TDRS-3 ORBIT DETERMINATION ACROSS UNKNOWN MANEUVERS

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ABSTRACT

On March 22, 2006, the Tracking and Data Relay Satellite TDRS-3 experienced an anomaly leading to a protracted period of loss of service. The anomaly included significant thrusting for more than 2 hours and minor thrusting for another 10 hours. This unexpected thrusting caused significant changes to its orbit. Recovery was complicated by the quality and unavailability of the tracking data and difficulty in obtaining a good orbit determination (OD) solution.

We revisit this event and the subsequent orbit recovery and use an optimal sequential filter OD method. The tracking data is processed using Orbit Determination Tool Kit (ODTK). Techniques for modeling unknown thrusts and identifying biased measurements will be presented, as well as methodologies for OD in the absence of detailed information.

1. INTRODUCTION

TDRS-3 experienced an anomaly in 2006 resulting in losing attitude control and significant thruster firing. The combination of the thrusting and unavailability of usable tracking data made OD during and after the anomaly very difficult. The following paragraph and table from [1] summarize the events:

“On March 22, 2006, TDRS–3 had an Emergency Time Out (ETO) resulting in an attitude divergence leading to a protracted period of loss of service. The anomaly included significant thrusting for more than 2 hours until near 0300 UTC, which accounted for nearly 90% of the total thrusting during the ETO. Minor thrusting continued for another 10 hours until approximately 1300 UTC and accounted for the remaining 10% of the total thrusting experienced during the ETO. The spacecraft was then drifting westward at a rate of 3 degrees per day. The FDF found that the orbital position change from the thrusting was approximately 4,380 km after 32 hours.”

The Flight Dynamics Facility (FDF) at NASA Goddard Space Flight Center routinely performs OD for the TDRS satellites. The difficulties in obtaining a good orbit solution warranted further investigation by the FDF to define the appropriate responses and procedures for this type of problem [2].

Table 1. Event Timeline

Date (UTC)	Event
3/22 ~01:00	Loss of attitude control and loss of Earth reference
~03:00	End of 90 percent of thrusting
~13:00	End of last 10 percent of thrusting
~14:30	TDRS-3 returned to normal mode, S-band TT&C tracking only
3/23	FDF provided solution based on pre-maneuver data.
3/23	First pass of DS46 data received.
3/23	Third and last pass of DS46 data received
3/23	FDF had not generated a usable solution from the data.
3/23	The first post-tumble United States Strategic Command (USSTRATCOM) solution was received.
3/23	FDF delivered a converged solution from three Canberra passes over a 7–hour arc using the USSTRATCOM vector as initial conditions.
3/24 00:15	Maneuver to stop drift.
12:15	Maneuver to return the spacecraft to its box (to start drift back).
3/25	Resumption of usable BRTS events
3/28 02:43	Maneuver to slow drift
14:37	Maneuver to stop drift and stay in the box
3/28	TDRS-3 emergency terminated

We decided to revisit these events to see if another approach could improve the recovery time and provide a template for solving similar problems in the future. This paper summarizes the approach and results.

2. ORBIT DETERMINATION APPROACH

Thrusting – planned or unplanned – introduces additional forces that must be modeled to perform OD across the period of thrusting. This can be challenging, particularly when the thrusting is unplanned or the details are not known. We will refer to a period of thrusting as a “maneuver” - regardless of why it is happening.

The primary OD tool used at the time of the anomaly was the Goddard Trajectory Determination System (GTDS) using a least squares method. When a maneuver occurs, the analyst collects tracking data and performs OD over a span following the maneuver. OD across any significant maneuver is typically not performed due to the complexities introduced. This is typical of most least squares OD processes.

We chose to use the optimal sequential filter available in ODTK [3] because it offers the ability to perform continuous OD across impulsive and finite maneuvers. We can then calibrate or reverse engineer the maneuver. A typical run consists of running the filter forward in time and a fixed interval smoother backwards.

3. MANEUVER MODELING

Maneuvers fall into two categories – cooperative or uncooperative. During a cooperative maneuver the details of the maneuver are reasonably well known – start time, duration, thrust direction and magnitude. An uncooperative maneuver is missing some or all of this information. It may be that the only thing known is that a maneuver occurred. This is typically determined when the filter diverges due to the unmodeled maneuver forces.

Unmodeled maneuvers are recognized by a series of rejected post-maneuver tracking data measurements. In this case we model one or more uncooperative maneuvers and the filter is restarted at a point before the maneuver. If the maneuver model is reasonable, the filter will successfully process across it and continue accepting measurements. The quality of the OD solution and the maneuver model it uses can be assessed by evaluating the McReynolds filter-smoother (FS) consistency test to the parameters in the OD state space. This allows us to solve for unknown maneuvers using an approach similar to that in [4].

Unplanned thrusting during a spacecraft anomaly can be treated as one or more uncooperative maneuvers with the thrust magnitude and direction varying in time. Multiple thrusters are often firing simultaneously. A typical example of this would be a Sun or Earth acquisition sequence or other tumble recovery.

