Operational Challenges in TDRS Post-Maneuver Orbit Determination

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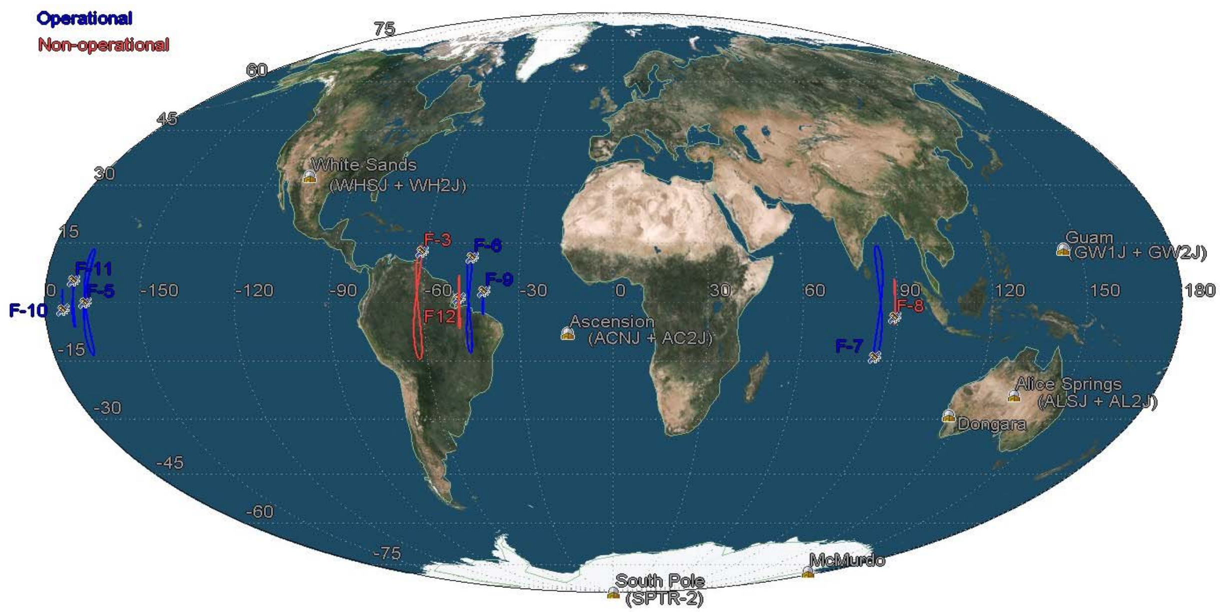
INTRODUCTION

- ***The GSFC Flight Dynamics Facility (FDF) performs daily and post-maneuver TDRS OD***
  - Terra, which receives tracking from the TDRSs, also uses the TDRS solutions for onboard navigation purposes
  - Terra's onboard navigation system presents the most stringent requirement for OD:
    - 75 meters total position accuracy predicted over one day
  - FDF provides post-maneuver OD 4 hours after a TDRS maneuver
    - Reliable support is provided by using both a Kalman Filter (ODTK) and a Batch Least Squares system (GTDS)
  - Challenges to TDRS Post-maneuver OD Support
    - Maneuver prediction uncertainty
    - Potentially unreliable tracking from User satellites
    - Predicted solution accuracy cannot be fully determined in real-time
- ***Post-maneuver Tuning Improvement***
    - Before improvement, TDRS-6 had shown some of the worst post-maneuver EKF performance in the fleet
    - Preliminary improvement showed 52% improvement in predictive accuracy
    - Further improvements are being tested with the other TDRSs

The TDRSS Constellation



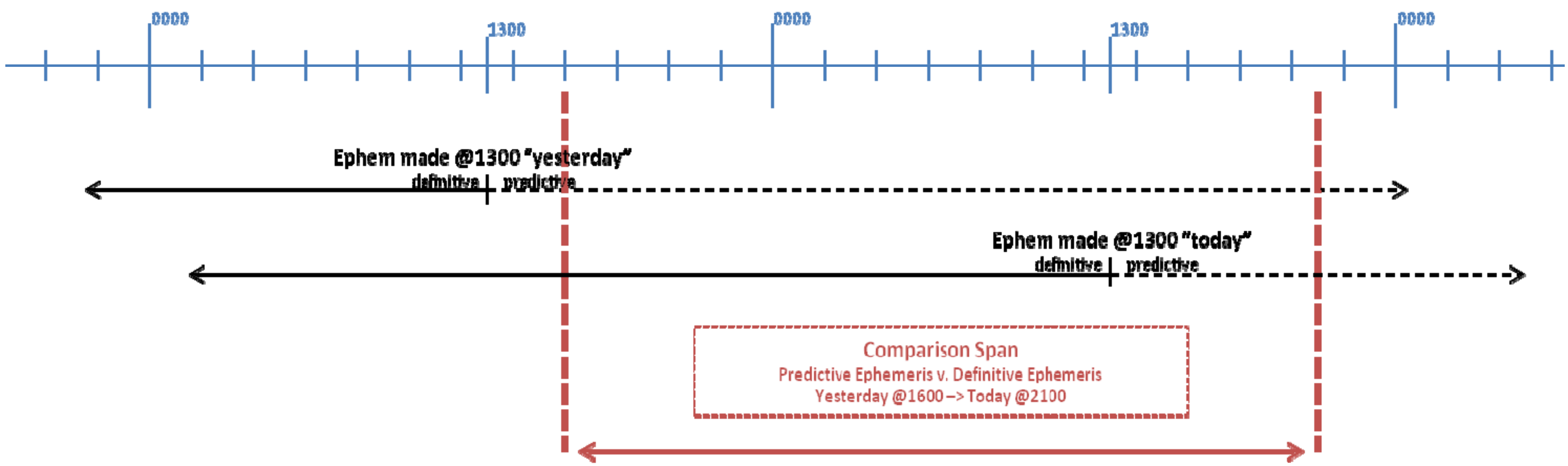
- ***Tracking and Data Relay Satellite System (TDRSS)***
- ***"Ground Stations in the Sky"***
- ***Provide global S-, Ku, and Ka-band communications for other satellites (Users)***
- ***For the FDF to provide OD, 3 types of data are used:***
  - Tracking, Telemetry and Commant (TT&C)
  - Bilateration Ranging Transponder System (BRTS)
  - User Satellite Tracking:
    - TDRS Satellites provide tracking for User satellites, which are solved for in the EKF
    - Consists of Aqua, Aura, Terra, and TRMM

FDF User Support

- FDF provides a number of different TDRS products to Users, with varying accuracy requirements:
  - Two-Line Elements
  - Osculating and Mean Elements
  - Predicted Site Views
  - TDRS Ground Tracks
  - TDRS predictive ephemerides
- ***Terra's TDRSS Onboard Navigation System (TONS) provides the most stringent requirement on the TDRS OD:***
  - TONS requires predictive TDRS information within 75 meters (m) to sufficiently maintain its own position history for correlation with science data and ground imagery.
  - This requirement is through 21:00UTC on the day after product generation.
    - The ephemeris accuracy is verified after the fact.

