# Application of Tracking and Data Relay Satellite (TDRS) Differenced One-Way Doppler (DOWD) Tracking Data for Orbit Determination and Station Acquisition Support of User Spacecraft Without TDRS Compatible Transponders*

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## Abstract

Many spacecraft are launched today with only an omni-directional (omni) antenna and do not have an onboard Tracking and Data Relay Satellite (TDRS) transponder that is capable of coherently returning a carrier signal through TDRS. Therefore, other means of tracking need to be explored and used to adequately acquire the spacecraft. Differenced One-Way Doppler (DOWD) tracking data are very useful in eliminating the problems associated with the instability of the onboard oscillators when using strictly one-way Doppler data.

This paper investigates the TDRS DOWD tracking data received by the Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) during the launch and early orbit phases for both the Interplanetary Physics Laboratory (WIND) and the National Oceanic and Atmospheric Administration (NOAA)-J missions. In particular, FDF personnel performed an investigation of the data residuals and made an assessment of the acquisition capabilities of the DOWD-based solutions. Comparisons of DOWD solutions with existing data types were performed and analyzed in this study. This evaluation also includes atmospheric editing of the DOWD data and a study of the feasibility of solving for Doppler biases in an attempt to minimize error. Furthermore, by comparing the results from WIND and NOAA-J, an attempt is made to show the limitations involved in using DOWD data for the two different mission profiles. The techniques discussed in this paper benefit the launches of spacecraft that do not have TDRS transponders on board, particularly those launched into low Earth orbit. The use of DOWD data is a valuable asset to missions which do not have a stable local oscillator to enable high-quality solutions from the one-way return-link Doppler tracking data.

## Introduction

Differenced One-Way Doppler (DOWD) (Reference 1) is an open-loop type of tracking data used to minimize the effects of the user spacecraft transmit frequency offset. The user spacecraft return signal is received by two Tracking and Data Relay Satellites (TDRSs), frequency translated, and then relayed independently to the White Sands Complex for processing. (See Figure 1.) TDRS-4 (East) and TDRS-5 (West), supported through the White Sands Ground Terminal (WSGT), were the two relay spacecraft used for the DOWD tracking test for the Interplanetary Physics Laboratory (WIND) mission. TDRS-3 (Spare/West) and TDRS-4 (East), supported through WSGT and the Second TDRS System (TDRSS) Ground Terminal (STGT), respectively, were the two TDRSs used for the National Oceanic and Atmospheric Administration-J (NOAA-J) DOWD tracking test.

Individual one-way Doppler measurements are dominated by atmospheric refraction, user spacecraft antenna offset, transponder delays, and oscillator frequency bias. If a user spacecraft has a wide-beam antenna system, or if two omni antennas are available, the signal can be received by two or more TDRSs simultaneously. The signals received from the TDRSs will have essentially the same biases. Therefore, differencing the measurements will almost completely cancel out the biases, and the resulting DOWD tracking data are as accurate as two-way Doppler measurements (Reference 2).

This paper gives a description of the DOWD methodology and the results of its application to the WIND and NOAA-J missions, followed by a summary and conclusions.

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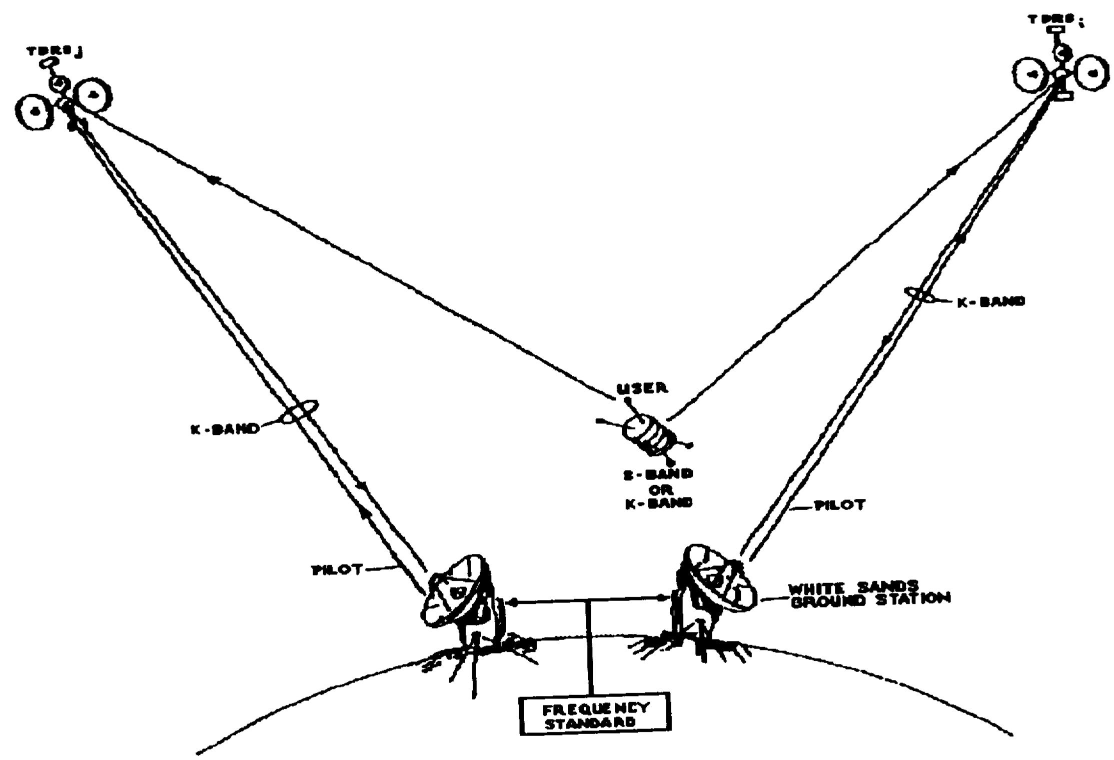



**Figure 1. Differenced One-Way Doppler Tracking Configuration (Reference 3)**

## Methodology

The Goddard Trajectory Determination System (GTDS) was used to obtain differential correction (DC) orbit solutions. Because the DOWD tracking data were routed to the Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) in a format that is not directly usable by GTDS, special processing was required to convert the data and then difference the TDRS one-way Doppler measurements for each matching time. Previous DC orbit solutions determined the TDRS position states used in these calculations. Therefore, the TDRS states were considered known at any instant of time, allowing only the WIND or NOAA-J states to be estimated. The following equation was used to compute the difference of the already reduced one-way Doppler measurements. (See Reference 4.)

$$\Delta v_d(T) = [v_d(T)]_{compare} - [v_d(T)]_{reference} \tag{1}$$

where

| | | |
|---|---|---|
| $\Delta v_d$ (T) | = | computed differenced one-way Doppler measurement at time T |
| $[v_d\,(T)]_{compare}$ | = | comparison TDRS one-way Doppler measurement ($TDRS_i$) |
| $[v_d\,(T)]_{reference}$ | = | reference TDRS one-way Doppler measurement ($TDRS_j$) |

When solving for the bias of a DOWD solution, the effects due to atmospheric refraction and the user biases cancel out. This occurs because the intrinsic nature of DOWD tracking is such that the data are the difference of two Doppler measurements and the biases associated with those Doppler measurements. The algorithms used in GTDS assume that the atmosphere is spherically symmetric with respect to the center of the Earth, meaning that the index of refraction varies radially with the altitude. The atmospheric biases attributed to each TDRS are theoretically the same. Therefore, the solved-for bias is simply the difference between two TDRS biases, which is a very small number. This can be shown mathematically as

$$\beta_{total} \equiv (\beta_{user} + \beta_{atm} + \beta_{TDRS-i}) - (\beta_{user} + \beta_{atm} + \beta_{TDRS-j}) = \beta_{TDRS-i} - \beta_{TDRS-j} \tag{2}$$

where

$\beta_{total}$ = total biases

$\beta_{user}$ = user biases

$\beta_{atm}$ = atmospheric biases

$\beta_{TDRS\text{-}i/j}$ = TDRS-i and TDRS-j biases

The application of this methodology to the WIND and NOAA-J missions is described below.

