-4 acquired the carrier, and provided good Doppler starting at 10:57:41 GMT, and except for a dropout spanning less than 180 seconds, continued to track the carrier providing good Doppler until RF occultation and service end at 12:30:00 GMT. The TDRS-3 second service start occurred at 11:28:30 GMT, but did not acquire until after the frequency was respecified for a -8 kHz shift due to the oscillator drift, after which the carrier was acquired, providing good Doppler at 11:30:07 GMT. After The TDRS-4 second service start and also after the frequency was respecified, the carrier acquired providing good Doppler at 11:43:43. This was when both TDRS's had valid Doppler, thus providing the conditions for DOWD, and when the data arc's for DOWD solutions began. TDRS-4 was occulted 11:55:10. TDRS-4 acquired again shortly after occultation , providing good Doppler and DOWD starting at 12:18:46. TDRS-3 service was terminated just prior to occultation at 12:29:57 GMT, which also ended the DOWD data arc. TDRS-4 continued to maintain carrier track until the end of the service at 12:40:30. The Operational Data Messages (ODM) from STGT provided estimates of the C/N_0 ,which ranged from 41.6 dB-Hz through 44.6 dB-Hz for the TDRS-5 support. This test not only demonstrated the DOWD capability, but it also demonstrated that the STGT IR's can provide carrier only tracking support. Previous carrier-only/Doppler tracking support had been performed using the WSGT WDD's, which have since been phased-out at the beginning of 1995 for the WSGT upgrade. It is not known why the Bi-phase level format worked for the WSGT WDD, but did not work with the STGT IR. It possibly may have been that the IR was expecting the data transition and that the WDD did not "care". It may be that the WDD had a lower acquisition threshold for the carrier tracking only case. Bi-phase formats double the bandwidth, and hence, reduce the signal margin by 3 dB. Scheduling carrier only support, renders the TLM format, coding, bit-rate input scheduling parameters as arbitrary. Therefore, in order to enhance acquisition for carrier only tracking, these TLM parameters should be scheduled to obtain the lowest symbol-rate possible: the lowest data rate (1 kb/s for DG2), no coding, and NRZ format.

Centaur/K23 SN Support

The SN supported the launch of Titan Centaur/K23 on May 14, 1995 from 11:00 GMT through 19:58 GMT, as part of testing to determine if the SN can replace ARIA (tracking aircraft) support of the Centaur upper stage. The Centaur TLM is BPSK modulated on the carrier, hence, it is TDRSS compatible. The Doppler data was monitored by the FDF to determine the Centaur transmitter local oscillator frequency (LOF) within acquisition range. The frequency varied by a magnitude of 20 kHz during a period of 6 Hours, which resulted in 20 frequency respecifications for the return link to maintain within acquisition range. The simultaneous Doppler was not referenced to the same frequency, so the resulting DOWD had a large bias roughly equal to the SHO frequency difference. The Centaur was tracked to geosynchronous altitude, at a distance over 80,000 km. from TDRS-4, and providing good quality TLM

(BER < 10^{-5}) forwarded to the Air Force Satellite Control Facility (AFSCF) , Sunnyvale, CA. As a result of the frequency related problems, STGT engineering personnel incorporated a modification to the IR, that would allow for a +/- 40 kHz expanded frequency search option for the signal for DG2 RTN services, as compared to the previous +/- 3 kHz expanded frequency search option.

Centaur/K19 SN Support

The SN supported the launch of Titan Centaur/K19 on July 10 , 1995 from launch at 12:38 GMT to 14:39 GMT, in addition to pre-launch checkout . The +/- 40 kHz expanded frequency search option was employed for all events immediately after service start. The frequency offset only varied from approximately -7 kHz to -4 kHz before launch , and -4 kHz to +4 kHz after launch. There were no frequency related problems during this test and no changes in the frequency were necessary. Good quality TLM was demodulated and forwarded to the AFSCF.

IUS/TDRS-G SN Support

The SN supported the launch of the Inertial Upper Stage (IUS)/TDRS-G on July 13,1995 with three events, two with TDRS-5 (West), 19:54 to 20:13 GMT and 20:46 to 21:10 GMT, and one with TDRS-4 (East), 21:42 to 21:49 GMT. The IUS TLM modulation was BPSK/PM with a symbol-rate of 32 ksymb/sec on a 1.024 MHz subcarrier. The EIRP was estimated to be +11.2 dBW. The IR had successful acquisition of the upper subcarrier using DG2 mode 2. The TLM was demodulated and recorded at STGT. The Bit Energy to Noise Density Ratio (E_b/N_0) was estimated to be as high as 12 dB during the times that the IUS was directing the signal directly at the tracking TDRS. The frequency offsets varied from approximately +3 kHz to -3 kHz during the first 2 events, which were non-coherent. The third event was coherent with the Guam Tracking Station (GTS) uplink. Acquisition of a 3-way signal was obtained for the first time ever by the SN user equipment. The combination of the translated uplink Doppler and the difference between the coherently translated uplink frequency and the specified return link frequency, resulted in offsets to IR of -25.7 kHz to 24.1 kHz, consistent with predictions made by VNS personnel. The 3-way Doppler which was obtained by IR, was also obtained during the Galileo IF support[5] , but using special receivers, now referred to as TurboRogue GPS Receivers[9]. Until the implementation of the 40 kHz expanded frequency search, acquisition by the IR (or WDD) for the 3-way case would have been difficult, if even possible.

METRIC DATA ANALYSES

Background

NASA's Tracking and Data Relay Satellite (TDRS) System (TDRSS) consists of six geosynchronous satellites (TDRS-1,3,4,5,6,7) and the Second TDRSS Ground Terminals (STGT) located at White Sands, New Mexico and provides tracking and communications support for user spacecraft. STGT recently replaced the White Sands Ground terminal (WSGT). The ground-based Bilateration Ranging Transponder System is used to provide the range and Doppler tracking data used for TDRS orbit determination (OD). Range data from the telemetry, tracking, and command (TT&C) subsytem can also be used for TDRS OD.

