TDRSS Augmentation for Launch and Ascent High Speed Navigation Filter

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An investigation was performed to evaluate the feasibility and possible advantages of augmenting the High Speed Trajectory Determination (HSTD) ground navigation filter with measurements from the Tracking & Data Relay Satellite System (TDRSS) constellation. The proposed communications system strategy for Constellation uses TDRSS rather than ground S-band, so the capability of replacing the S-band navigation capability with TDRSS was considered. HSTD simulations were performed with combinations of S-band, C-band, and TDRSS measurements. Several assumptions are made with regard to measurement biases and signal noise characteristics to produce "first-look" level accuracies. Preliminary results show that solutions using TDRSS instead of S-band have similar or improved performance from the view of filter covariance and may be a feasible alternative. These results also show that TDRSS tracking alone gives poorer observations and resulting performance Operational and other constraints to the use of TDRSS in a high-speed ground navigation filter are not addressed.

Nomenclature

G Observation State Relation
$\vec{H}$ Measurement Partial Derivatives
K Kalman Gain
$\vec{P}$ State Error Covariance
R Measurement Noise Covariance
$\vec{X}$ Filter State Vector

Subscripts

j Time Index

Symbols

γ Residual Underweight Factor

I. Introduction

The High Speed Trajectory Determination (HSTD) ground navigation filter processes measurements from up to 3 radar tracking sites at rates up to 5Hz to provide a near real-time estimate of the vehicle state. The filter is designed to read data from 2 C-band stations (range, azimuth, and elevation) and one S-band station (range, x-gimbal angle, y-gimbal angle, and integrated Doppler range). This system has been utilized by shuttle flight controllers since its development in 1977.

II. Filter Augmentation

II.A. TDRSS Description

The Tracking & Data Relay Satellite System (TDRSS) constellation can be used as a navigation instrument by relaying a transponder tracking signal between the TDRSS ground segment and the target vehicle.

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By this method, range and Doppler measurements may be obtained. To augment the HSTD filter, the TDRSS measurement partials were included in the state-covariance update. The HSTD assumes uncorrelated measurement errors and processes each measurement separately, so inclusion of TDRSS simply involves an extra set of measurement processing cycles per time epoch. Inclusion of TDRSS measurements may allow the filter to maintain a state vector solution with less radar support.

II.B. HSTD Mathematical Technique

The HSTD is an Extended Kalman Filter routine that processes high sample rate tracking data to determine current estimates of the shuttle state vector during both the launch and landing flight phases.[1] It nominally processes measurements from any combination of one S-band radar and two C-band radars. A 19-parameter process noise algorithm is used, with 3 state vector components for position, 3 scaled velocity, 3 scaled acceleration, and 10 measurement biases as shown in Eq. 1.

$$\vec{X} = \begin{bmatrix} x \\ y \\ z \\ v_x \Delta T \\ v_y \Delta T \\ v_z \Delta T \\ a_x \Delta T_2/2 \\ a_y \Delta T_2/2 \\ a_z \Delta T_2/2 \\ \epsilon, C1_{range} \\ \epsilon, C1_{azimuth} \\ \epsilon, C1_{elevation} \\ \epsilon, C2_{range} \\ \epsilon, C2_{azimuth} \\ \epsilon, C2_{elevation} \\ \epsilon, S_{range} \\ \epsilon, S_{x-gimbal} \\ \epsilon, S_{y-gimbal} \\ \epsilon, S_{doppler} \end{bmatrix} \tag{1}$$

The filter uses linearized dynamics, so the state and covariance are propagated using a discrete state transition matrix as shown in Eq. 2.

$$\begin{aligned} \vec{X}(t_j) &= \phi(t_j, t_{j-1})\vec{X} + \vec{W}_{j-1} \\ \vec{P}(t_j) &= \phi(t_j, t_{j-1})\vec{P}(t_{j-1})\phi^T(t_j, t_{j-1}) + \vec{Q} \end{aligned} \tag{2}$$

The discrete state transition matrix is shown in Eq. 3. It is notable that the acceleration and measurement bias terms are propagated as exponentially correlated random variables.

$$\phi(t_j, t_{j-1}) = \left[\begin{array}{c|c} \phi_A & 0 \\ \hline 0 & \phi_B \end{array}\right] \tag{3}$$

where

$$\phi_A = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ & & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ & & & 1 & 0 & 0 & 2 & 0 & 0 \\ & & & & 1 & 0 & 0 & 2 & 0 \\ & & & & & 1 & 0 & 0 & 2 \\ & \mathbf{0} & & & & & e^{\frac{-\Delta T}{\tau_a}} & 0 & 0 \\ & & & & & & & e^{\frac{-\Delta T}{\tau_a}} & 0 \\ & & & & & & & & e^{\frac{-\Delta T}{\tau_a}} \end{bmatrix}$$

$$\phi_B = \begin{bmatrix} e^{\frac{-\Delta T}{\tau}} & & & & & & & & & \\ & e^{\frac{-\Delta T}{\tau}} & & & & & & & & \\ & & e^{\frac{-\Delta T}{\tau}} & & & & \mathbf{0} & & & \\ & & & e^{\frac{-\Delta T}{\tau}} & & & & & & \\ & & & & e^{\frac{-\Delta T}{\tau}} & & & & & \\ & & & & & e^{\frac{-\Delta T}{\tau}} & & & & \\ & & \mathbf{0} & & & & e^{\frac{-\Delta T}{\tau}} & & & \\ & & & & & & & e^{\frac{-\Delta T}{\tau}} & & \\ & & & & & & & & e^{\frac{-\Delta T}{\tau}} & \\ & & & & & & & & & 1 \end{bmatrix}$$