**WIND Support**

FDF personnel conducted tests using data from the launch of the WIND spacecraft on November 1, 1994, at 09:31:00.057 universal time coordinated (UTC). Several DC solutions were performed, four of which are described below. Of the four solutions presented, two solutions are DOWD-only runs with differing tracking data spans, one solution contains both DOWD and Deep Space Network (DSN) tracking data measurements, and the fourth solution is a DSN-only based solution.

The test was run in parallel with the actual operational launch support. An operational solution, generated by the launch support team during launch, will be used for comparison purposes. This solution will be referred to as the reference solution throughout this report. The observation span of the reference solution is slightly more than 4 hours and includes 26-meter range-rate data from the Goldstone, California, and Madrid, Spain, DSN tracking sites (referred to as DS16 and DS66, respectively, throughout this report). DSN 26-meter range data were also received from the DS16 site. Only 4 hours of data could be included in this solution because of a spacecraft maneuver. Table 1 lists the tracking data, excluding angles, that were available for orbit determination through 12:52:00 UTC, which was the end of the DS66 one-way and two-way data. The transition from the noncoherent mode to the coherent mode occurred at approximately 11:16:42 UTC. Table 2 lists the data types and the parameters used in generating the four solutions. Angle data were not used in this analysis so as to simulate support using 34-meter antennas, even though the support was done with 26-meter antennas. The 34-meter antennas do not have autotrack capability and therefore do not provide valid angle measurements. This simulates the worst-case scenario.

For the first solution, the nominal premission spacecraft separation vector from the WIND Mission Support Plan was used as the a priori state. Keplerian covariance constraints were applied to the a priori state to allow the estimation of the semimajor axis, eccentricity, and mean anomaly. This effectively allows estimation of the energy and perigee position, while restricting the a priori orbit plane, which was assumed to be generally accurate due to the geometry of the WIND trajectory during the transfer orbit phase.

**Table 1. WIND Tracking Data**

| Time of Tracking Data Pass on November 1, 1994 HHMMSS–HHMMSS (UTC) | Type of Tracking Data | Supporting Station |
|---|---|---|
| 105700–114200 | DOWD (total span) | TDRS-4/TDRS-5 |
| 105700–111642 | DOWD (valid span) | TDRS-4/TDRS-5 |
| 111910–113150 | Range-Rate | DS16 (two-way) |
| 113200–113800 | Range-Rate | DS16 (one-way) |
| 113200–113800 | Range-Rate | DS66 (one-way) |
| 113810-121900 | Range-Rate | DS16 (two-way) |
| 113810-121900 | Range-Rate | DS66/DS16 (three-way) |
| 121910-122200 | Range-Rate | DS16 (one-way) |
| 121940–125200 | Range-Rate | DS66 (two-way) |
| 122210-125200 | Range-Rate | DS16/DS66 (three-way) |
| 111919–121817 | Range | DS16 (two-way) |
| 122044–125140 | Range | DS66 (two-way) |

**Table 2. WIND Solution Parameters**

| Solution | Data Type | A Priori State | Constrained Solution | Data Arc Selected (hh:mm:ss) | Usable Valid Span (mm:ss) |
|---|---|---|---|---|---|
| 1 | DOWD only | Nominal separation vector | Yes (Keplerian) | 10:57:00–11:04:26 | DOWD 04:14 |
| 2 | DOWD only | Solution 1 | No | 10:57:00–11:42:00 | DOWD 15:45 |
| 3 | DOWD and DSN | Solution 1 | No | 11:00:04–11:28:40 | DOWD 15:46<br>DS16 10:26 |
| 4 | DSN only | Solution 1 | No | 11:00:10–11:38:40 | DS16 20:00 |
| Reference | DSN only | Operational intermediate solution | No | 11:19:10–15:21:00<br>12:19:40–12:52:00 | DS16 241:50<br>DS66 32:20 |

To simulate support using only DOWD data, the solution state from the first DC solution was used as the a priori state in the second DOWD-only solution. The a priori state for the DSN-only solution was also the same as the a priori states from the second and third solutions. Two attempts were also made at solutions using only 10 and 15 minutes of valid DSN data; however, these attempts were unsuccessful and the solutions did not converge.

**NOAA-J Support**

Task personnel conducted tests using data from the launch of the NOAA-J spacecraft that occurred on December 30, 1994, at 10:02 UTC. Several DC solutions were performed, nine of which are described below. Of the nine solutions presented, five solutions are DOWD-only with differing data spans, three solutions contain both DOWD and C-Band (skin tracking) data, and the ninth solution is based on C-band tracking data only. Table 3 lists the tracking data that were available for orbit determination.

**Table 3. NOAA-J Tracking Data**

| Time of Tracking Data Pass on December 30, 1994 HHMMSS–HHMMSS (UTC) | Type of Tracking Data | Supporting Station |
|---|---|---|
| 114343–115510 | DOWD | TDRS-3/TDRS-4 |
| 114500–115200 | C-Band | Pillar Point, California (PPTQ) |
| 114800–120042 | C-Band | Kaena Point, Hawaii (KPTQ) |
| 121846–123000 | DOWD | TDRS-3/TDRS-4 |
| 132648–133918 | C-Band | Kaena Point, Hawaii (KPTQ) |
| 133048–134624 | C-Band | Kwajalein Island (KMRT) |
| 142000–143736 | C-Band | Ascension Island (ASCQ) |
| 151018–152706 | C-Band | Kwajalein Island (KMRT) |
| 160154–161454 | C-Band | Ascension Island (ASCQ) |

An operational solution, generated by the launch support team, is used for comparison. This solution will be referred to as the reference solution throughout this report. The observation span of the reference solution is slightly more than 6 hours and includes all the C-band tracking data that were available on the day of launch. This reference solution, considered the best estimate of the orbit, was used to update acquisition data at launch plus 7 hours.

Table 4 lists the tracking data types and the parameters used in generating the NOAA-J solutions. The first solution was based on all the DOWD data that were available at 115510 UTC, which is when Earth occultation occurred for TDRS-4. Because of the geometry of NOAA-J and the TDRSs, atmospheric editing was performed for the DOWD data that were below 200 kilometers (km) in altitude to obtain a convergent solution for solutions 2, 4, 5, 7, and 8. Atmospheric editing was not applied to the shorter arc solutions because too much data were edited out and the solutions would not converge.

The modeling for solution 6 was identical to the modeling for solution 1, except that the position was tightly constrained (to 10 centimeters). In addition, the modeling for solution 8 was identical to that for solution 7, except that solution 8 solved for the TDRS biases. Solution 9 was generated during real-time support of NOAA-J based on all the C-band data available for orbit determination at launch plus 3 hours. This solution was considered to be the best estimate of the orbit at that time.