State vector propagation, OD, ephemeris generation, and tracking data evaluation were performed using the Goddard Trajectory Determination System (GTDS). User spacecraft state vectors were propagated using Cowell-type numerical integration utilizing the JGM-2 geopotential model (50 x 50) and the Jacchia-Roberts atmospheric density model, and including the effects of atmospheric drag, solar radiation pressure, and solar and lunar gravity. TDRS state vectors were propagated using Cowell-type numerical integration utilizing the JGM-2 geopotential model (8 x 8) including the effects of solar radiation pressure and solar and lunar gravity. The user satellite orbital state and in some cases, a drag scale factor, were estimated using a batch weighted least-squares differential correction algorithm. Doppler noise estimates were obtained using a third order variate difference noise analysis (VDNA) technique on the Doppler residuals or observed minus computed (O-C) values.

The FDD has used TDRSS one-way return S-band Doppler tracking data operationally for OD, solving for the LO bias and drift assuming a constant drift, for spacecraft like NASA's Cosmic Background Explorer (COBE), which have USO's. However, for spacecraft with less stable LO's, the TDRSS one-way return Doppler tracking data is typically used only for LO center frequency determination, and not for OD because the LO bias and drift are unpredictable resulting in tracking data of poor quality. However, if a spacecraft with a LO is tracked simultaneously by two TDRS spacecraft at significantly different longitudes, the two TDRSS one-way return Doppler measurements can be subtracted producing higher quality differenced one-way Doppler (DOWD) measurements, essentially subtracting out the LO bias. The less significant error sources which remain result from the drift rate of the oscillator and different signal propagation times and from the error in the frequency used to compute the Doppler data. The DOWD data was generated from the simultaneous TDRSS one-way Doppler data using the FDD offline utility the General Data Handler (GDH). All DOWD statistics and results presented in this paper are for TDRSS DOWD tracking data.

UARS Tracking Data

In May of 1994 seven sets of simultaneous TDRS-4 and TDRS-5 one-way return tracking passes of the Upper Atmosphere Research Satellite (UARS) were scheduled to confirm the FDD's capability to process TDRSS DOWD tracking data and to evaluate the TDRSS DOWD tracking data. This marked the first time this TDRSS data type had been processed by the FDD. UARS is a three-axis stabilized Earth-pointing NASA satellite in a nearly circular orbit with an inclination of 57 degrees and a semimajor axis of 6955 km. The UARS omni antenna and the local oscillator, which is not an ultra-stable oscillator, were used. TDRS-4 and TDRS-5, designated TDRS-East and TDRS-West, respectively were located at approximately 319 degrees east longitude and 186 degrees East longitude respectively and were both supported by WSGT when the UARS tracking data was collected.

VNS personnel generated separate UARS orbit solutions using 34 hour data arcs of the abundant TDRSS two-way Doppler tracking data, a tracking data type used by the FDD for operational UARS OD, to evaluate each span of DOWD tracking data (solving for a drag scale factor); the data arc started at 00:00Z on the day of the DOWD pass and ended at 10:00 GMT on the day after the DOWD pass. The 34 hour data arc used is identical to the tracking data arc used to generate the TDRS solution vectors. A summary of the statistics computed for the residuals (O-C) computed using these 34 hour arc solution vectors follows in two tables, Tables 3 and 4.

Table 3 contains statistics for the residuals (O-C) computed for the one measurement per 10 seconds UARS/TDRS-4 and UARS/TDRS-5 one-way return Doppler tracking data.

Table 3
UARS TDRSS ONE-WAY DOPPLER RESIDUALS

Date, 1994	Span (GMT) hhmmss - hhmmss	TDRS	O-C Mean (Hz)	O-C Standard Deviation (Hz)	O-C Noise (Hz)
May 3	130420 - 131050	4	-203.5738	5.6412	0.31617
May 3	130420 - 131050	5	-203.5763	5.6427	0.31625
May 5	145820 - 150450	4	-181.4088	6.7532	0.28165
May 5	145820 - 150450	5	-181.4904	6.7621	0.28357
May 7	113945 - 114555	4	-201.5173	2.9729	0.42812
May 7	113945 - 114555	5	-201.5233	2.9709	0.42693
May 9	152120 - 152800	4	-162.4232	3.8038	0.40208
May 9	152120 - 152800	5	-162.4185	3.8035	0.40158
May 11	134320 - 134920	4	-209.3664	14.2787	0.33762
May 11	134320 - 134920	5	-209.3938	14.2794	0.33866
May 13	140220 - 140700	4	-157.7680	2.6100	0.30324
May 13	140220 - 140700	5	-157.7522	2.6219	0.30433
May 15	103020 - 103700	4	-192.0257	2.2544	0.28036
May 15	103020 - 103700	5	-192.0997	2.2435	0.28168

Table 4 contains statistics for the residuals (0-C) for the one measurement per 10 seconds and one measurement per second UARS/TDRS-4,5 differeneced one-way return Doppler tracking data.