TDRS Comparison Span for Terra

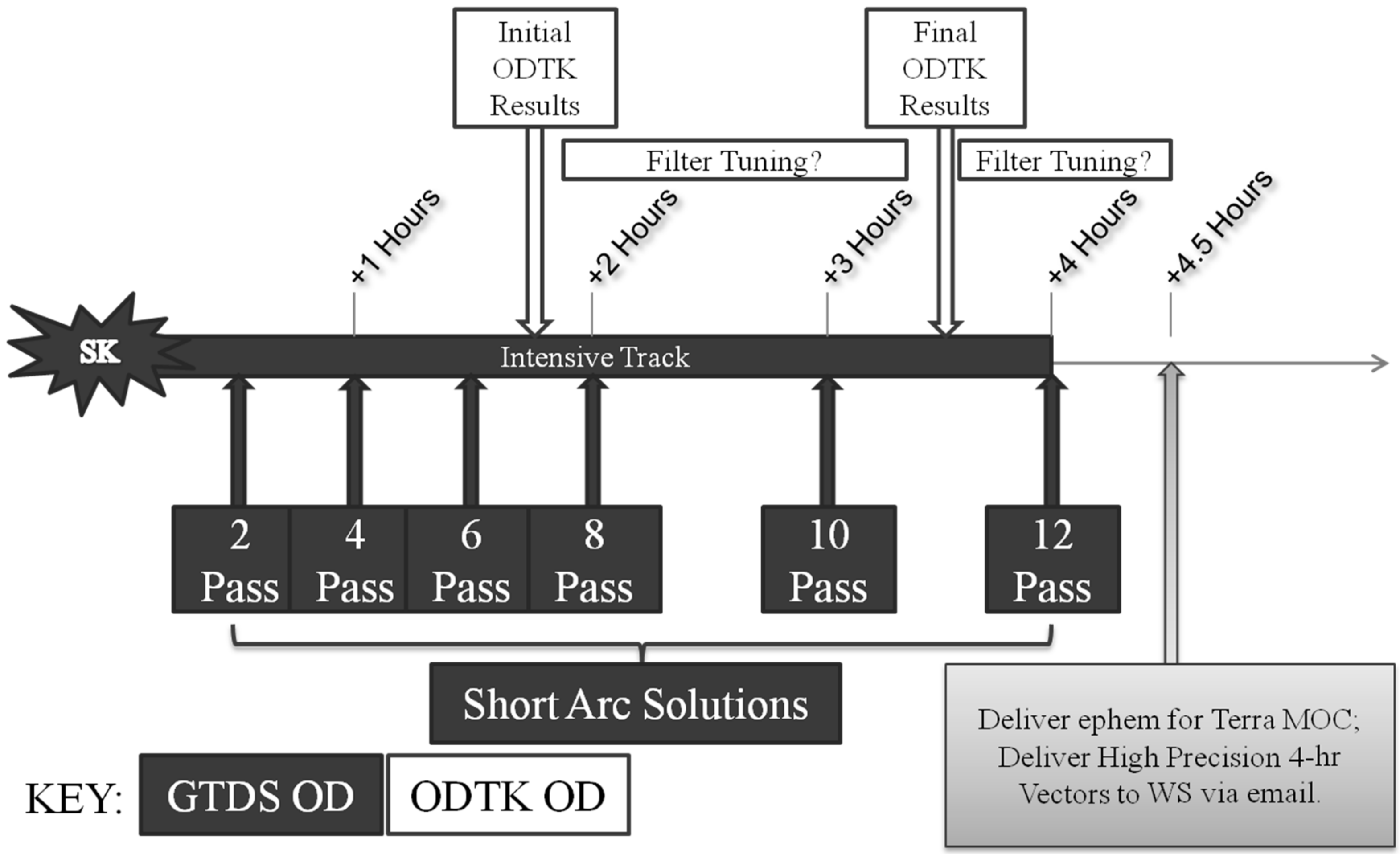
- ***FDF uses ephemeris compares to evaluate TDRS accuracy***
  - For daily support (shown below), FDF compares “yesterday’s” predictive span to “today’s” solution, which includes both definitive and predictive sections.
  - For post-maneuver support, compare span is potentially shortened
    - For this study, a longer post-maneuver compare span was chosen to overcome operational limitations.