## Table 4. NOAA-J Solution Parameters

| Solution | Data Type | Atmospheric Editing / Bias Solve-For | Constrained Solution | Data Arc Selected (hh:mm:ss) | Usable Valid Data (mm:ss) |
|---|---|---|---|---|---|
| 1 | DOWD only | No / No | No | 11:43:43–11:55:10 | DOWD 11:27 |
| 2 | DOWD only | Yes (below 200km) / No | No | 11:43:43–12:30:00 | DOWD 22:41 |
| 3 | DOWD and C-Band | No / No | No | 11:43:43–11:55:10 | DOWD 11:27<br>PPTQ 01:42<br>KPTQ 04:18 |
| 4 | DOWD and C-Band | Yes (below 200km) / No | No | 11:43:43–12:30:00 | DOWD 22:41<br>PPTQ 04:36<br>KPTQ 11:00 |
| 5 | DOWD and C-Band | Yes (below 200km) / No | No | 11:43:43–16:15:00 | DOWD 22:41<br>PPTQ 04:24<br>KPTQ 20:24<br>KMRT 09:54<br>ASCQ 15:06 |
| 6 | DOWD only | No / No | Yes (position constrained to 10 cm) | 11:43:43–11:55:10 | DOWD 11:27 |
| 7 | DOWD only | Yes (below 200km) / No | Yes (position constrained to 10 cm) | 11:43:43–12:30:00 | DOWD 22:41 |
| 8 | DOWD only | Yes (below 200km) / Yes | Yes (position constrained to 10 cm) | 11:43:43–12:30:00 | DOWD 22:41 |
| 9 | C-Band only | No / No | No | 11:45:00–12:00:42 | PPTQ 04:30<br>KPTQ 10:54 |
| Reference | C-Band only | No / No | No | 11:45:00–16:14:54 | PPTQ 04:42<br>KPTQ 20:30<br>KMRT 09:54<br>ASCQ 16:12 |

## Results

The results from applying the DOWD methodology to the WIND and NOAA-J missions are given below.

### WIND Mission

Table 5 lists the pertinent parameters for the four solutions. The target semimajor axis of this transfer orbit mission phase was 249475.5340 km. The reference solution was based on slightly more than 4 hours of data. This solution used tracking data from two DSN antennas (DS16 and DS66). Compared to the reference solution, the shorter arc solutions significantly underestimated the size of the orbit.

The DOWD data residuals for the entire span of the accepted data only are shown in Figure 2. These residuals range from ~ –9 to ~ +9 hertz.

## Table 5. WIND Solution Parameters

| Solution No. | Solution | Semimajor Axis (km) | Eccentricity | Inclination (degrees) | RAAN | Argument of Latitude | DOWD Mean Residual (hertz) | DOWD Standard Deviation (hertz) |
|---|---|---|---|---|---|---|---|---|
| 1 | DOWD-only (short span) | 249475.5340 | 0.9737 | 28.7353 | 2.3860 | 30.4191 | –0.0026 | 6.162 |
| 2 | DOWD-only (full span) | 248604.2948 | 0.9736 | 30.5321 | 0.9950 | 31.7291 | 0.711 | 6.121 |
| 3 | DOWD and DSN | 245342.8617 | 0.9732 | 28.7815 | 2.3470 | 30.5752 | 2.144E–06 | 6.119 |
| 4 | DSN-only | 246308.2120 | 0.9734 | 28.7828 | 3.0666 | 29.9468 | N/A | N/A |
| 5 | Reference | 248941.0706 | 0.9732 | 28.7541 | 2.4186 | 30.5168 | N/A | N/A |

NOTE: All elements are osculating true-of-date Keplerian, with an epoch of 941101 10:52:05.532 UTC, except for the reference solution, which has an epoch of 10:52:41.000 UTC. N/A = not applicable; RAAN = right ascension of the ascending node

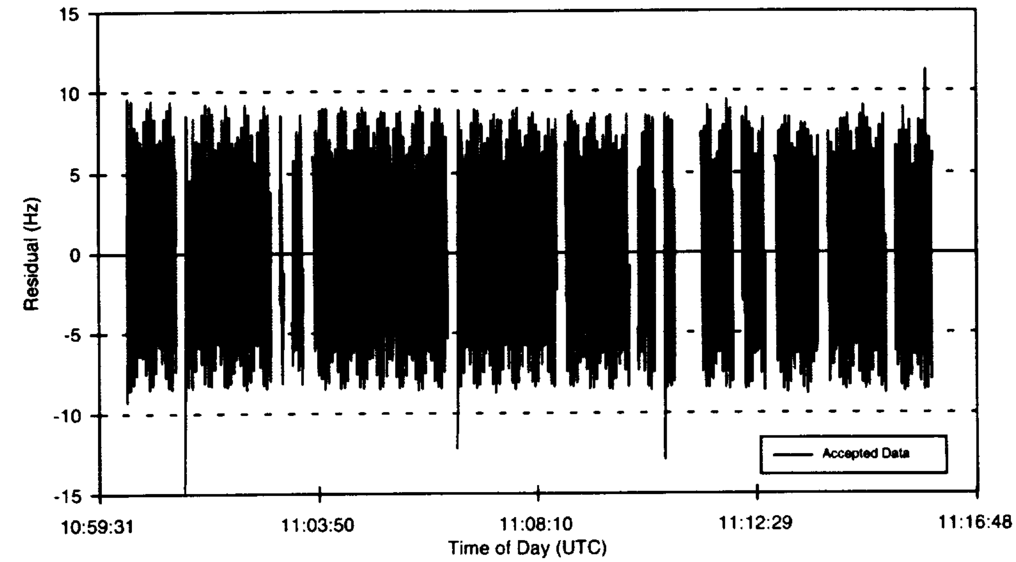



**Figure 2. WIND Orbit Determination DOWD Residuals**

To better characterize the nature of the residuals, a 1-minute span was evaluated. Figure 3 shows the DOWD residuals for a 1-minute span of the data arc. The standard deviation of the residuals shown in Figure 3 is 6.112 hertz. This is comparable to the 6.121 hertz value for the entire DOWD-only solution. The sinusoidal nature of the plot is due to the spin rate of the WIND spacecraft (~ 15.6 rpm). The modulation of the amplitude is a result of the sampling rate of the data (one per second). The high residuals are caused by the lack of modeling of the spin in the DC solution. The two omni antennas were not aligned along the spin axis. (A more detailed spin rate analysis is given in Reference 5).

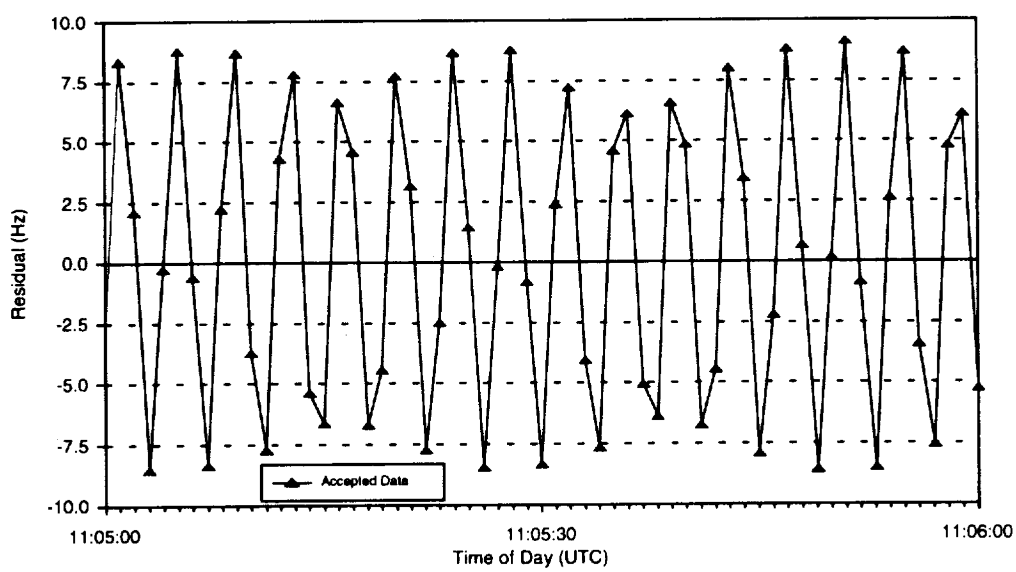



**Figure 3. WIND Orbit Determination DOWD Residuals**

The antenna-pointing acquisition tolerance for the WIND spacecraft was a half-cone angle of 0.13 degree during the early, postseparation phase for the 34-meter antennas. To determine if this tolerance was met, the azimuth and elevation angles for WIND acquisition from the DS16 and DS66 sites were generated for both the DOWD-only solution and the reference solution. It is assumed that acquisition aid antenna capabilities do not exist, thus simulating the worst case scenario. The total angle differences were then determined with respect to each site, using the following equation:

$$\Delta\Theta = \cos^{-1}[\sin(El_1)\sin(El_2) + \cos(El_1)\cos(El_2)\cos(\Delta az)] \qquad (3)$$

where

$\Delta\Theta$ = total angle difference between trajectories
$\Delta az$ = azimuth angle difference between trajectories
$El_{1/2}$ = elevation angles for DOWD solution and reference solution, respectively

Figures 4 and 5 display that the full-span, DOWD-only solution was within the acquisition tolerance for approximately 40 minutes after the end of the definitive data arc. The total angle differences rapidly increase over the next 4 hours, up to nearly 0.6 degree, which is well above the acquisition tolerance. The data from acquisition of signal (AOS) through the end of the definitive data span were omitted from the figures because only the predictive acquisition capabilities were of interest.