Table 4
UARS DIFFERENCED ONE-WAY DOPPLER (DOWD) RESIDUALS

Date, 1994	Span (GMT) hhmmss - hhmmss	Sample Rate (sec^{-1})	O-C Mean (Hz)	O-C Standard Deviation (Hz)	O-C Noise (Hz)
May 3	130420 - 131050	1/10	-0.0029	0.0063	0.00360
May 3	130407 - 131059	1/1	-0.0036	0.0216	0.01891
May 5	145820 - 150450	1/10	-0.0823	0.0148	0.00916
May 5	145806 - 150459	1/1	-0.0815	0.0340	0.02575
May 7	113945 - 114555	1/10	-0.0055	0.0072	0.00291
May 7	113945 - 114555	1/1	-0.0060	0.0219	0.01889
May 9	152120 - 152800	1/10	0.0041	0.0133	0.00693
May 9	152107 - 152800	1/1	0.0039	0.0306	0.02466
May 11	134320 - 134920	1/10	-0.0277	0.0128	0.00500
May 11	134306 - 135000	1/1	-0.0271	0.0332	0.02778
May 13	140220 - 140700	1/10	0.0156	0.0138	0.00393
May 13	140207 - 140700	1/1	0.0159	0.0252	0.01934
May 15	103020 - 103700	1/10	-0.0753	0.0135	0.00422
May 15	103006 - 103700	1/1	-0.0742	0.0311	0.02520

The behavior of local oscillators used to control the S-band return link transmit frequency of spacecraft like UARS is difficult to predict accurately. As an example, Figure 1 portrays the non-linear behavior of the UARS one-way return TDRSS Doppler data during the May 3, 1994 pass.

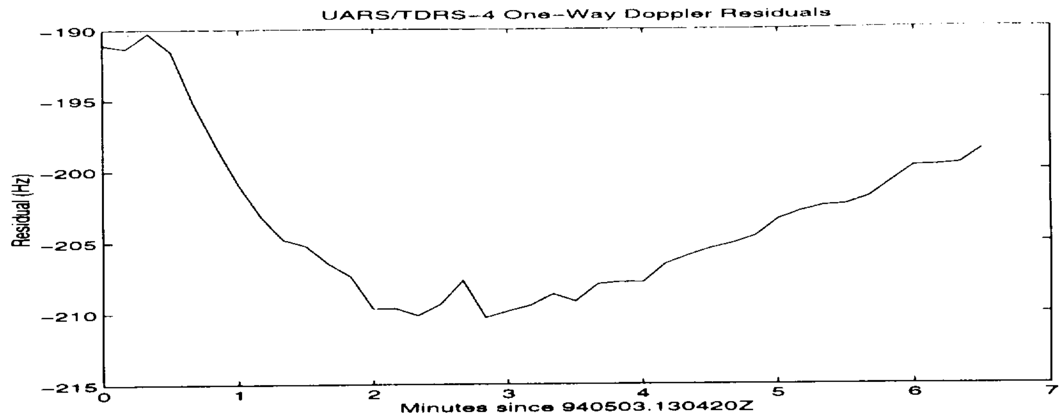


Figure 1. UARS TDRSS One-Way Doppler Residuals

TDRSS one-way return Doppler only and TDRSS DOWD only (starting at May 3, 13:04 GMT, and ending at May 9, 1994, 15:28 GMT) with a measurement interval of one per 10 seconds were used to generate two UARS orbit solutions with an epoch of May 6, 1995, 00:00 GMT. These two solutions and the a priori state vector were propagated to create ephemerides covering this tracking data span which were compared with an ephemeris generated by propagating a UARS orbit solution generated using only the abundant one per 10 seconds TDRSS two-way Doppler tracking data between May 3, 1994, 13:04 GMT and May 9, 1994, 15:28 GMT. A drag scale factor was solved for in all three cases, and the same a priori state vector with an epoch of May 2, 1994, 00:00 GMT was used in all three cases. The bias and drift of the S-band return link frequency were solved for when the TDRSS one-way return Doppler was used to generate the orbit solution. As expected, the ephemeris generated using TDRSS DOWD only compared much more favorably with the ephemeris generated using TDRSS two-way Doppler only than the ephemeris generated using TDRSS one-way return Doppler tracking data only. When compared with the ephemeris generated using TDRSS two-way Doppler tracking data, the total position difference was 0.121 to 0.431 kilometers for the ephemeris generated using TDRSS DOWD only, 4.591 to 18.076 kilometers for the ephemeris generated using TDRSS one-way return Doppler only, and 2.508 to 52.115 kilometers for the ephemeris generated using the a priori state vector. An orbit solution and ephemeris were generated using the one per second TDRSS DOWD only, and this ephemeris was compared with the ephemeris generated using the one per 10 second TDRSS DOWD only. The total position difference was 1 to 4 meters indicating little difference (from an early orbit support perspective) between the orbit solutions generated using the one per second and one per 10 seconds DOWD data in this case.

WIND Tracking Data

The launch of WIND occurred on November 1, 1994 at 9:31 GMT, and spacecraft separation occurred at approximately 10:47 GMT. WIND was in a highly elliptical transfer orbit with a semimajor axis of 242641 km, an eccentricity of 0.97, and inclination of 29 degrees. The S/C was spinning at approximately 15.6 revolutions per minute, and was radiating non-coherent through both of its omni antennas, which were offset from the spin axis, during the TDRSS support period. The tracking support geometry with respect to the view from TDRS-4 (East) and TDRS-5 (West) using the SA gimbal angle data at a sample interval of 60 seconds is provided in Figure 2.