ODTK models finite maneuver states as Gauss-Markov processes with a one sigma uncertainty and a half-life. The user has the option to choose whether these are specified in magnitude and direction space or as individual X, Y, Z components in a specified coordinate frame. When specifying the uncertainty in magnitude and direction space individual half-lives are set for the magnitude and direction. When the uncertainty is specified in component space there is one-half life set for all three components.

The method we have found most useful for uncooperative maneuvers is to model the maneuver as if it had no thrust along any axis, but to specify that there is an uncertainty in the thrust along each axis. For example, a typical uncooperative intrack maneuver might be modeled in the radial, intrack, and crosstrack (RIC) frame with thrust components 0, 0, 0 N, and a one sigma uncertainty in each axis of 0.001, 5, 0.001 N. The sigma settings are dependent on the nominal thruster size and any intuition as to the direction of the maneuver. In the worst case we can assume that the direction is completely unknown and use a large uncertainty in each axis (depending on the size of the spacecraft thrusters).

4. NOMINAL SOLUTION

An ODTK scenario was configured using the following force model settings: 8x8 EGM96 gravity field, solar and lunar perturbations, and solar radiation pressure. The orbit state, solar radiation pressure coefficient Cp, and initial measurement biases were all estimated. Known maneuvers due to momentum dumps were modeled as instantaneous maneuvers.

The primary tracking station during routine operations was GWMK in Guam collecting azimuth, elevation, and range measurements. Additional ranging data was obtained using the Bilateral Ranging Transponder System (BRTS) where a ranging signal was uplinked from GWMK, relayed through the satellite down to a ground transponder ALSJ in Alice Springs, Australia, and then returned back through the satellite to GWMK. BRTS Doppler data was also available through the same path, but it was not used as it did not improve the solution accuracy.

An OD was performed to assess the performance before the anomaly. The solution was based on the GWMK azimuth, elevation, range, and BRTS Range measurements. All measurements were used (no thinning was performed). Fig. 1 shows the range residuals and the blue line is the correction to a fixed range bias. The residuals look as expected and are within the 3σ editing bounds. Fig. 2 shows the position consistency test results from the filter and smoother. The RIC position states are within the desired ±3 range.

5. ANOMALY SOLUTIONS

The next step was to investigate the OD performance across the anomaly period. We used an approach similar to that in operations – we must perform the OD without benefit of the knowledge gained in the post-anomaly investigation.

The NASA report [2] states

> "The anomaly included significant thrusting for over 2 hours until near 0300 UTC and minor thrusting continuing for another 10 hours until approximately 1300 UTC, when the thrusting ended."

The FDF analysts knew this much at the time of the first OD runs. To model the unknown thrusting, a finite maneuver was modeled from 22 March 00:48 until 13:00.

The start time was chosen since it was the time of the last available range measurement before the anomaly began. This may be a bit early, but is a conservative assumption as it is guaranteed to include the beginning of the thrusting. The stop time was chosen based on the time that the thrusting ended.

The thrust profile as a function of time was unknown, so the RIC thrust magnitudes were set to zero. A TDRS satellite has 1-lb thrusters, and we understand that two thrusters were firing at a time (in a given direction) during the anomaly period. Therefore we set the one sigma thrust uncertainties to 2 N (approximately 0.5 lb) and the half-life to 30 minutes.

A series of OD runs were performed beginning with 21 March 21:00 during routine pre-anomaly operations using a filter restart record from the nominal OD run and ending on 22 March 21:00, eight hours after the thrusting ended. Restart records are used during normal OD operations to save the filter state space and covariance to disk so that future OD runs can continue without having to reinitialize the filter each time.

Run 1 used all measurements from GWMK (azimuth, elevation, range, and BRTS range) and the first pass from DS46 (X, Y, Doppler, and range). DS46 is a tracking station in Canberra, Australia that was tasked to provide additional tracking data following the anomaly. Angles collected while the antennas were not in autotrack mode were discarded.

It quickly became evident that this solution would not succeed, as the filter immediately diverged during the anomaly period and did not recover afterwards. This is illustrated in the azimuth, elevation, and range residuals in Figs. 3 and 4. The maneuver period is shaded in light blue-purple. The thrust uncertainty causes the position and velocity covariance to expand quickly – this is evident in the rapidly increasing measurement editing sigmas. Note the very large scale of the range residuals. A closer look at the range residuals during the mid-anomaly pass around 22 March 09:33 showed the filter managed to accept a couple of them before rejecting the rest. A similar problem occurs with the next range pass around 22 March 14:35. All the post-maneuver angle measurements are also being rejected. This implies that either the anomaly thrusting model is incorrect or that the range measurements were biased. No other measurements were available during the anomaly period to provide a means to cross-check the range measurements.