FDF OD Systems

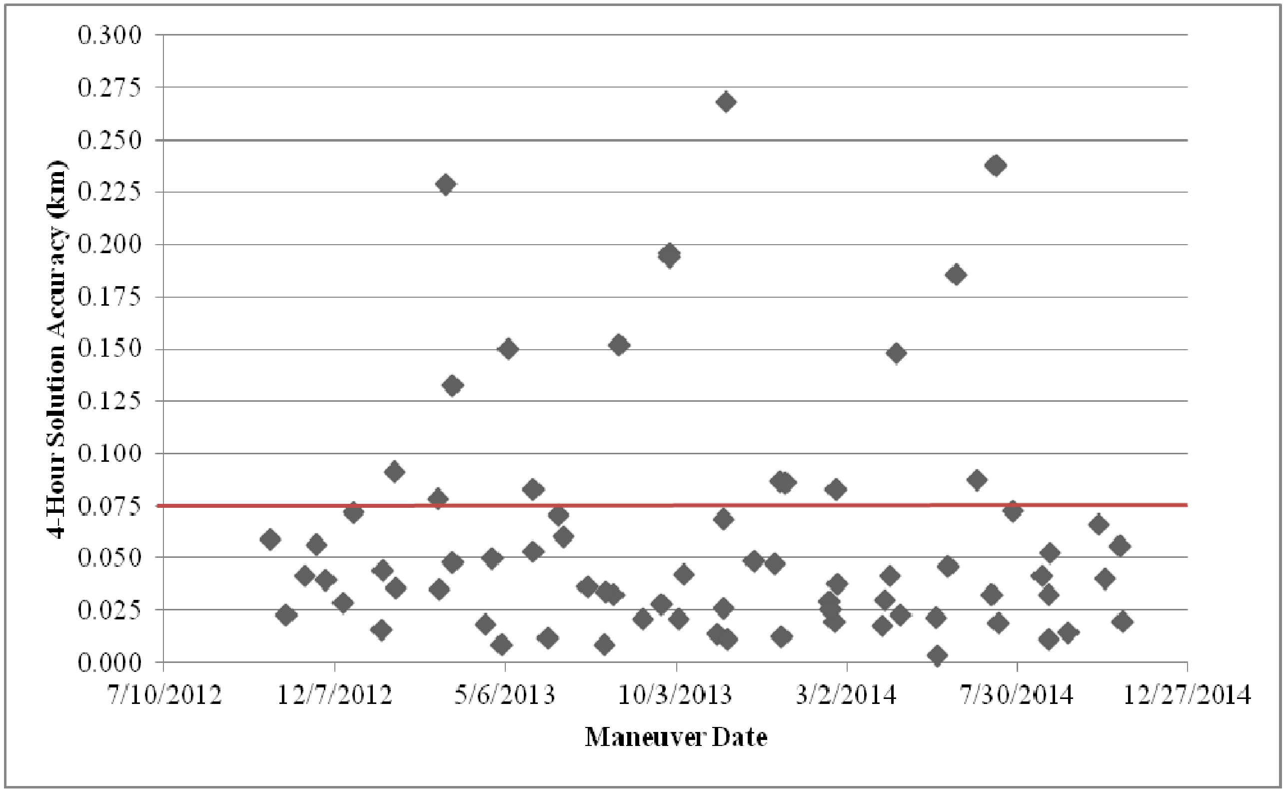
- ***Two Systems are used for Orbit Determination in the FDF:***
  - Batch Least Squares, implemented in the Goddard Trajectory Determination System (GTDS)
    - Long-standing OD tool in the FDF
    - Many custom modifications over the years to account for the nuances of TDRS support
      - Most notably the ability to estimate and apply chain-specific biases for TDRSs
  - Extended Kalman Filter, implemented in the Orbit Determination Tool Kit (ODTK), a COTS program provided by AGI.
    - Allows for simultaneous OD with the TDRSS Fleet, as well as 4 Users: Aqua, Aura, Terra, and TRMM
    - Provides a variety of built-in visualizations for determining solution accuracy and filter performance.

Post-Maneuver Support Strategy



TDRSS Constellation Post-Maneuver EKF Solution Accuracy

- ***Reflects all operational TDRSs between October 2012 and October 2014: TDRS-5, -6, -7, -9 and -10***



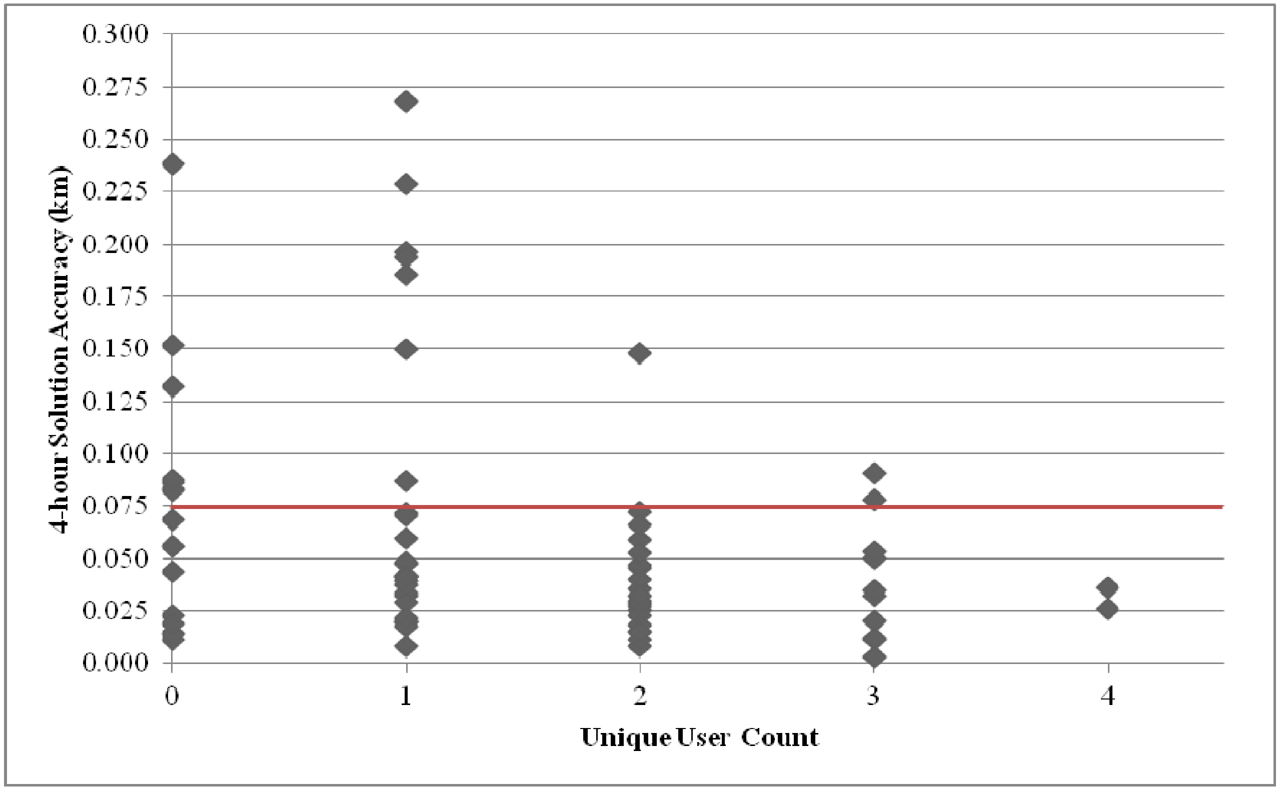
Ensure Mission Success

Potential Failure Drivers

- ***Two potential failure drivers investigated***
  - 1) Lack of User tracking on the solution
  - 2) Maneuver mis-modeling in predicted post-maneuver (a priori) vectors
- ***Relationship between User Tracking and Solution Accuracy:***
  - Four Users were available for tracking in the EKF:
    - Terra
    - Aqua
    - Aura
    - TRMM
  - No direct correlation was found with regards to the amount of time spent tracking User satellites or with regards to the amount of User tracking events
  - Correlation identified with respect to the number of <u>unique</u> Users tracked in the post-maneuver tracking window
  - Solutions with a higher number of unique Users were more likely to meet the 75m accuracy requirement