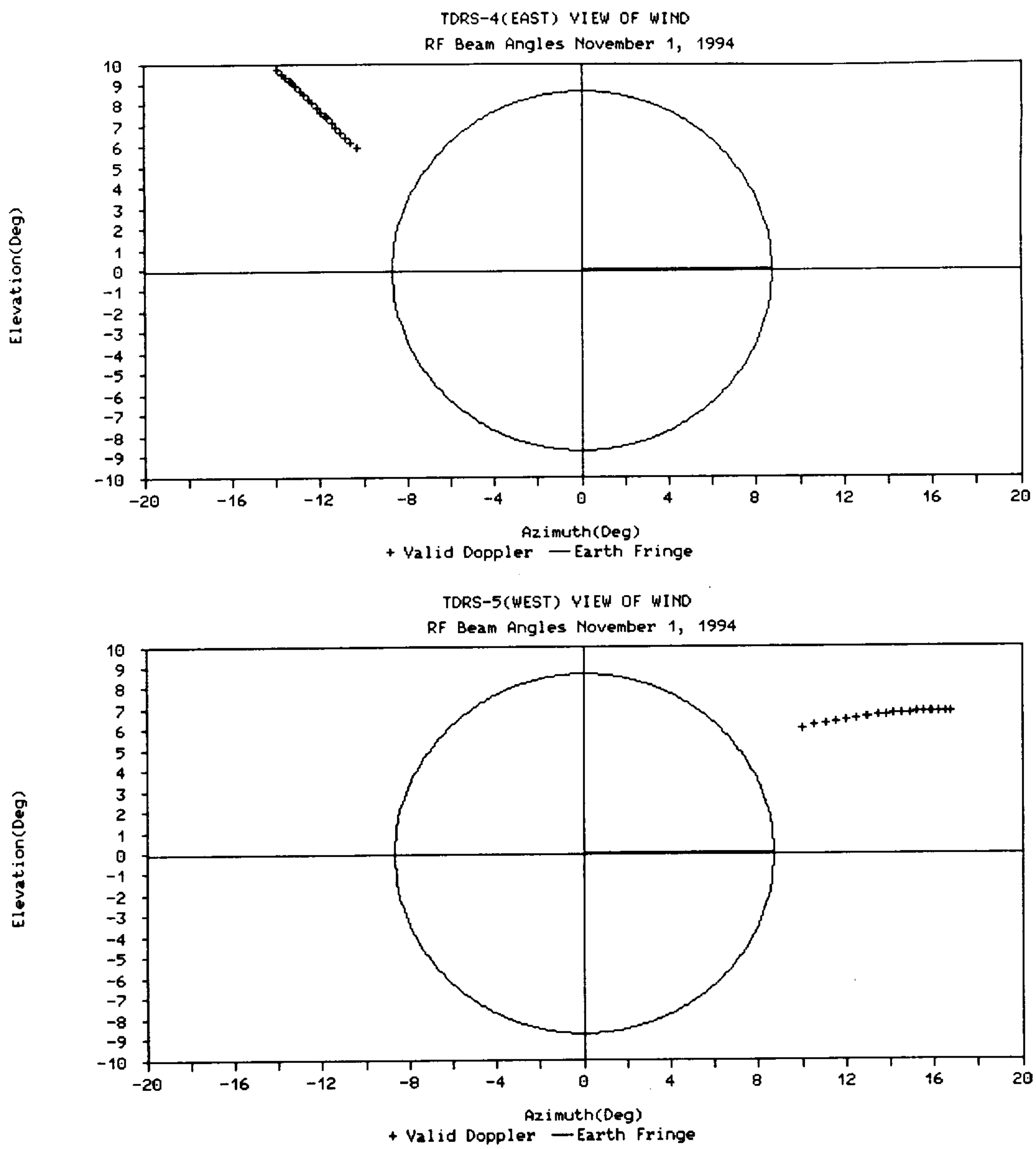


Figure 2. TDRS- 4 and TDRS-5 View of WIND

TDRSS tracking data residual (O-C) statistics were generated using an orbit solution based on range and coherent Doppler data from the Deep Space Network (DSN) 26 meter stations at Goldstone (DSS-16) and Madrid (DSS-66) . A graph of the WIND one-way Doppler residuals between 10:59:44 and 11:15:57 GMT is provided in figure 3. Residuals below -10000.0 Hz and above +10000.0 Hz (extraneous data) were excluded from figure 3.

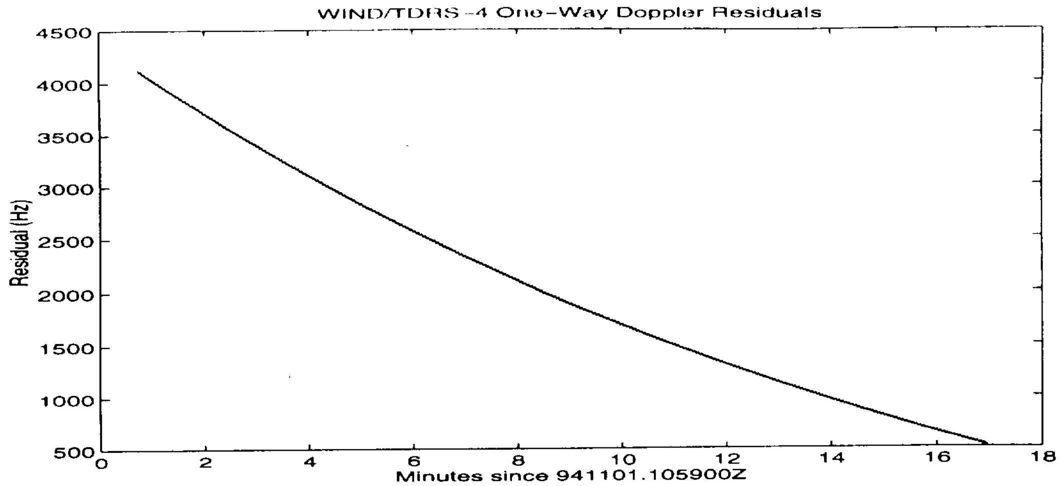


Figure 3. WIND One-way Doppler Residuals

Figure 4 is a plot of the WIND DOWD residuals between 10:59:44 and 11:15:57 GMT where the residuals below -12.0 Hz and above +12.0 Hz (extraneous data) were excluded.