Similar analyses were performed for the DOWD/DSN solution and the DSN-only solution. The DOWD/DSN solutions (Figures 6 and 7) show that the 0.13-degree tolerance is met for several hours after AOS at both DS16 and DS66. However, the DSN-only solution (Figures 8 and 9) did not meet the tolerance at any time for either site.

Figures 4 through 9 illustrate the importance of having a sufficient mix of tracking data types in the solution. As these figures show, the DSN-only solution was insufficient for acquisition capabilities, and the full-span, DOWD-only solution was only sufficient if the spacecraft could be acquired and lock maintained in the short time that the tolerance is not exceeded. However, the combined DSN and DOWD solutions were more than capable of acquiring the spacecraft throughout the entire tracking span. This shows that the solution state is much more stable over time for combined data type solutions than for single data type solutions.

Several other solutions were performed in addition to the test case solutions described above. Solutions using atmospheric editing of the DOWD data showed that the editing had no effect on the solution because the WIND-to-TDRS line of sight is outside the Earth's atmospheric effects throughout the DOWD tracking data span. Other solutions were generated using position constraints in an attempt to improve the estimate of the velocity. Premission error analysis showed that angle data should not be used for constrained solutions (Reference 6). A better estimate of the velocity allows a determination of whether a correction burn is necessary to achieve the nominal trajectory. However, when these constrained solutions are propagated over time, the ephemeris accuracy degrades rapidly. The DOWD-only constrained solution did not give an accurate estimate of the velocity, primarily due to the short span of the data arc. When the DOWD data are combined with 10 minutes and 26 seconds of DSN data (as in solution 3), the velocity estimate improves considerably.