Run 2 tested the hypothesis that the range measurements were biased. The filter is configured to force reject all GWMK range measurements from 22 March 00:49. Unfortunately, the filter still diverged at 22 March 17:14 as it began processing the DS46 Doppler measurements (Fig. 5). Again, the issue can be with the anomaly thrusting model or the measurements. Since DS46 XY angle measurements were also available we decided to see if the Doppler data was also an issue.

Run 3 had the filter configured to force reject all the Doppler measurements. This filter still diverged, but the patterns in the XY angle residuals led us to believe that the angle measurements from DS46 before 22 March 18:47 were unusable [or biased].

Run 4 had the filter force reject the following measurements: all Doppler, GWMK range, and DS46 XY angles (until 22 March 18:47). This run was very successful, with the filter accepting the angle measurements from both GWMK and DS46 and the range measurements from DS46. This is also like the initial solution FDF delivered.

Run 5 is the same as Run 4, but extended to include all passes until 24 March 00:00. We include the Run 5 results in the interest of brevity, as they are identical to Run 4 for the time period they overlap. The GWMK range residuals in Fig. 6 show an interesting step function signature. The same step function was observed by the FDF team and discussed in [1] and [2]. Note the scale of the residuals is on the order of 100's of kilometers. This confirms the theory that the GWMK range measurements were biased during and following the anomaly. A zoomed in view of the DS46 range residuals is inset, indicating they are being accepted by the filter.

The DS46 Doppler residuals in Fig. 7 also show some very strange patterns. They are being force rejected during this run, but it appears there are three groups of possibly valid measurements. The XY angle residuals in Fig. 8 look good.

Fig. 9 shows the filter 3σ position uncertainty in the RIC frame. Following the anomaly, the in-track uncertainty was as high as 6250 km and collapsed to less than 5 km (see inset) by 23 March 00:00, only 11 hours after the end of the maneuver. The solution is now good enough to begin recovery maneuver planning. The recovery time is dependent on the availability of the measurements and the orbit geometry [7]. In this case the half an orbit recovery is typical. The position consistency in Fig. 10 stays within the desired ±3 range, so we believe our solution is valid.

Fig 11 shows the thrust corrections calculated by the smoother. No measurements were available during the maneuver, so it's difficult to characterize the specific details of when the thrusting occurred (unless available from telemetry). However, it's interesting to note that most of the corrections occur in the first half of the maneuver. This is consistent with the note from [1] that the majority of the thrusting occurred in the first 2 hours.

The post-maneuver azimuth, elevation, X, and Y angle measurements were very useful for reducing the orbit uncertainty when range data was unavailable. Angle measurements typically don't contribute much to a high accuracy solution, but when the OD uncertainty is large, they make a significant contribution.

The OD ephemeris from the smoother was compared to state vectors from the FDF solution at 20 March 00:00 (pre-anomaly) and 26 March 00:00 (post anomaly and after two longitude drift rate control maneuvers) with total position differences of 48 and 53 m, respectively. The FDF post-maneuver solution used a least squares (LS) fit span from 24 March 16:23 to 26 March 14:23. The filter and smoother solution were run continuously until 26 March 14:23 (consistent with the LS fit span) and across all maneuvers (anomaly and drift rate). The smoother ephemeris was used because it incorporates all measurements known up to the end of the LS fit span.

The filter solution was also compared to ephemeris from Two-Line Element (TLE) sets (switching TLEs at each TLE epoch). Ten TLE sets were available for 23 March, reflecting the high priority that was placed on recovering TDRS-3. The first post-anomaly TLE had an epoch of 23 March 09:54. During the pre-anomaly period the differences were generally less than 12 km (fairly reasonable for a geostationary satellite using TLEs). From 23 March 10:00 to 24 March 00:00 the difference was less than 15 km. This is consistent with the pre-anomaly TLE accuracy. Following the drift rate maneuvers, the differences between the smoother and the TLEs were less than 5 km at 26 March 00:00.

6. CONCLUSIONS

The filter-based OD combined with the finite maneuver model was successful at obtaining a valid OD solution across a period of significant unknown thrusting. It was particularly useful for identifying unusable tracking data. A useable orbit solution was obtained 24 hours sooner than the original OD process.