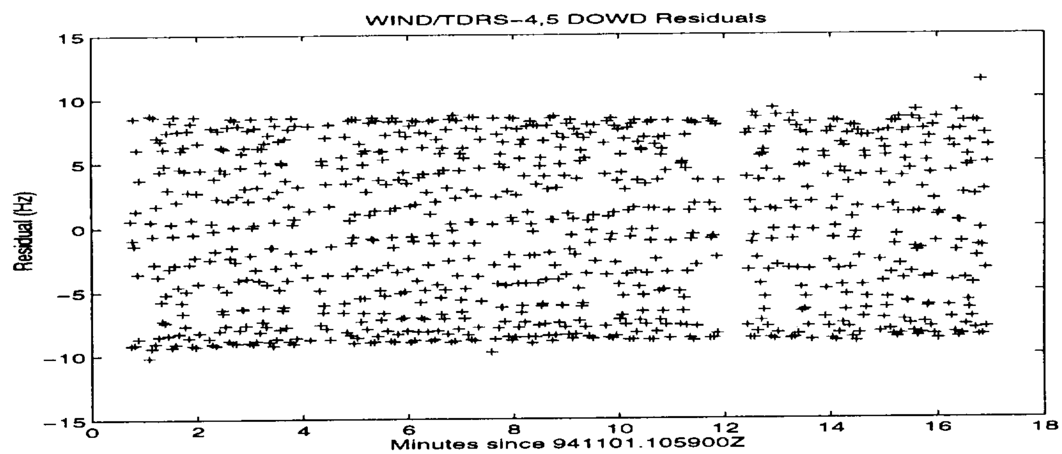


Figure 4. WIND Differenced One-way Doppler (DOWD) Residuals

Figure 5 is a plot of the WIND DOWD residuals between 11:00:05 and 11:00:55 GMT follows at 1 per second. No data points were excluded from figure 5.

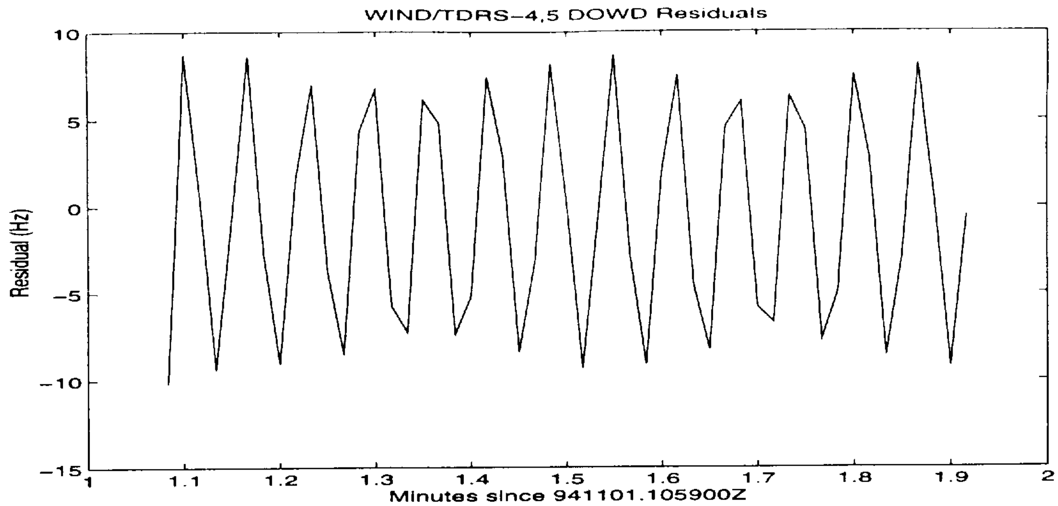


Figure 5. WIND Differenced One-way Doppler (DOWD) Residuals

Table 5 contains statistics computed for three continuous spans of one measurement per second WIND/TDRS-4 and WIND/TDRS-5 one-way return Doppler tracking data using residuals (O-C) computed using the solution vector obtained using range and coherent Doppler data from DSS-16 and DSS-66.

Table 5
WIND TDRSS ONE-WAY DOPPLER RESIDUALS

Date, 1994	Span (GMT) hhmmss -hhmmss	TDRS	O-C Mean (Hz)	Standard Deviation (Hz)	Noise (Hz)
November 1	110005 - 110103	4	3843.4378	92.1194	3.78122
November 1	110005 - 110103	5	3842.8852	92.1255	4.36664
November 1	110344 - 110623	4	2568.3743	191.8871	3.84693
November 1	110344 - 110623	5	2568.1407	191.9142	4.39240
November 1	111353 - 111502	4	737.6015	51.9717	3.98575
November 1	111353 - 111502	5	737.5459	52.2406	4.42499

Table 6 contains statistics computed for three continuous spans of one measurement per second WIND/TDRS-4,5 differenced one-way Doppler tracking data using residuals (O-C) computed using the solution vector obtained using range and coherent Doppler data from DSS-16 and DSS-66.

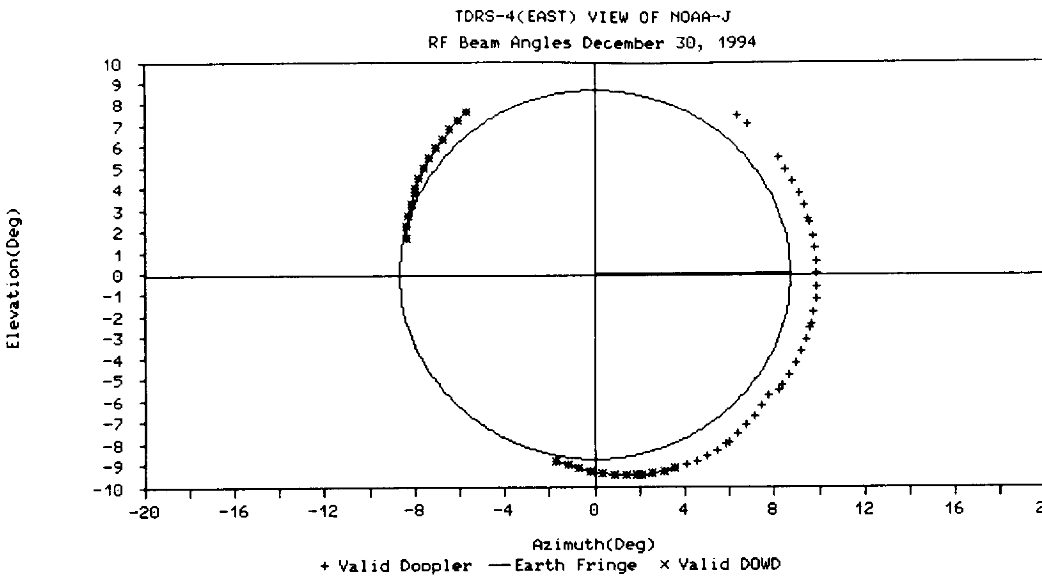
Table 6
WIND DIFFERENCED ONE-WAY DOPPLER (DOWD) RESIDUALS