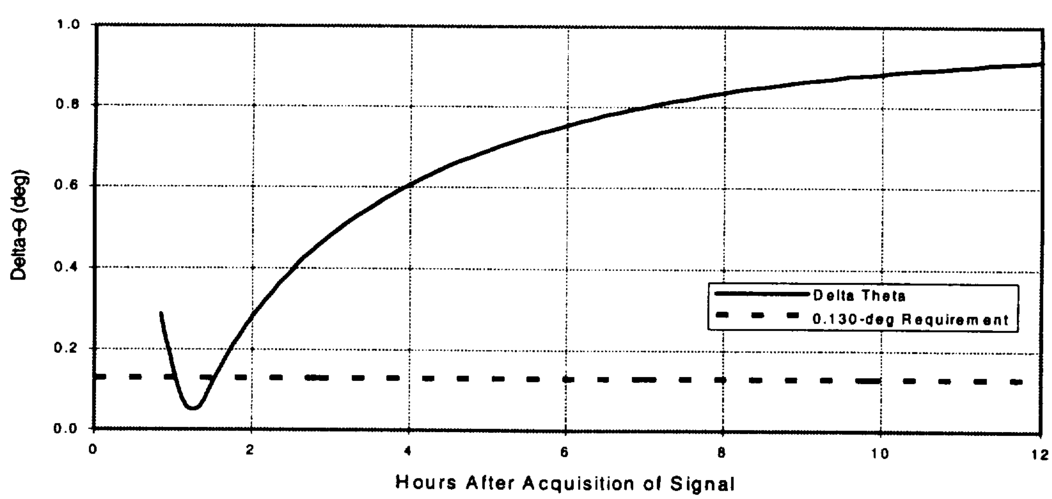



**Figure 4. WIND Angle Difference for DS16 During Contact Times Only (DOWD Only)**

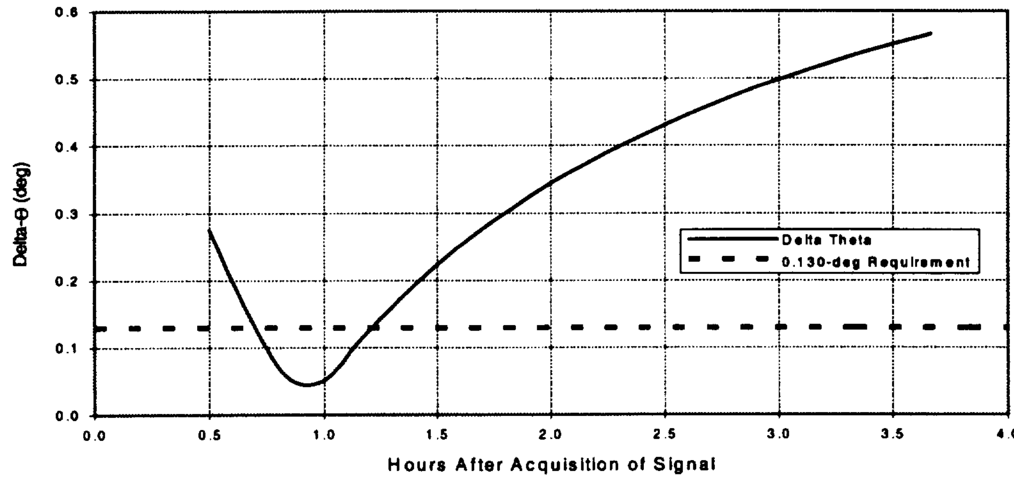



**Figure 5. WIND Angle Difference for DS66 During Contact Times Only (DOWD Only)**

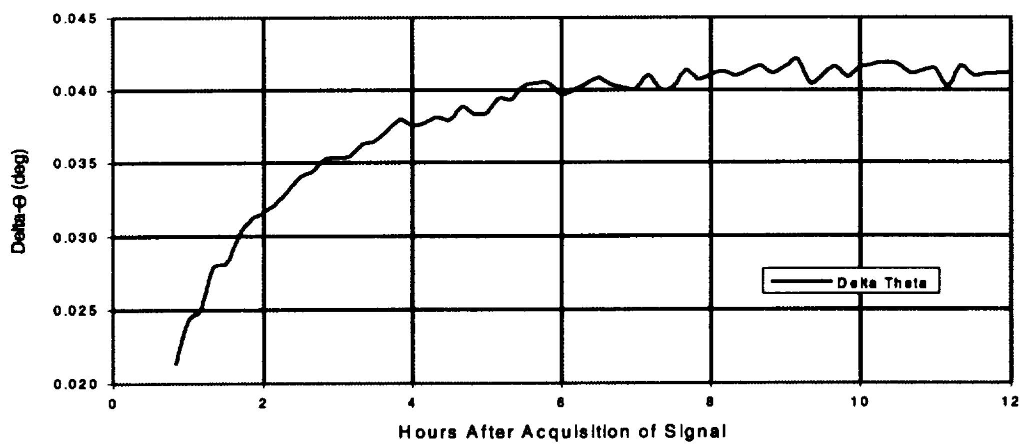



**Figure 6. WIND Angle Difference for DS16 During Contact Times Only (DOWD/DSN)**

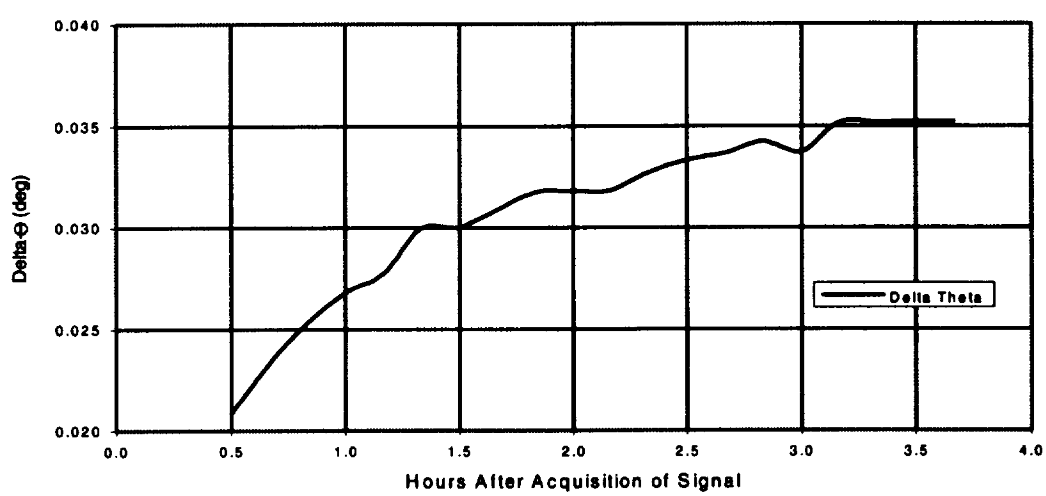



**Figure 7. WIND Angle Difference for DS66 During Contact Times Only (DOWD/DSN)**

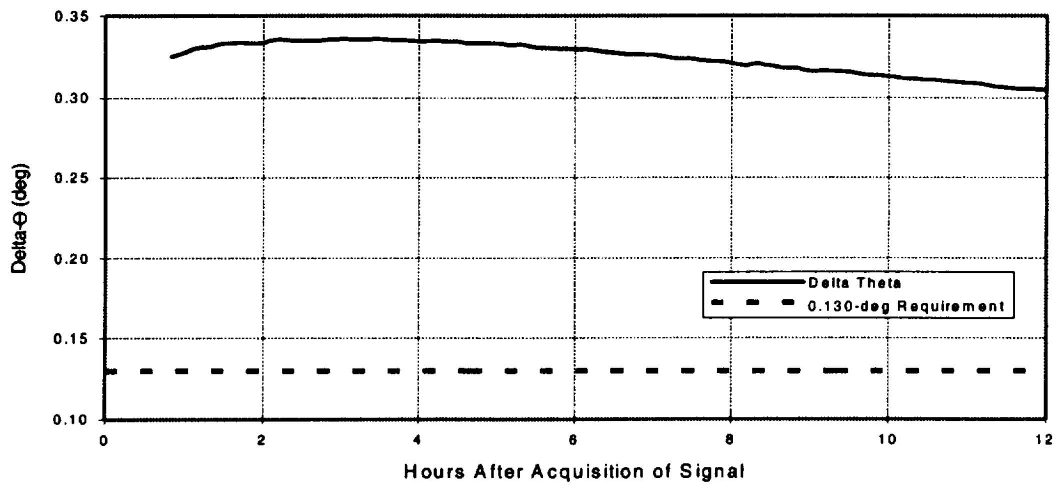



**Figure 8. WIND Angle Difference for DS16 During Contact Times Only (DSN Only)**

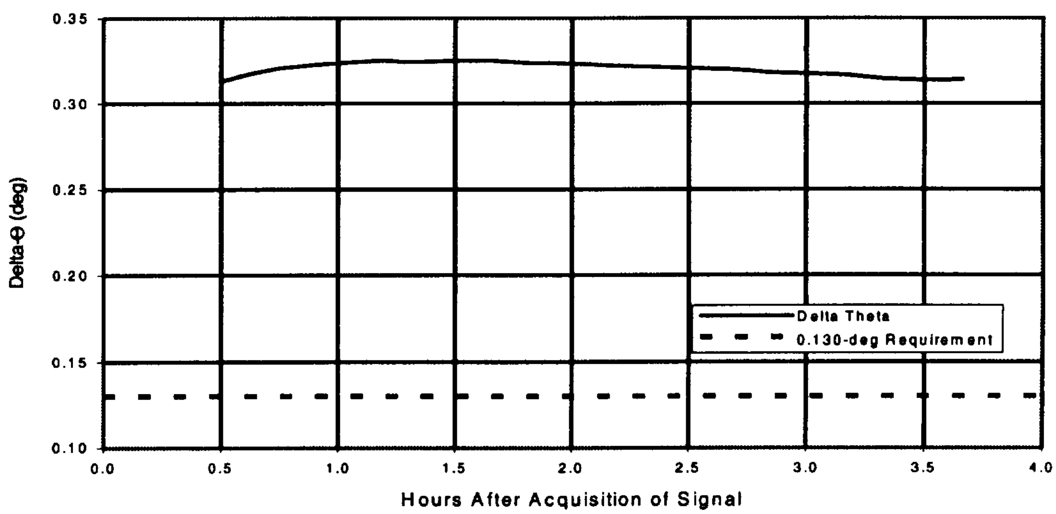



**Figure 9. WIND Angle Difference for DS66 During Contact Times Only (DSN Only)**

### NOAA-J Mission

Table 6 lists the pertinent parameters for the test case solutions, and for other intermediate, operational support solutions and ephemerides.

Comparisons were made between the ephemeris for each solution and the reference solution ephemeris to determine how the small differences in the elements affect the solution state over time. This is of critical importance to acquisition capabilities because if the solution state diverges rapidly (from the truth) and is not updated, then acquisition of the spacecraft can be inhibited and possibly not occur. Figures 10 through 12 show how the ephemerides compare over time.

The DOWD data residuals for the entire span of the accepted data only are shown in Figure 13. These residuals range from ~ –0.12 to ~ +0.16 hertz.

## Table 6. NOAA-J Solution Parameters

| Hours From Injection | Solution Number | Solution | Semimajor Axis (km) | Eccentricity | Inclination (degrees) | RAAN | Argument of Latitude |
|---|---|---|---|---|---|---|---|
| 0:00:00 | – | Nominal injection | 7237.3832 | 0.00024 | 98.8622 | 303.4543 | 181.3522 |
| 0:00:00 | – | LTAS | 7242.8635 | 0.00404 | 98.8542 | 303.4335 | 182.0072 |
| 0:50:38 | – | NORAD two-liner | 7239.7017 | 0.00049 | 98.8891 | 303.4503 | 181.5041 |
| 1:37:55 | 1 | DOWD | 7238.2915 | 0.00042 | 98.8879 | 303.4435 | 181.4571 |
| 1:37:55 | 6 | DOWD (position constraints) | 7238.1937 | 0.00042 | 98.8924 | 303.4449 | 181.4544 |
| 1:37:55 | 3 | DOWD and C-Band | 7238.6703 | 0.00045 | 98.8778 | 303.4420 | 181.4735 |
| 1:43:37 | 9 | C-Band | 7238.2479 | 0.00037 | 98.8803 | 303.4416 | 181.4548 |
| 2:12:55 | 2 | DOWD | 7238.2216 | 0.00045 | 98.8861 | 303.4446 | 181.4491 |
| 2:12:55 | 4 | DOWD and C-Band | 7238.4648 | 0.00043 | 98.8795 | 303.4414 | 181.4616 |
| 2:12:55 | 7 | DOWD (position constraints) | 7238.2306 | 0.00045 | 98.8867 | 303.4448 | 181.4503 |
| 2:12:55 | 8 | DOWD (position constraints; bias solve-for | 7238.2306 | 0.00045 | 98.8867 | 303.4448 | 181.4503 |
| 3:30:19 | – | C-Band | 7238.4657 | 0.00041 | 98.8801 | 303.4412 | 181.4647 |
| 4:20:31 | – | C-Band | 7238.4606 | 0.00043 | 98.8791 | 303.4417 | 181.4614 |
| 5:10:01 | – | C-Band | 7238.4640 | 0.00043 | 98.8795 | 303.4415 | 181.4618 |
| 5:57:49 | Reference | C-Band | 7238.4637 | 0.00043 | 98.8794 | 303.4415 | 181.4618 |
| 5:57:49 | 5 | C-Band and DOWD | 7238.4616 | 0.00043 | 98.8795 | 303.4415 | 181.4614 |