Response plans for future anomalies involving unplanned maneuvers should include collection of *any* available tracking data, provided that higher priority items such as vehicle safety are not compromised. This is particularly valuable if it can be done while the thrusting is on-going, as it allows for better characterization of the thrust profile. The use of multiple tracking stations is encouraged as it makes trouble-shooting data quality much easier.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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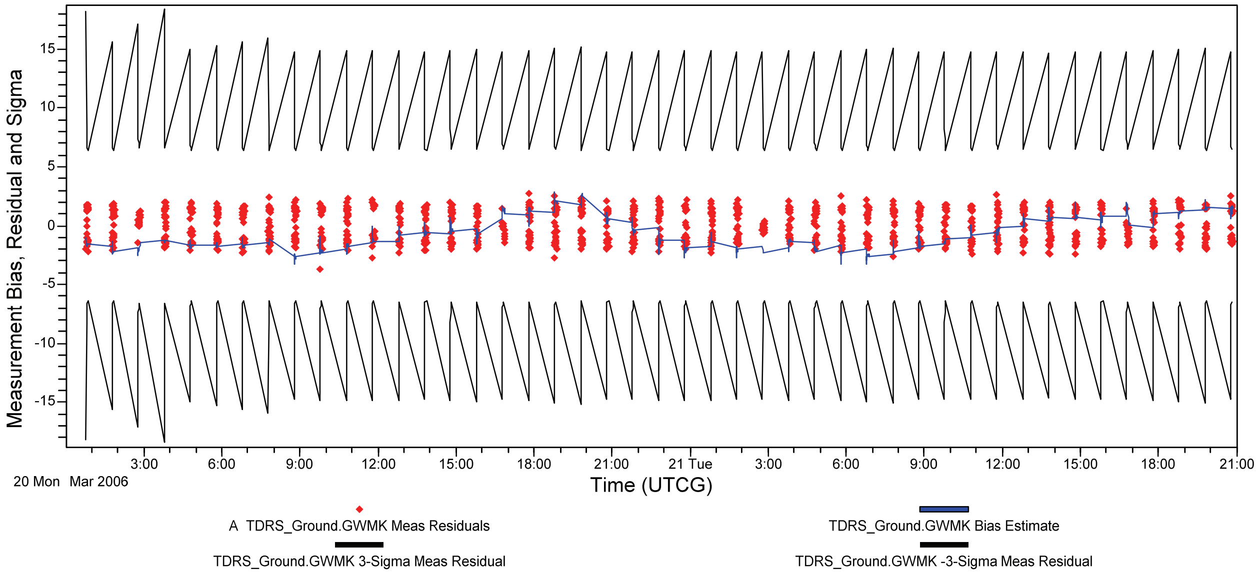

Figure 1. Nominal OD Range Residuals (m)

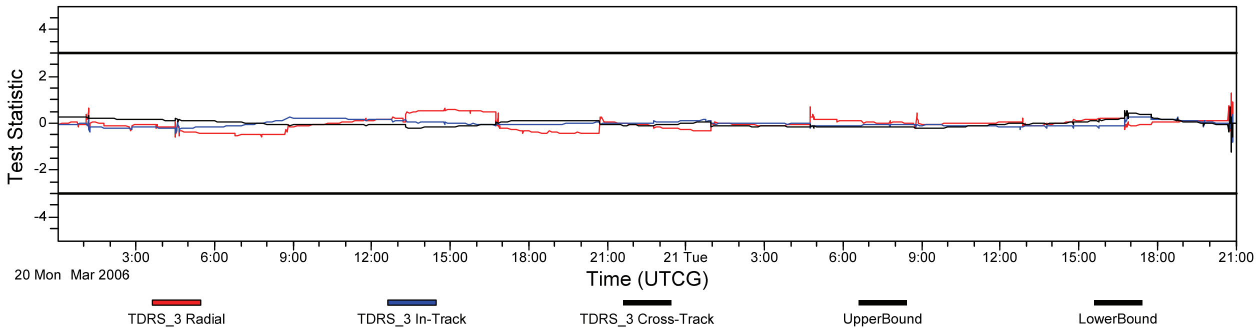

Figure 2. Nominal OD Position Consistency Test Statistics (Target-Reference)