Date, 1994	Span (GMT) hhmmss - hhmmss	O-C Mean (Hz)	Standard Deviation (Hz)	Noise (Hz)
November 1	110005 - 110103	-0.5530	6.3108	3.30150
November 1	110344 - 110623	-0.2341	6.0921	3.22955
November 1	111353 - 111502	-0.0560	6.0334	3.23676

By itself, WIND DOWD did not give a reasonable solution (i.e. diverged). However, comparably poor results were obtained with a 2-way range-rate solution from DSS-16 for the arc length 16 minutes and 40 seconds, immediately after the S/C went coherent. This is because Doppler lacks adequate geometry required for post-TTI HEO solutions using this data alone, particularly for a relatively short tracking arc, as was the case for WIND. Range is usually required for these cases. However, the DOWD does further enhance early short-arc solutions with ground tracker range, angles, and, if applicable, range-rate, by providing additional tracking data and by extending the tracking arc length closer to the TTI in this case. A solution was obtained using the DSS-16 angles and TDRSS DOWD data during the period that the transponder was non-coherent and the DOWD data was valid.

NOAA-J Tracking Data

The National Oceanic and Atmospheric Administration-J (NOAA-J) satellite, a three-axis stabilized Earth pointing spacecraft, was launched from the Western Range (WR) in California, United States into a nearly circular Sun Synchronous orbit with a semimajor axis of 7238 km and an inclination of 99 degrees on December 30, 1994. Liftoff occurred at 10:02 GMT, and injection occurred at 10:17 GMT. NOAA-J does not have a TDRSS-compatible transponder, but NOAA-J was very well suited to TDRSS one-way return Doppler tracking support. NOAA-J radiated continuously (non-coherent) at the S-band frequency with sufficient power through both of its omni antennae during the early orbit phase. There were no significant attitude perturbations during the period of TDRSS support. The simultaneous TDRS views of a spacecraft launched into a sun synchronous orbit from the WR are excellent. A view of the NOAA-J SN support from TDRS-3(Spare/West) and TDRS-4(East) using the SA gimbal angle data at a sample interval of 60 seconds is provided in figure 6. Valid, usable TDRS-3 and TDRS-4 one-way return Doppler tracking data not edited by the selected minimum ray path height of 200 km was received simultaneously between 11:43 to 11:52 GMT, and between 12:19 to 12:29 GMT. It was necessary for FDF to monitor the TDRSS one-way Doppler residuals in real-time and provide information to the Network Control Center. Because of the change in the LO bias, TDRSS service schedule order (SHO) frequency updates were necessary prior to the periods of simultaneous valid TDRS-3 and TDRS-4 one-way return Doppler tracking data. TDRS-3 designated TDRS-Spare was located at approximately 189 degrees East longitude and was supported by WSGT. TDRS-4 designated TDRS-East was located at approximately 319 degrees East longitude and was supported by STGT. The first ground network tracking pass, a Pillar Point pass, started at 11:45 GMT. The FDD used range data (skin track) obtained from four C-band radar sites, Pillar Point (California), Kaena Point (Hawaii), Kwajalein Atoll, Ascension Island, between 11:45 and 16:14 GMT to generate an orbit solution which was used to generate updated acquisition data for the ground stations supporting NOAA-J, meeting its NOAA-J mission support requirements. Orbit solutions and ephemerides were generated using only C-band range data edited by a minimum elevation angle of 6 degrees, and using only TDRSS DOWD (1 measurement per second) data edited by a minimum ray path height of 200 km, and the ephemerides were compared. See Figure 7. Between the start and end of the DOWD data arc, the total position difference was 0.439 to 1.251 kilometers.



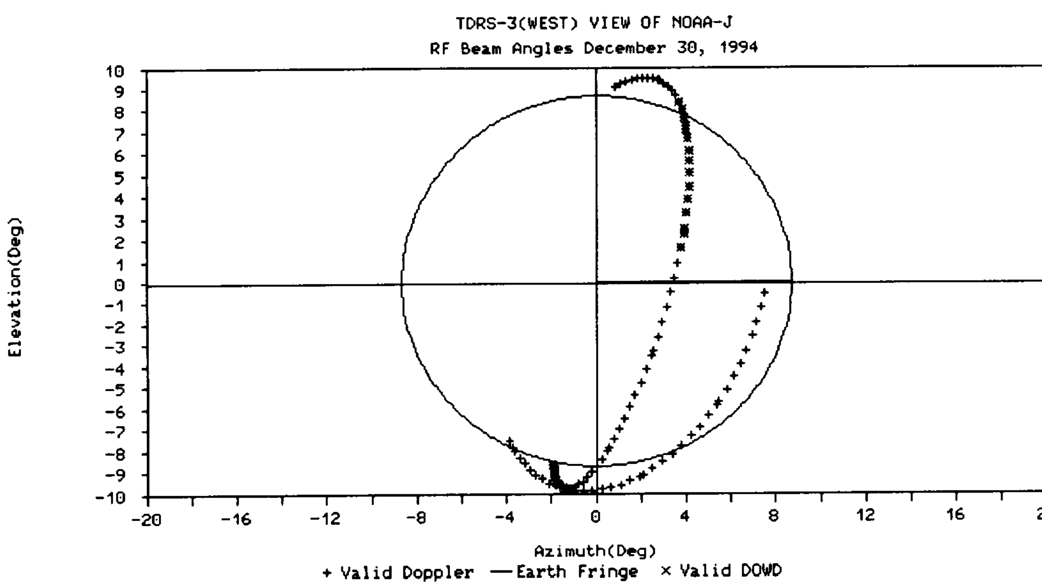


Figure 6. TDRS- 4 and TDRS-3 View of NOAA-J

Figure 7 is a plot of comparisons of the ephemeris generated by propagating the C-band range orbit solution with the ephemerides generated using the TDRSS DOWD orbit solution and using the pre-mission nominal post-injection state vector. For the C-band versus DOWD ephemeris comparison, the along track difference was the most significant difference.