Potential Failure Driver 1: Lack of Unique User Tracking

- ***Unique Users Tracked vs. Solution Accuracy***
  - "Unique" reflects the fact that additional passes for the same user during the post-maneuver support did not provide additional improvement



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User Threshold and Failure Rate

- ***A threshold was determined to help indicate potential failures in real-time.***
- ***Maneuvers with less than 2 unique users are flagged as having a higher risk of failing the 75 meter requirement.***
  - Analysts could request specific User tracking during the post-maneuver window.
    - No guarantee that such a request would be fulfilled.

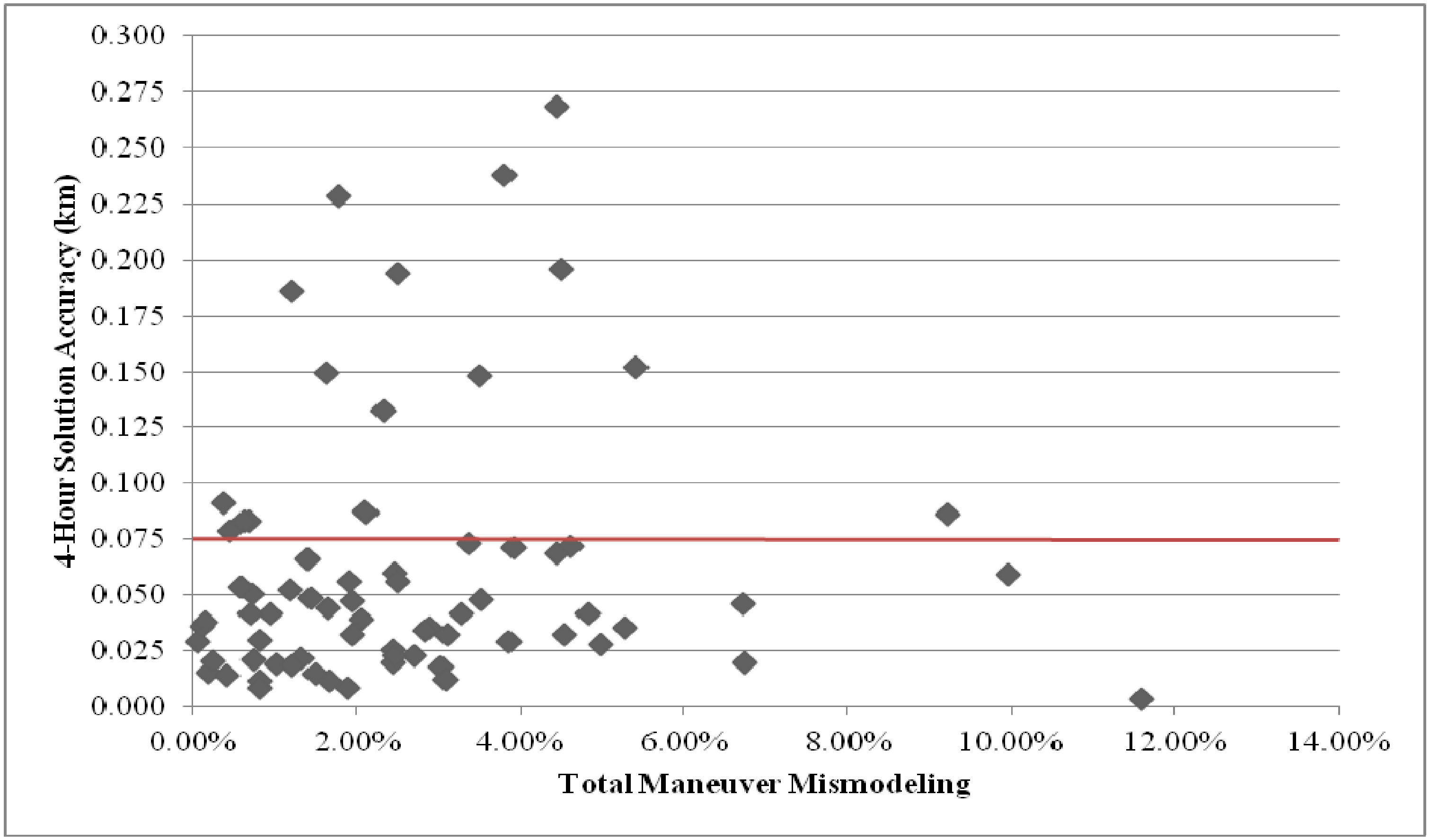
User Count Tolerance	Maneuvers that Meet the Tolerance	Maneuvers that Meet the Tolerance and Fail	Failure Rate
0	16	7	44%
1	59	10	17%
2	32	3	9%
3	12	2	17%
4	2	0	0%

Potential Failure Driver 2: Maneuver Mis-modeling

- ***Many potential sources of error in predicted post-maneuver a priori vectors:***
  - The FDF does not receive real-time telemetry data from the TDRS spacecraft.
    - Some thrusting events are unknown to the FDF analysts. These include attitude hold thrusting events.
  - Certain TDRSs have known thruster problems that result in off-nominal maneuvering.
    - Wherever possible, these factors are accounted for in the force modeling.
- ***For each maneuver a mis-modeling percentage was computed***
  - Compared the planned maneuver, provided by TDRS analysts at the WSC facility, to a recomputed maneuver based on a sufficiently long tracking data arc.
- ***No direct correlation was determined between Maneuver mis-modeling and post-maneuver solution accuracy.***