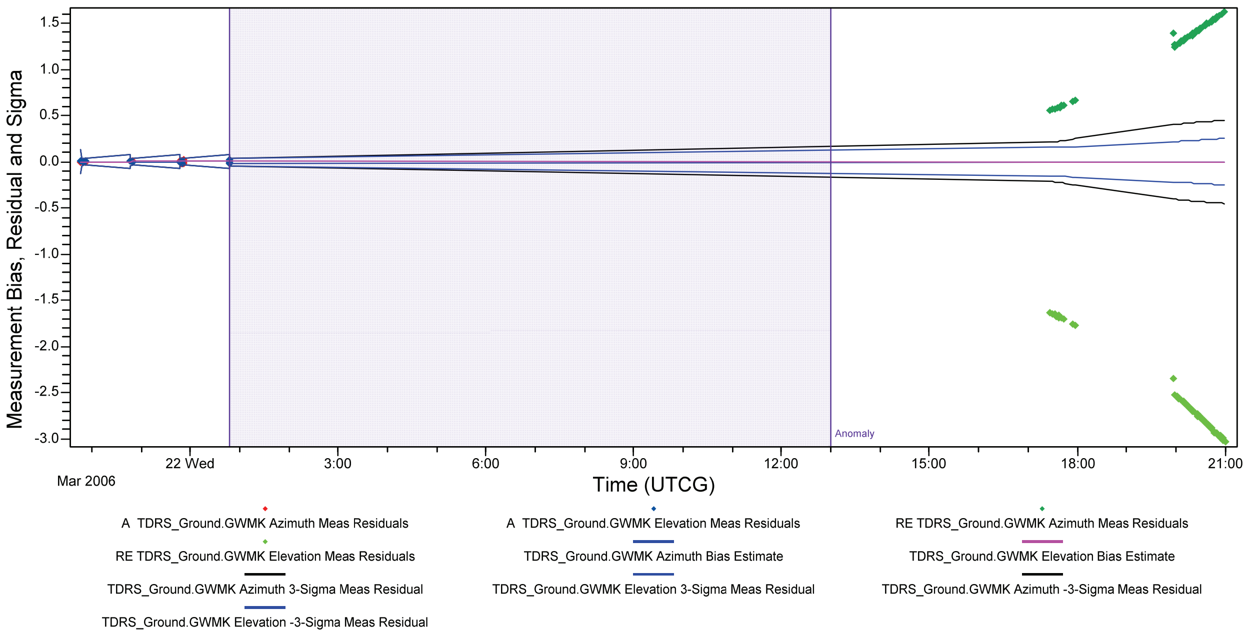

Figure 3. Run 1 Azimuth and Elevation Residuals (deg)

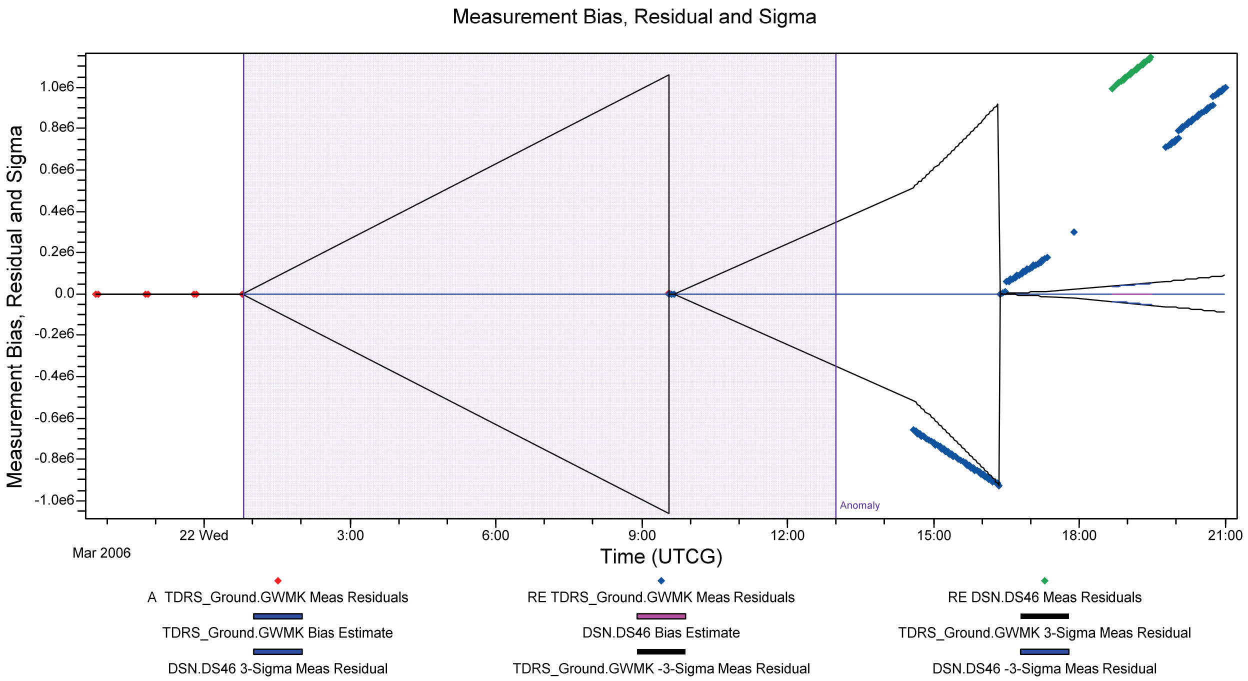

Figure 4. Run 1 Range Residuals (m)