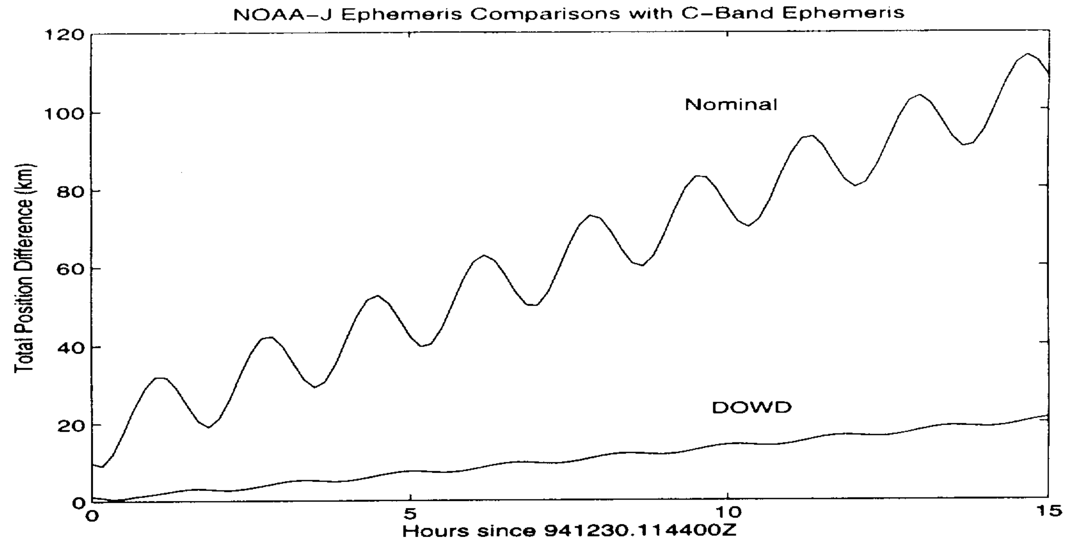


Figure 7. NOAA-J Ephemeris Comparisons C-band Radar Range versus DOWD Only and versus Nominal

Figure 8 is a plot of the NOAA-J/TDRS-4 one-way Doppler residuals during the DOWD periods (11:43:43 - 11:51:09 GMT and 12:19:40 - 12:28:55 GMT) computed using the DOWD only orbit solution.

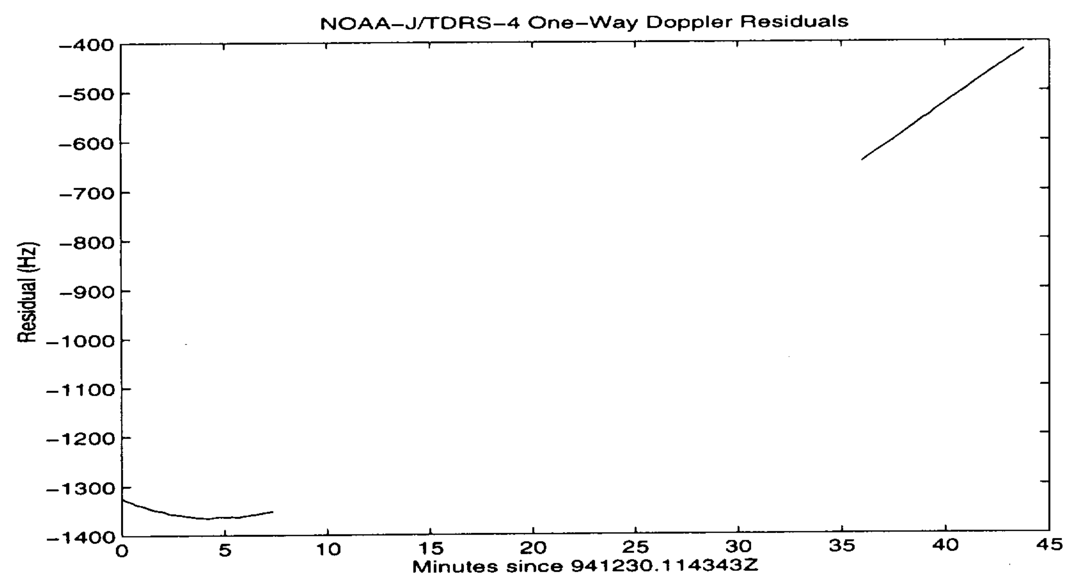


Figure 8. NOAA-J/TDRS-4 One-way Doppler Residuals

Figure 9 is a plot of the NOAA-J DOWD residuals (11:43:43 - 11:51:09 GMT and 12:19:40 - 12:28:55 GMT) computed using the DOWD only orbit solution.