NOTE: All elements are osculating true-of-date Keplerian, with an epoch of 941230 10:17:05 UTC, except for the nominal injection ephemeris, which has an epoch of 10:17:02.418 UTC.

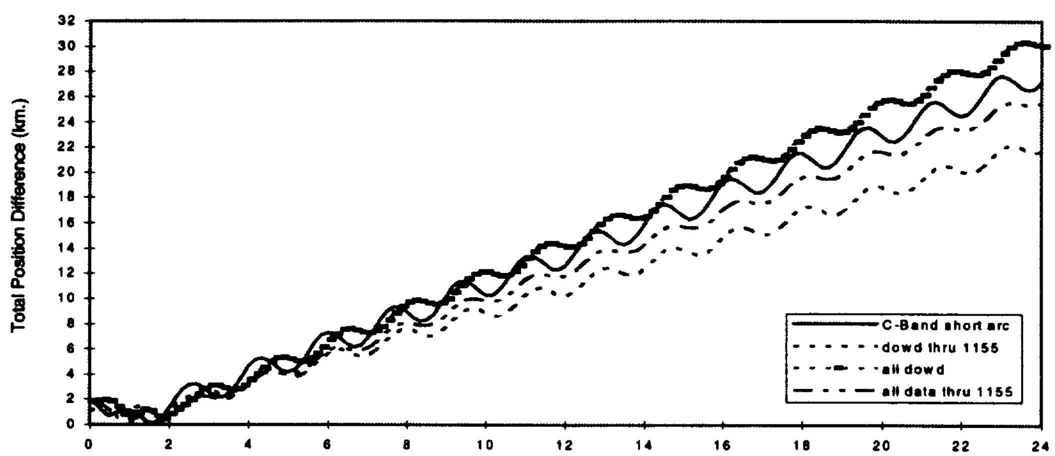



**Figure 10. NOAA-J Comparisons of Solutions With Reference Solution**

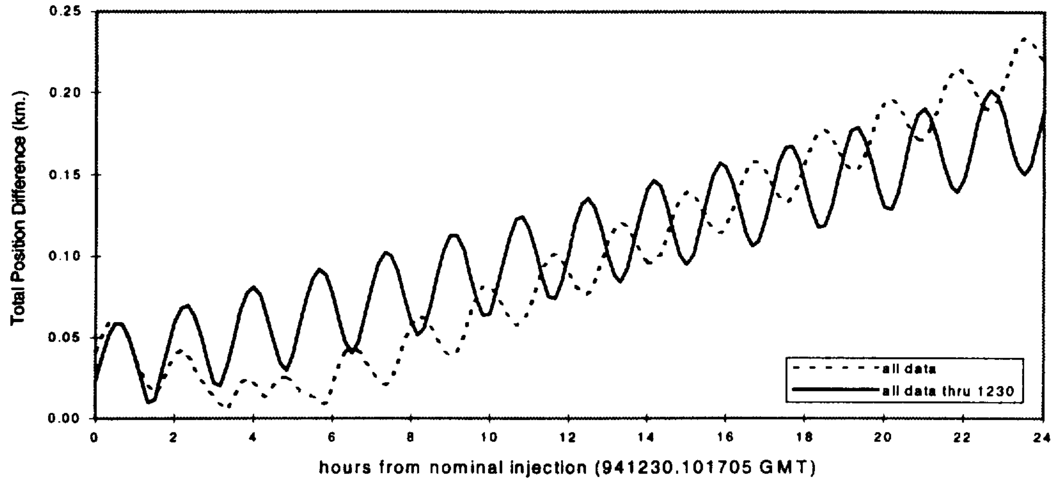
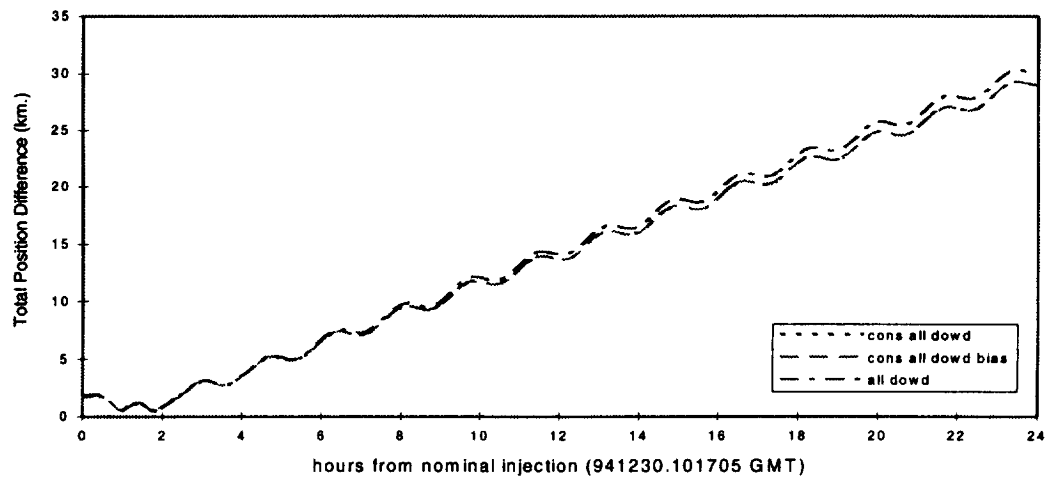



**Figure 11. NOAA-J Comparisons of Solutions With Reference Solution**




**Figures 12. NOAA-J Comparisons of Solutions With Reference Solution**

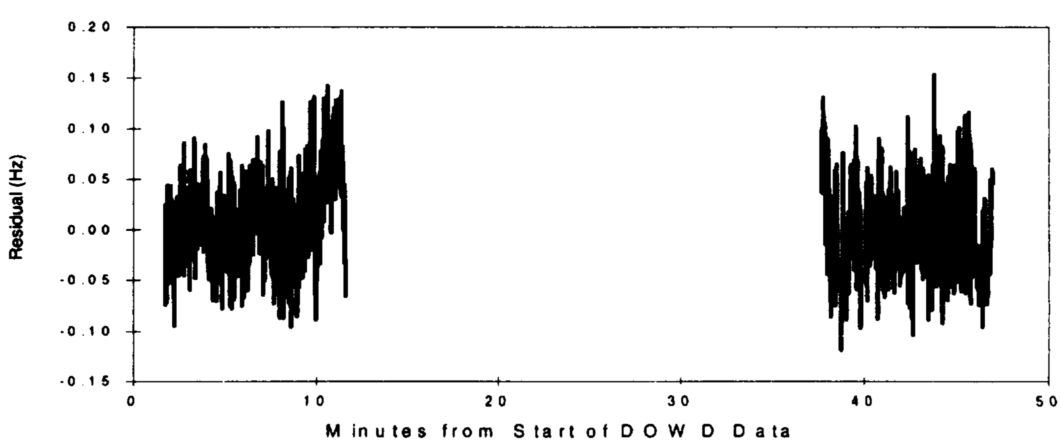



**Figure 13. NOAA-J Differenced One-Way Doppler Residuals for Accepted Data**

To better characterize the residuals, a 2-minute span was evaluated. The results of this evaluation are shown in Figure 14. It is apparent from Figure 14 that NOAA-J is not a spin-axis stabilized spacecraft. The two omni antennas were not aligned along the neutral axis of the spacecraft.