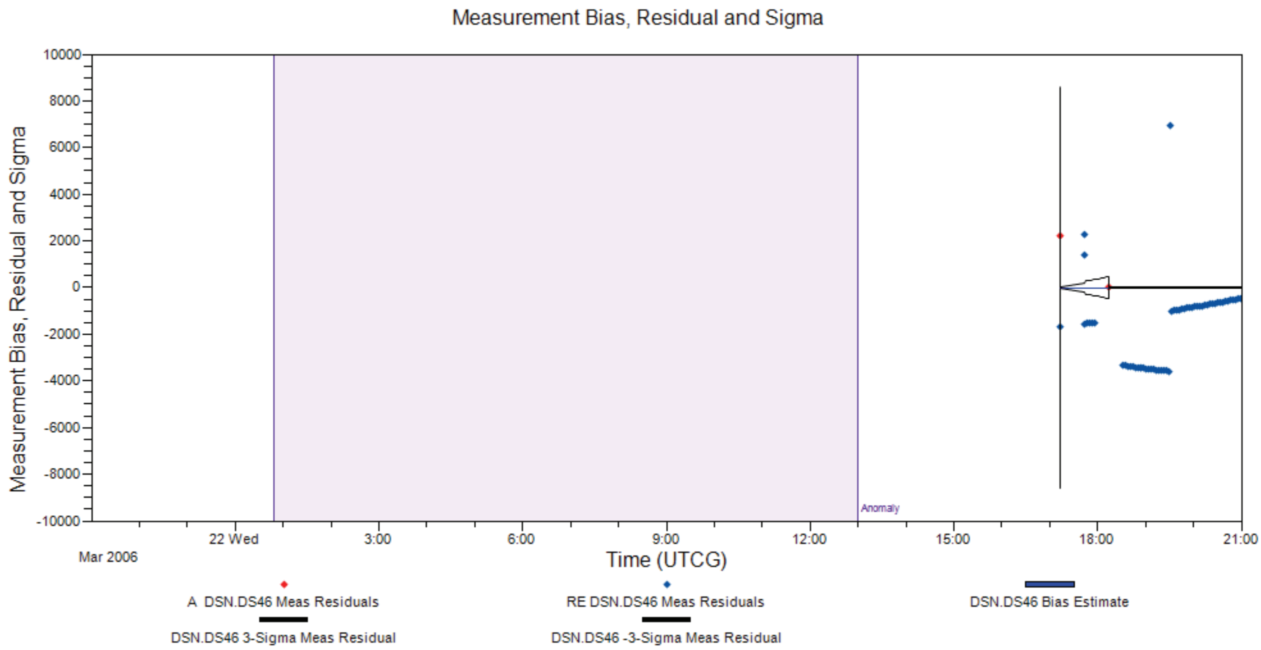

Figure 5. Run 2 Doppler Residuals (cm/s)

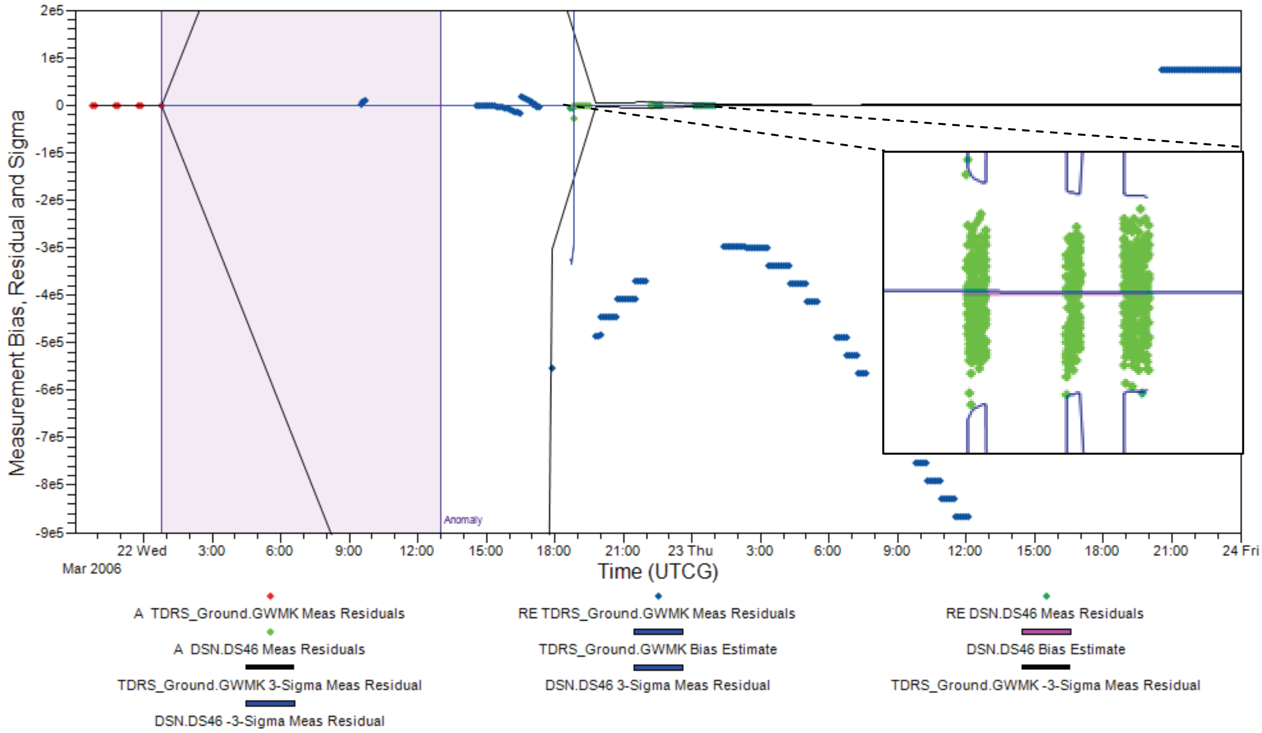

Figure 6. Run 5 Range Residuals (m)