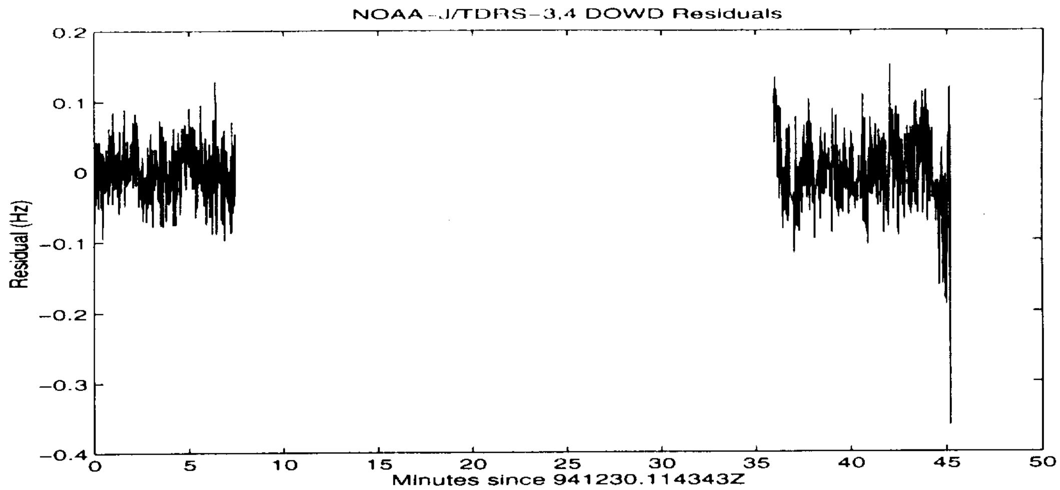


Figure 9. NOAA-J DOWD Residuals

Table 7 contains statistics computed for the one measurement per second NOAA-J/TDRS-3 and NOAA-J/TDRS-4 one-way return Doppler data using residuals (O-C) computed using the solution vector obtained only using the DOWD data.

Table 7
NOAA-J TDRSS ONE-WAY DOPPLER RESIDUALS

Date, 1994	Span (GMT) hhmmss - hhmmss	TDRS	O-C Mean (Hz)	O-C Standard Deviation (Hz)	O-C Noise (Hz)
December 30	114343 - 115109	3	-1353.8315	10.2970	0.18406
December 30	114343 - 115109	4	-1353.8259	10.2945	0.18466
December 30	121940 - 122855	3	-505.9492	76.7508	0.16126
December 30	121940 - 122855	4	-505.9454	76.7474	0.16460

Table 8 contains statistics for the one measurement per second NOAA-J/TDRS-3,4 differenced one-way Doppler tracking data computed using residuals (O-C) computed using the orbit solution vectors obtained using only the DOWD tracking data and using only the C-band tracking data.

Table 8
NOAA-J DIFFERENCED ONE-WAY DOPPLER (DOWD) RESIDUALS

Date, 1994	Span (GMT) hhmmss - hhmmss	Data Used for Orbit Solution	O-C Mean (Hz)	Standard Deviation (Hz)	O-C Noise (Hz)
December 30	114343 - 115109	DOWD	-0.0004	0.0365	0.02921
December 30	114343 - 115109	C-Band	-0.2413	0.1151	0.02924
December 30	121940 - 122855	DOWD	0.0005	0.0453	0.03458
December 30	121940 - 122855	C-Band	-0.0362	0.1581	0.03463

There was abundant NOAA-J TDRSS DOWD and ground station C-band radar tracking data available during the early orbit phase. However, in a case where only limited TDRSS and ground station tracking data is available, combing the space and ground based tracking data to generate an orbit solution could be the only way to obtain a quality orbit solution. For some spacecraft, ground network angle data and TDRSS one-way Doppler and differenced one-way Doppler may be the only quality tracking data types available during the period of non-coherent operations during the early orbit phase. For NOAA-J, there was a Kaena Point (Hawaii) C-band radar pass with a maximum elevation of 39.4 degrees between 11:48 and 12:00 GMT on December 30, and there was, as noted earlier, a period of valid, usable TDRSS differenced one-way Doppler tracking data between 11:43 and 11:52 GMT on December 30. It was not possible to obtain reasonable orbit solutions using only the Kaena Point angle data (azimuth and elevation) between 11:48 and 12:00 GMT or using only the TDRSS differenced one-way Doppler tracking data between 11:43 and 11:52 GMT (first pass). However, when both the Kaena Point angle data between 11:48 and 12:00 GMT and the TDRSS differenced one-way Doppler tracking data between 11:43 and 11:52 GMT were used to generate an orbit solution (with weights of 0.02 degrees for azimuth, 0.015 degrees for elevation, and 0.25 Hz for DOWD) and an ephemeris (from this solution), this ephemeris compared considerably more favorably with the ephemeris generated using the C-band range data between 11:45 and 16:14 GMT than did the pre-mission nominal ephemeris. The range of total position difference between 11:44 GMT December 30 and 02:44 GMT December 31 was 0.024 to 26.244 km (compared with 9.111 to 113.890 km over the same span for the pre-mission nominal ephemeris).

CONCLUSIONS

The SN can be used to support users without TDRSS compatible transponders to obtain one-way Doppler tracking and possibly obtain telemetry. For users whose LO is not stable enough for OD using one-way Doppler, DOWD may be obtained if the user can radiate to 2 TDRS's simultaneously. Solutions using DOWD can provide solutions with accuracies comparable to that from solutions using C-band radar range data as was demonstrated with NOAA-J. Furthermore, covariance analyses has shown that the TDRSS DOWD solutions will provide the same accuracy to that of corresponding TDRSS 2-way Doppler solutions for LEO users[10] . The implementation of the 40 kHz expanded frequency search further simplifies operations, enhances the probability of acquisition, and allows for 3-way acquisition. Furthermore, 3-way Doppler from the SN may possibly be used for OD. The requirement to have TDRSS compatible transponders, which have been cost, weight, size, or power prohibitive for many missions, may no longer be necessary for SN support, particularly for early-orbit and emergency support. However, a user desiring the SN for support should consult the Networks Division , GSFC Code 530 for scheduling, and to determine what type of onboard communications subsystem would be adequate. Future enhancements that have been proposed for these users are coherent services yielding 2-way Doppler, and evolving to a command capability, giving a complete TT&C capability[11] to these users once thought to be "incompatible users".

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