Impact of Mismodeling on TDRS Post-Maneuver Accuracy

- ***No direct correlation was determined between Maneuver mis-modeling and post-maneuver solution accuracy.***



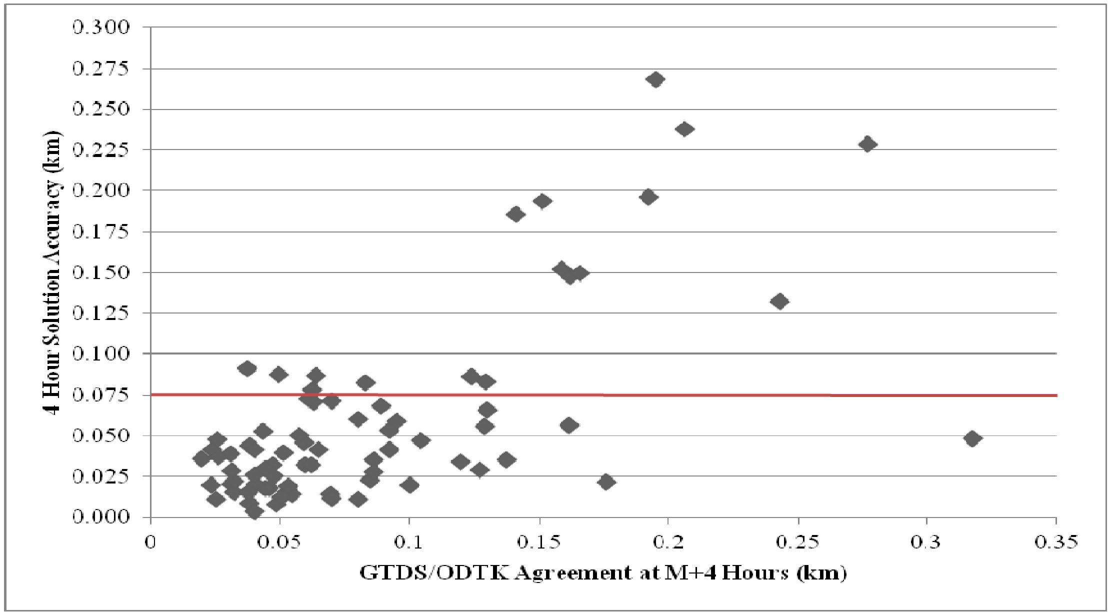
Real-Time Failure Indicators

- ***FDF analysts identified operational methods to be used during post-maneuver support to forecast the predictive accuracy in real-time.***

  1. System Agreement: Comparison of EKF solutions against the Batch Least Squares solutions was used to determine solution consistency.
  2. Residual Plots: Residual ratio plots, as well as position and velocity uncertainty plots were used to monitor filter performance.
  3. Identifying and characterizing User tracking events that took place during the post-maneuver support, as identified in the previous section, added another litmus test.

Real-Time Failure Indicator 1: System Agreement

- *During the post-maneuver ODTK process, comparisons are generated by propagating and comparing the ODTK EKF solution and the GTDS BLS solutions through 21:00 UTC on the following day.*
- ***A correlation was identified between OD system agreement and the overall solution accuracy.***



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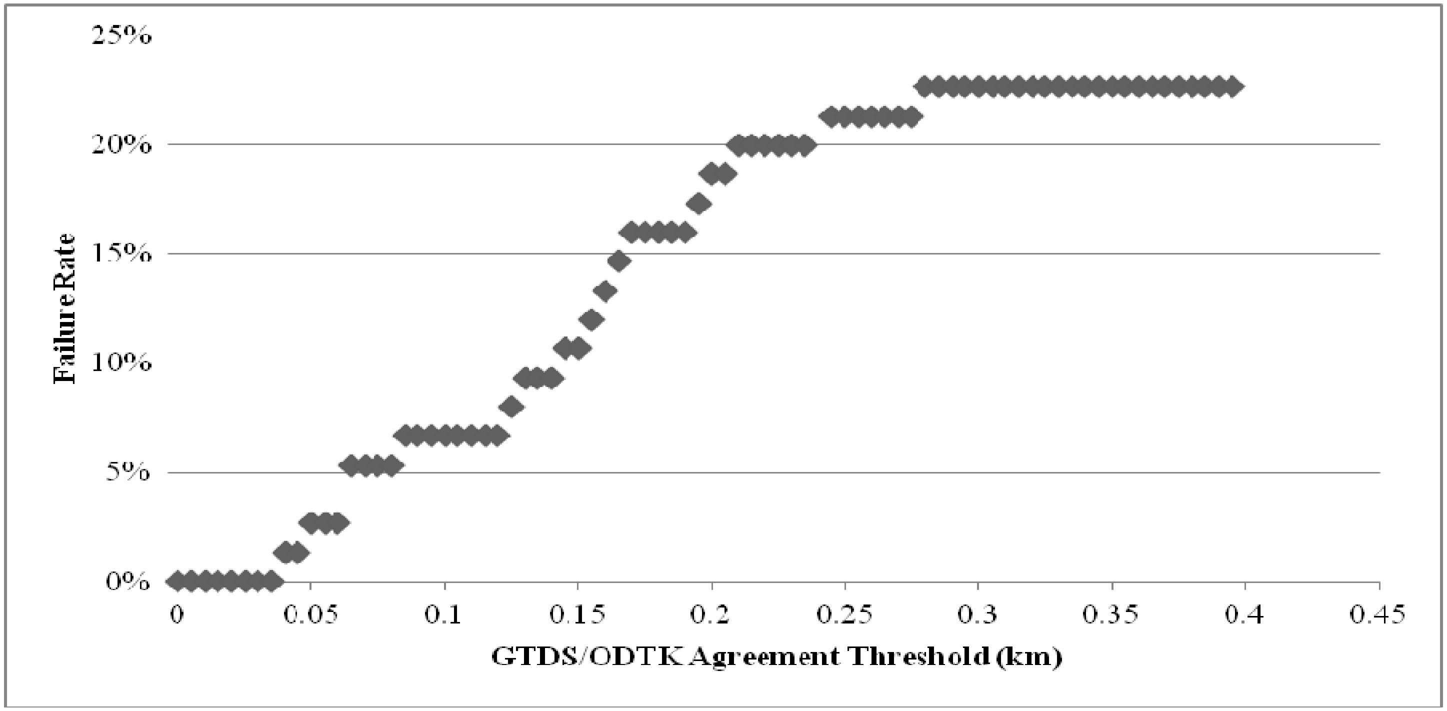
Applying a Threshold for System Agreement