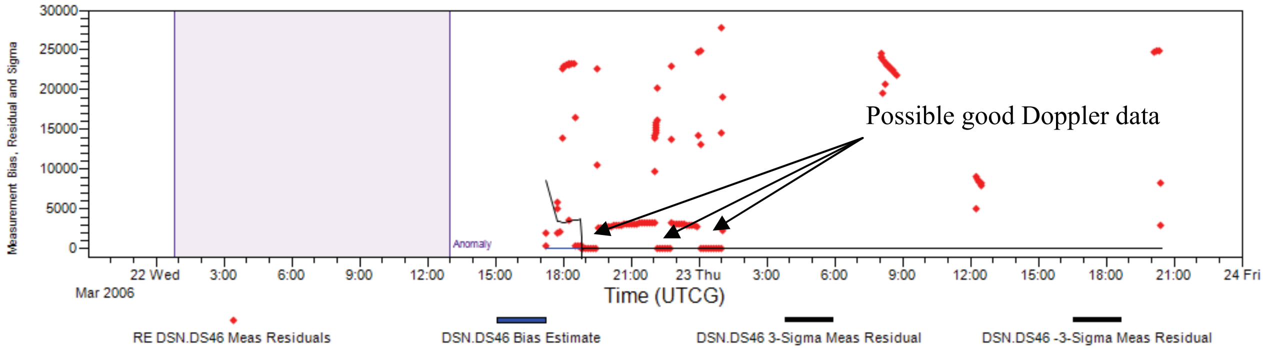

Figure 7. Run 5 Doppler Residuals (cm/s)

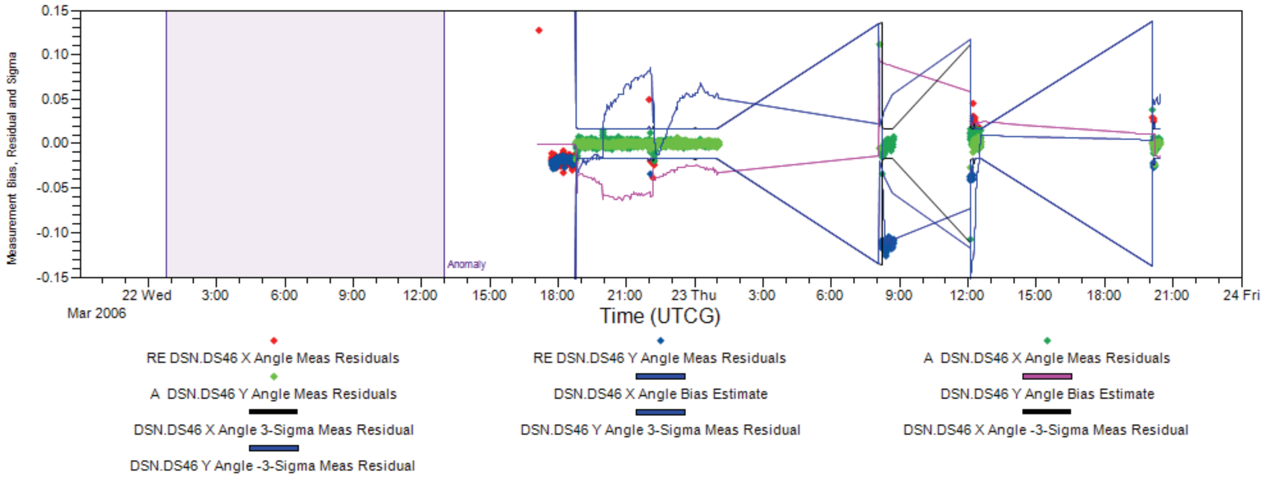

Figure 8. Run 5 XY Angle Residuals (deg)