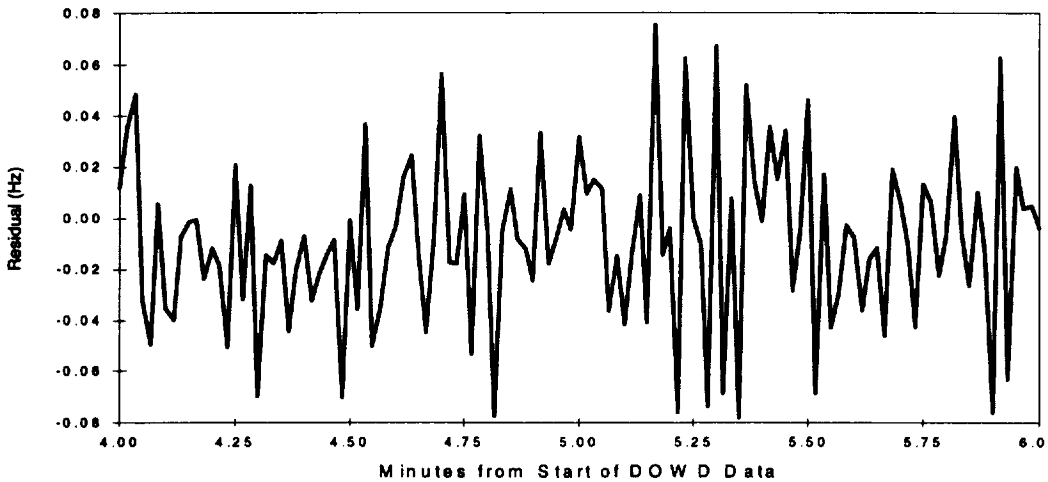



**Figure 14. NOAA-J Differenced One-Way Doppler Residuals for Accepted Data**

The antenna-pointing acquisition tolerance for the NOAA-J spacecraft was a half-cone angle of 0.215 degree and 0.220 degree for the Wallops and Ascension sites, respectively. As with WIND, the azimuth and elevation angles for NOAA-J acquisition from the Wallops and Ascension sites were generated for both the full-span, DOWD-only solution and the reference solution to determine if the acquisition tolerances were met. The total angle differences were also determined with respect to each site.

Figures 15 and 16 show that the DOWD-only solution (solution 1) was within the acquisition tolerance throughout most of the data arc. There are some spikes that exceed the tolerance in the angle differences; however, the spacecraft would probably still be acquired because there are approximately 20 minutes of data before these spikes that could be used for acquisition. These spikes represent the times at which NOAA-J is at the maximum elevation; hence, the corresponding velocity is also a maximum, which could inhibit the ability to acquire. It should be stressed that solution 1 was based on only 11 minutes and 27 seconds of useable DOWD data. Figures 17 and 18 show that the DOWD/C-band short-arc solution (solution 3) and the C-band-only short-arc solution (solution 9) are also within tolerance throughout most of the data arc.