- ***An associated failure rate was determined using historical system agreement.***
- ***A threshold for system agreement was set at 50 meters. Historically, solutions that failed to meet this threshold were more likely to fail the 75 meter Terra requirement***



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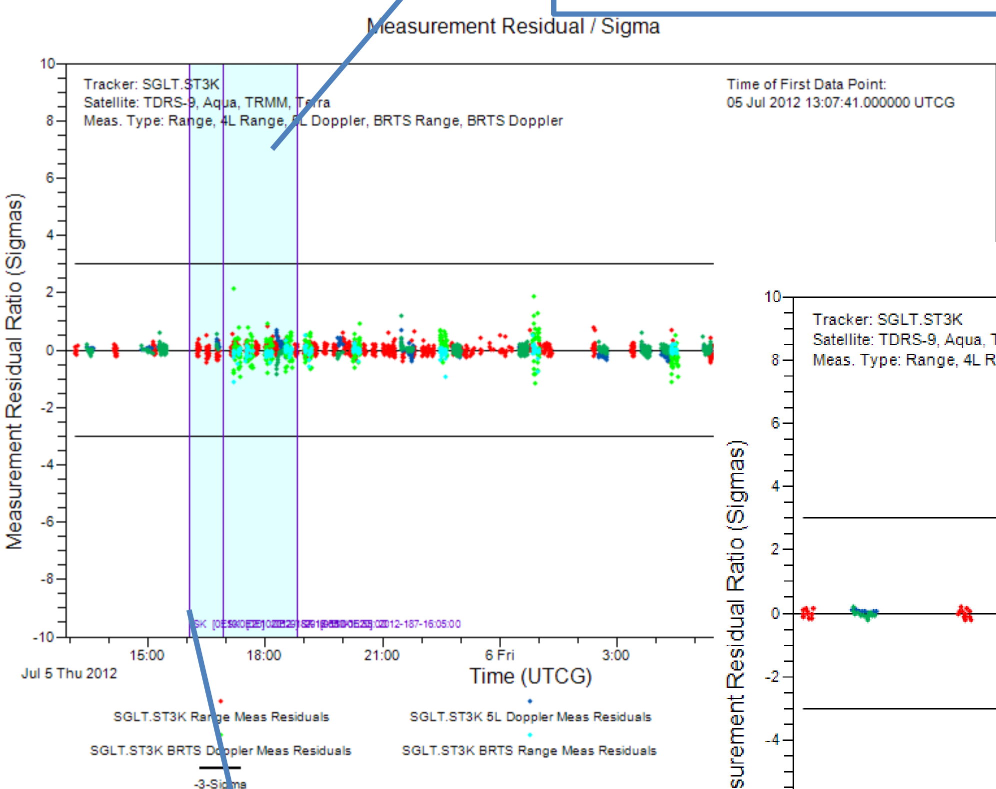
Real-Time Failure Indicator 2: Residual Ratio Plots

- ***Another strategy used to identify possible issues in real time was the residual ratio plots generated through ODTK.***
  - If issues are apparent in these plots during the post-maneuver support, measures can be taken to resolve them quickly.
  - TT&C data occasionally exhibits range biases in multiples of 300 meters, as a result of phase ambiguity in the tracking data.
    - Usually, this is automatically edited out of the solution, and can be identified as an apparent lack of TT&C data in the post-maneuver ODTK plots.
  - The ODTK solution can occasionally be "mis-converged," resulting in residual ratio plots with sinusoidal patterns that exceed the 3-sigma edit criteria.
  - Analysts in the FDF are trained to recognize such data as indicators of faulty ODTK solutions.
  - Analysts also have the ability to compare, pass by pass, which data was accepted into each of the EKF and BLS solutions.

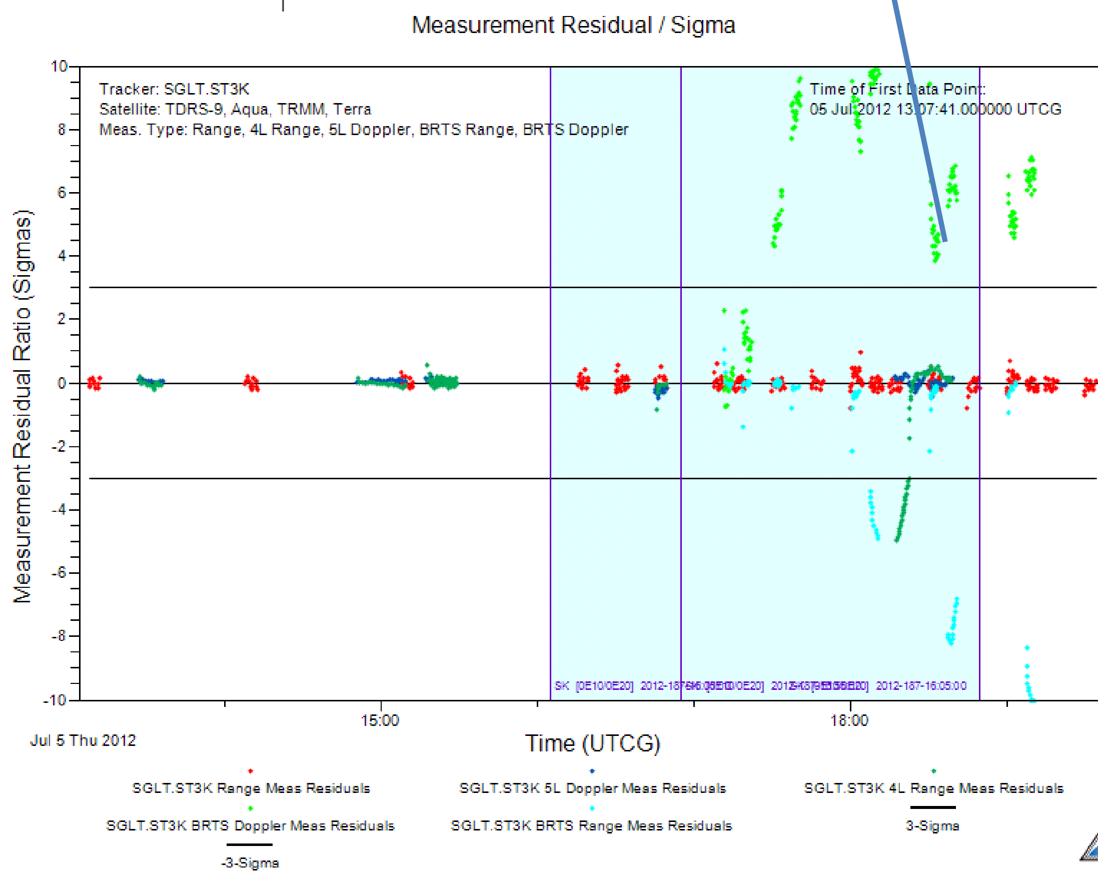
Real-Time Failure Indicator 2: Residual Ratios