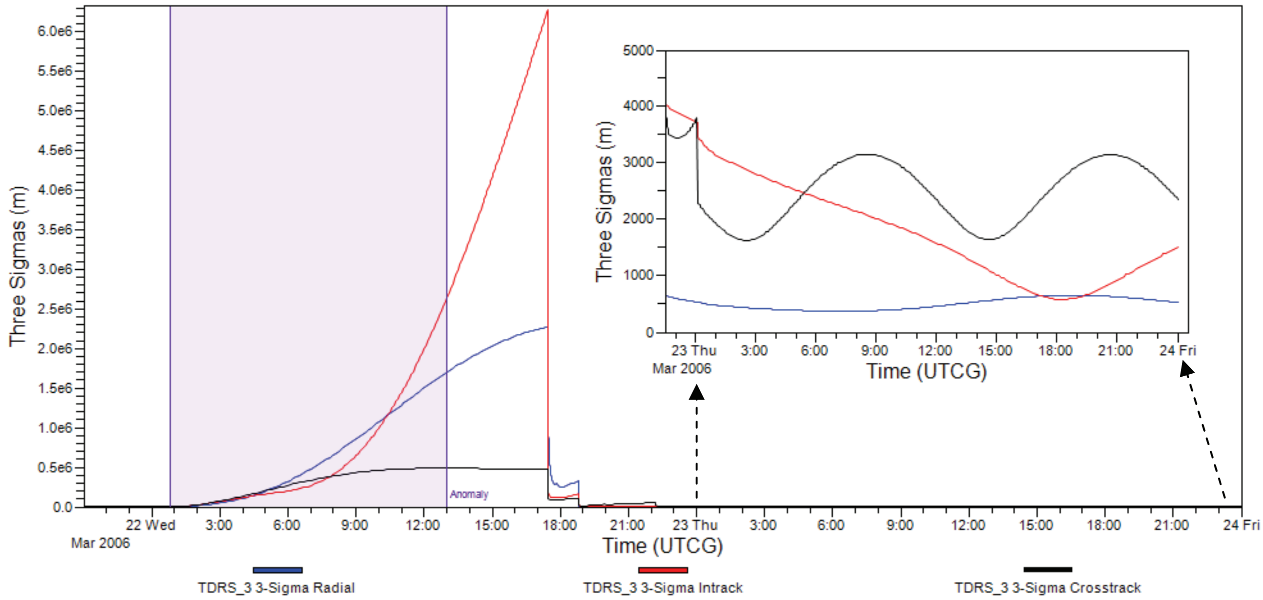

Figure 9. Run 5 Filter RIC Position (0.99) Uncertainty (m)

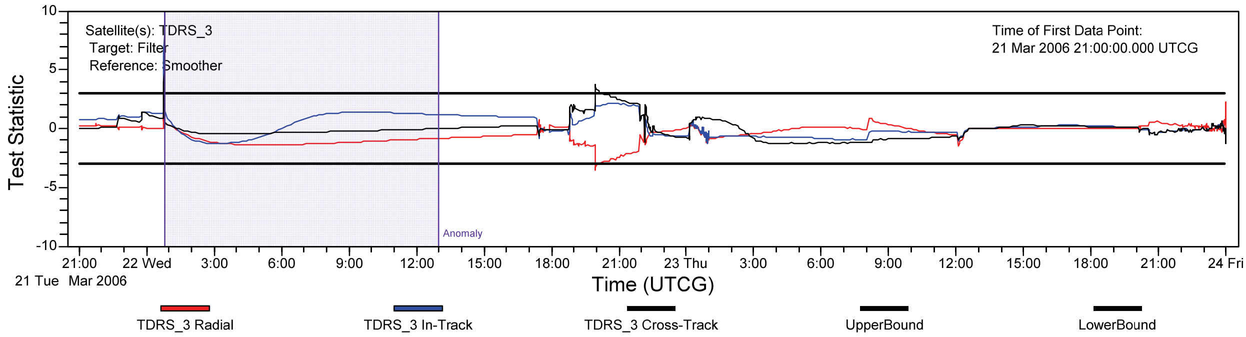

Figure 10. Run 5 Position Consistency Test (Target-Reference)

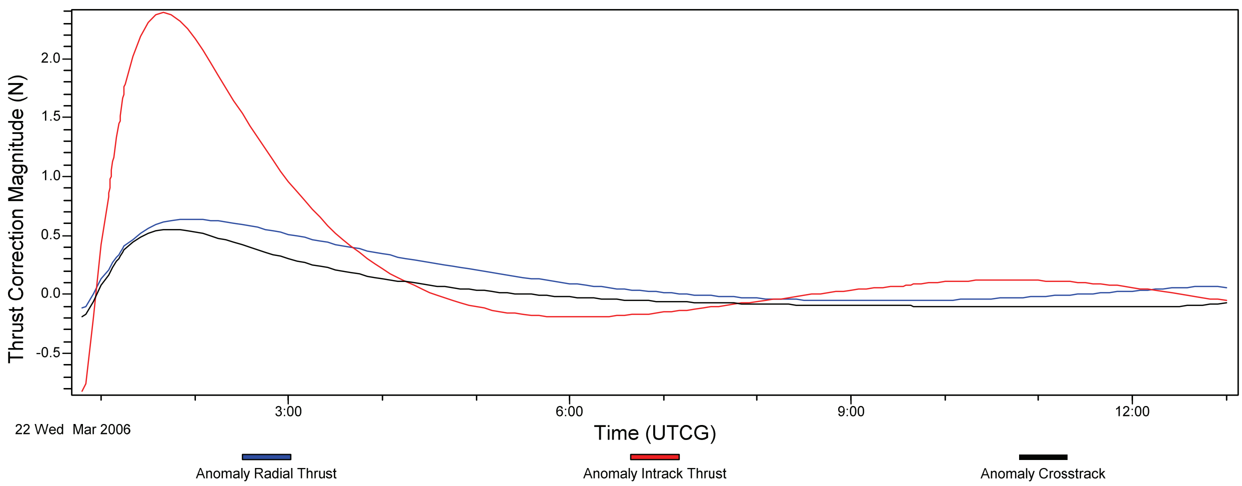

Figure 11. Run 5 RIC Thrust Corrections (N)