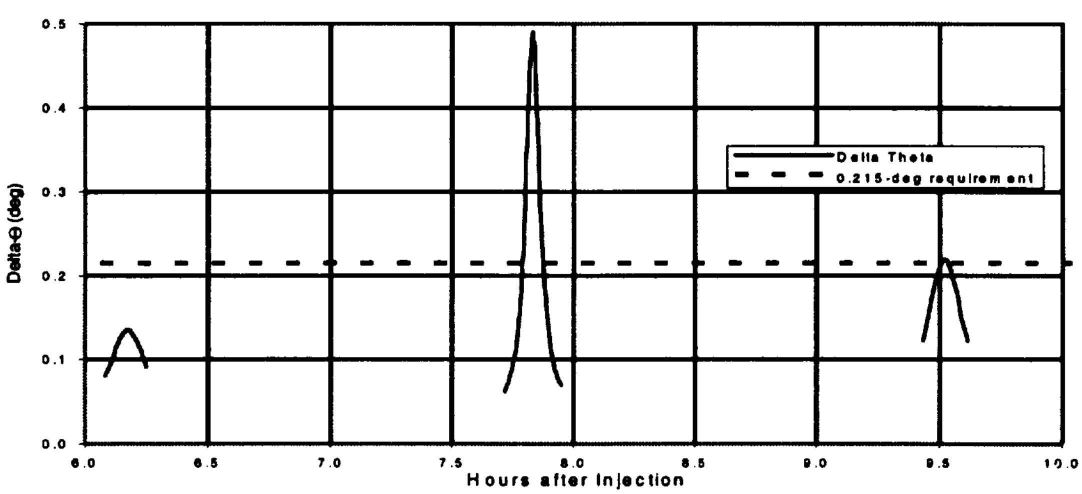



**Figure 15. NOAA-J Angle Difference for Wallops During Contact Times Only (Solution 1)**

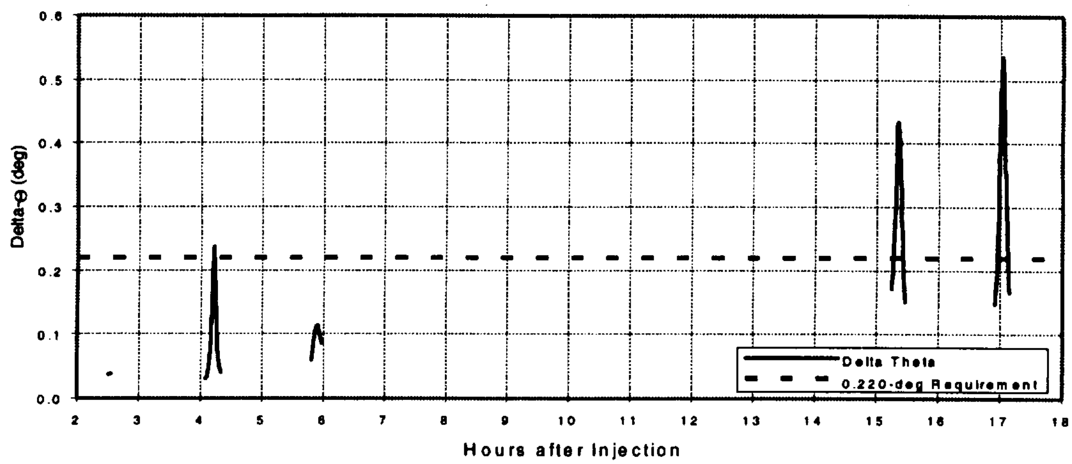



**Figure 16. NOAA-J Angle Difference for Ascension During Contact Times Only (Solution 1)**

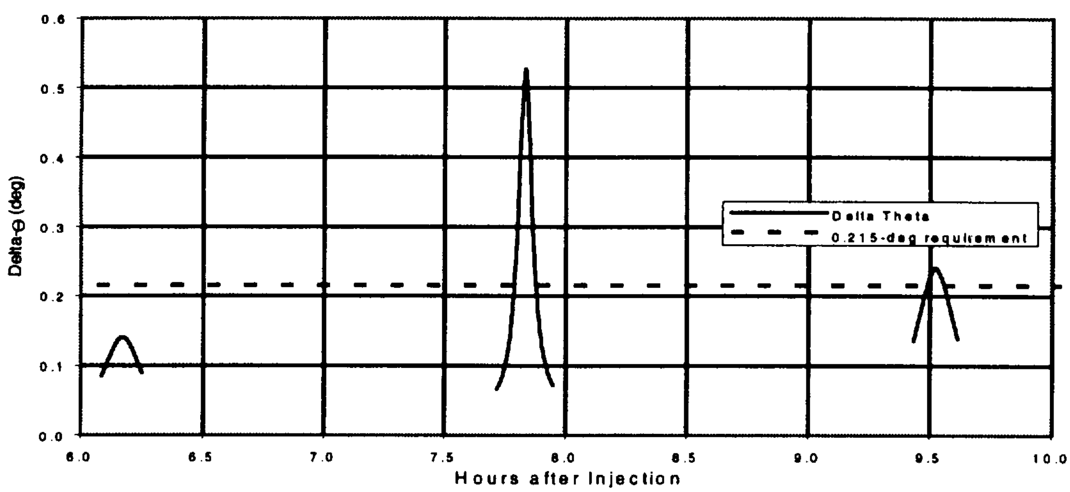



**Figure 17. NOAA-J Angle Difference for Wallops During Contact Times Only (Solution 3)**

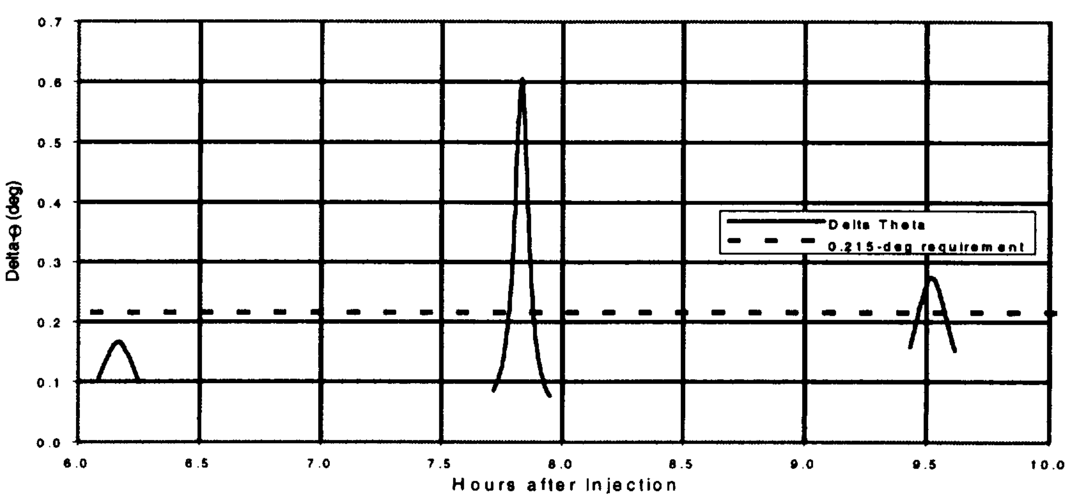



**Figure 18. NOAA-J Angle Difference for Wallops During Contact Times Only (Solution 9)**

In addition to the test case solutions described above, several other solutions were performed. In particular, several solutions were generated using all of the available DOWD data while changing the atmospheric editing criteria. The solutions did not converge when the editing criterion was set to edit the data below 100 km, 400 km, and 600 km. The solution also diverged when the atmospheric editing option was not implemented, i.e., all of the data were considered in the solution regardless of any possible atmospheric effects. When the criterion was set at 300 km, the solution did converge; however, the maximum position difference between the solution ephemeris and the reference ephemeris was 63.3 km. The final solution had the atmospheric editing criterion set at 200 km. This solution converged and compared better with the reference ephemeris than the solution with the atmospheric editing criteria set at 300 km.

Attempting to solve for the TDRS biases did not significantly improve the solution. TDRS biases are inherently small, and the combined solved-for bias, which is the difference of the two TDRS biases, was only -0.01170 hertz.

## Summary and Conclusions

This investigation determines the viability of using TDRS DOWD tracking data during the critical launch and early orbit phases of both the WIND and the NOAA-J missions. Orbit determination solutions were generated using solely the DOWD tracking data, as well as DOWD data in conjunction with standard data types such as C-band, DSN range, and DSN range-rate. The quality assessment was based on determining whether the antenna beamwidth constraints were met using the acquisition data (azimuth and elevation angles) derived from the DOWD-based ephemerides.

The results showed that the DOWD-only solution for WIND was theoretically viable for a 30-minute period after separation. Note that in actual mission operations, the DOWD-only solution might not be timely enough for acquisition purposes. By the time the DOWD tracking data are processed and used in an orbit determination solution for an ephemeris propagation, and the acquisition data are generated and transmitted, the stations might not have enough time to use these acquisition data. (More than 30 minutes would probably have elapsed.) On the other hand, using the DOWD data in conjunction with only 10 minutes of DSN range-rate data yielded far better results in terms of meeting the antenna beamwidth constraints for extended periods of time (at least 12 hours). The DSN-only, single-station solution, based on 10 minutes of range-rate data, was not acceptable for acquisition purposes at any time. Therefore, the DOWD data were essential for generating a quality solution based on minimal amounts of tracking data. This would have been significant if a contingency had arisen during the WIND mission calling for more immediate acquisition data updates.

For the WIND spacecraft, deleting data through the use of atmospheric editing criteria had no effect on the solution because the WIND trajectory was outside the effects of the Earth's atmosphere throughout the span of DOWD data. Also, attempting to solve for a TDRS bias would not be prudent because the data arc is extremely short and because of the highly elliptical nature of the orbit. Errors are introduced into the solution when solving for a bias over such a short arc, because another variable must be solved for in addition to the orbital state variables.

The NOAA-J results showed that all the solutions were viable for acquisition throughout the entire early orbit support period of approximately 10 hours. These solutions included DOWD-only and C-band-only tracking data spans. When the DOWD and C-band tracking data were combined over shorter tracking data spans, the solutions were enhanced, thus improving acquisition capabilities. The optimal solutions were obtained when the atmospheric editing criterion was set at 200 km. However, this is dependent on the amount of tracking data available and the type of orbit. If the tracking data available are sparse, then no atmospheric editing should be done, so as to permit the maximum amount of data to be brought into the solution.

Solving for TDRS biases did not improve the solutions for NOAA-J because the solved-for biases were simply the difference of two TDRS biases and were therefore very small. This is due to the fact that the atmospheric effects and the user transponder biases are effectively cancelled out. Combining the DOWD data with the C-Band data drastically improved the solution state of NOAA-J. This was the case for the short-arc solution as well as for the longer arc solution. This is of great importance early in a mission when the tracking data can be scarce, or when the mission is nonnominal.

Both the WIND and the NOAA-J results show the possible benefits of TDRS DOWD tracking data for critical launch and early orbit support. The WIND short-span solutions were only viable when DOWD data were included in the solution. The NOAA-J DOWD-only solutions were viable without any other data types included in the orbit determination. This is significant for a contingency scenario, such as a ground station going down before an expected pass. Given the nature of some orbit profiles, specifically polar-orbiting spacecraft, the available ground station coverage might not be sufficient for a timely orbit determination solution unless DOWD data were available.

An additional benefit of the DOWD data was investigated with the WIND spacecraft. Because WIND is a spin-stabilized spacecraft where the omni antennas are not aligned along the spin axis, the tracking data residuals could be processed to give an estimate of the rotational rate of the spacecraft. This procedure could be used for other missions as an additional means of quantifying the rotational status during critical support periods.

In summary, the availability of TDRS DOWD tracking data reduces the reliance on ground stations by providing an alternative source of tracking data via the SN. DOWD data could prove beneficial for missions that have significant gaps in ground station coverage if the spacecraft can radiate to two TDRS's simultaneously. (See References 2 and 7.)

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