Finite Uncertainty (Shaded Region)

Residuals Showing Unacceptable Behavior



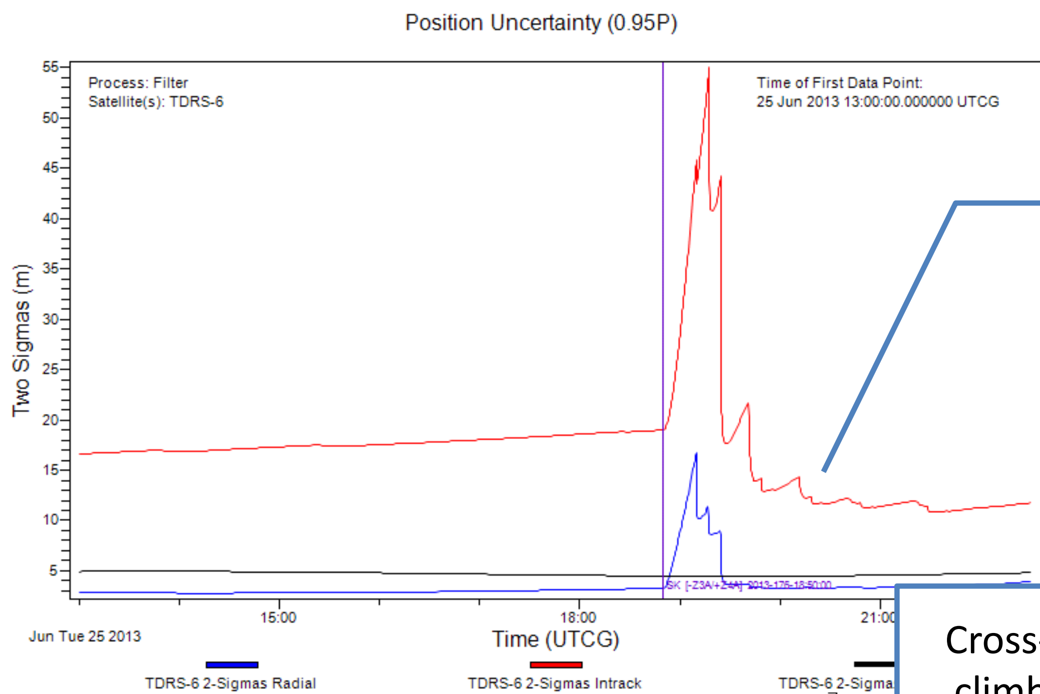
Maneuver Indicator (Two Firings)



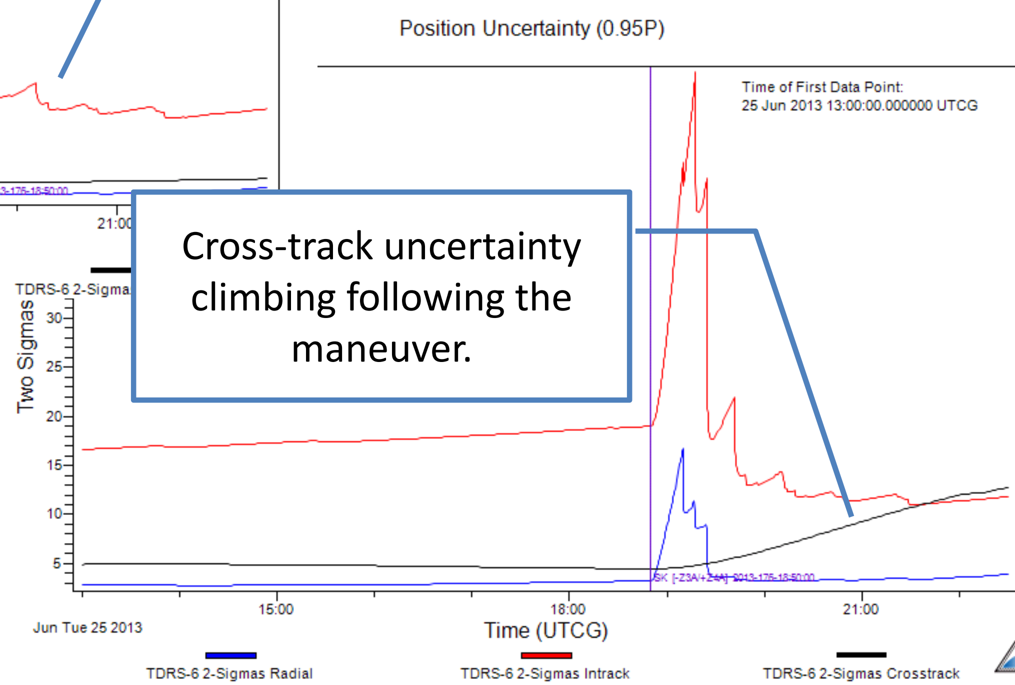
Real-Time Failure Indicator 2: Uncertainty Plots

- ***Plots of position and velocity uncertainty can also be used to predict solution accuracy in real-time.***
  - Application is much more nuanced.
  - Need to take into account the tracking profile, as the geometry of the ground stations could result in appropriately high uncertainty in one direction or another.
  - In addition, if a certain thruster is known to have inconsistent performance, then it would be appropriate to apply a greater degree of impulsive or finite uncertainty.
- ***"Does the uncertainty shown in the plots reflect what we expect based on the details of this specific maneuver?"***

Real-Time Failure Indicator 2: Uncertainty



Uncertainty levels out, drops to pre-maneuver levels.



Cross-track uncertainty climbing following the maneuver.

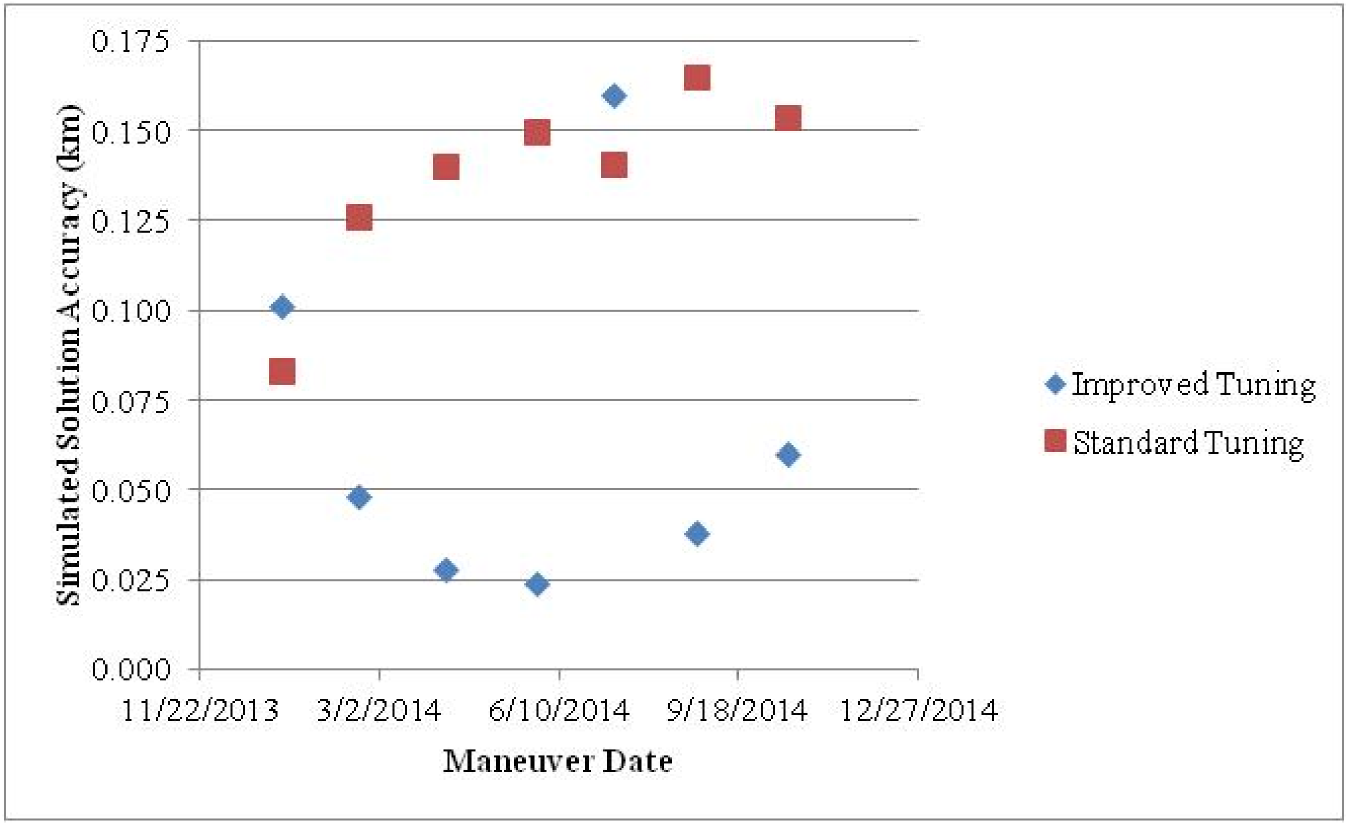
Ensure Mission Success

Filter Tuning Improvement Effort

- ***A higher failure rate was noted specifically for TDRS-5 and TDRS-6.***
  - Both are first generation TDRSs
    - TDRS-7, also first generation, did not show an equally high failure rate
  - User tracking profiles for each of these satellites was significantly different, with TDRS-6 performing less User tracking following maneuvers than TDRS-5.
  - As no clear trend was identified regarding the failures for these satellites in any of the prior sections of this study, it was proposed that the filter tuning in terms of post-maneuver applied uncertainty be updated.
- ***Several maneuvers were selected and replayed in ODTK numerous times with varying degrees of finite maneuver uncertainty.***
  - Goal: Minimize the difference between the short arc solution prediction and the long arc, smoothed ephemeris from two days later.
- ***Selected values of finite uncertainty that were most likely to improve performance across the whole set of maneuvers.***
  - These values of finite maneuver uncertainty were then applied as a baseline to all TDRS-6 maneuvers in 2014.

Filter Tuning Improvement Effort

	Instant Uncertainty	Finite Uncertainty
Standard Tuning	10%	Typically none
Improved Tuning	10%	.075 N cross-track, duration of 1.5 hours .015 N along-track, duration of 1 hour



Conclusions and Recommendations

- ***For successful post-maneuver TDRS support, a number of real-time strategies should be implemented.***
  - The tracking of Users during post-maneuver OD period should be monitored closely.
  - Comparisons between the two main OD systems used in the FDF should be appropriately small.
  - Plots generated using ODTK (Residual Ratio, Position Uncertainty, and Velocity Uncertainty) can be used to monitor real-time performance
  - Regularly correlating post-maneuver OD performance with applied finite and impulsive uncertainty can prevent failures in the future.
- ***A direct correlation was not identified between maneuver mis-modeling and post-maneuver accuracy.***
  - Improving maneuver knowledge is often suggested as a way to improve OD accuracy, but filter tuning plays a much more powerful role in the OD process.
- ***Additional analysis can be performed***
  - One particular area of interest is the estimation of biases in the ODTK filter: position and velocity uncertainty from tracking data might be aliasing into changes in the measurement biases. By investigating the bias estimation before, during, and after maneuvers, this theory could be evaluated.

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