Measurements are then incorporated one at a time using a standard Kalman update shown in Eq. 4

$$K_j = \bar{P}_j \tilde{H}_j^T [\gamma(\tilde{H}_j \bar{P}_j \tilde{H}_j^T) + R_j]^{-1} \tag{4}$$

$$\hat{X}_j = \vec{X}_j + K_j(Y_j - G(\vec{X}_j, t)) \tag{5}$$

$$\hat{P}_j = (I - K_j \vec{H}_j)\vec{P}_j$$

II.C. Augmentation Technique

The mathematical technique for sensor combinations is based on Holt.[2] Rather than augment the measurement partial matrix with new sensor models, however, the measurements are taken sequentially and assumed uncorrelated. This is consistent with the current operation of HSTD where the radar measurements are processed sequentially.

II.D. Filter Validation

The HSTD simulation was compared with actual flight data residuals to validate the measurement models and assumptions. This comparison is shown in Figure 1, where agreement is shown to within the $1-\sigma$ filter covariance.

III. Analysis Assumptions

For the purposes of this “first-look” study, it was assumed that the radar site measurement biases are correctly calibrated during filter initialization. The measurement error model used for the simulation was simple additive Gaussian noise. It was also assumed that TDRS range and Doppler measurements were available at a 1Hz rate during the entire simulation. Assumed values for filter coefficients are used based on the ascent dynamics. Finally, it was assumed that all measurement time tags are correctly aligned during filter initialization. The results presented, therefore, should be considered “best-case” for a given set of sensor measurements.

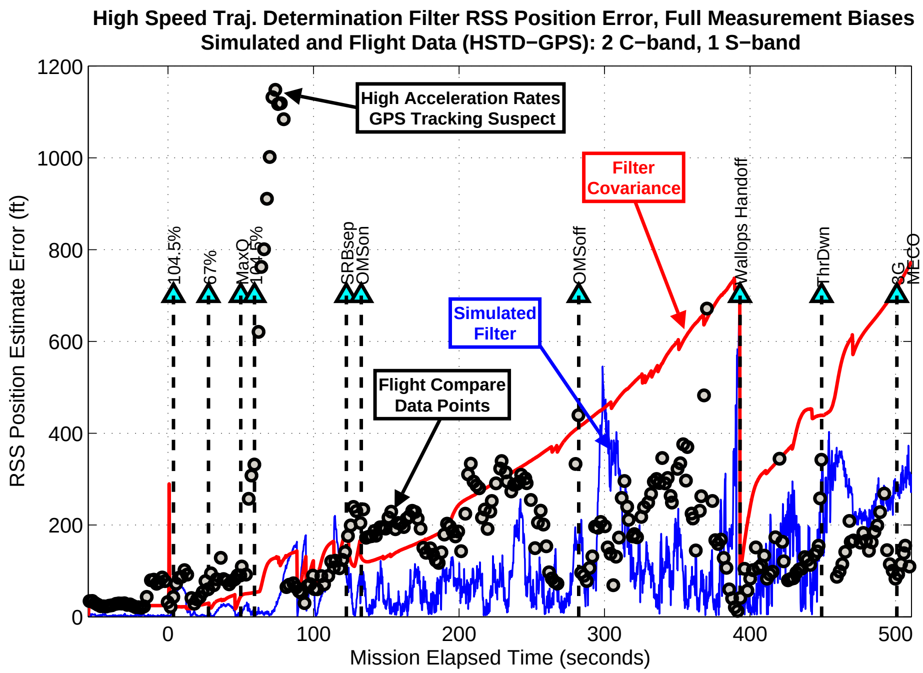


Figure 1. Simulated Data Comparison with Shuttle Flight Data

IV. Scenario and Simulation

IV.A. Software

A simplified MATLAB version of HSTD was written for this preliminary study. The estimation algorithms are identical to those used in the MCC version. Station switching in the MATLAB version is handled in the same manner as the MCC.

IV.B. Measurement Generation

The simulated measurements used for radar and TDRSS data were derived from the STS-121 Best Estimate Trajectory (BET) and corrupted with zero-mean uncorrelated Gaussian noise. The noise parameter assumptions for each measurement type are summarized below (approximate values based on USAF radar specs). TDRSS values are derived from Phung.[3]

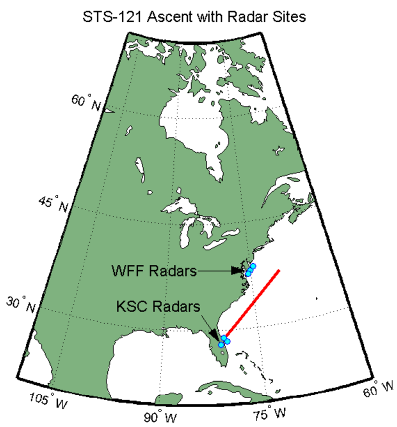
Table 1. Simulated Measurement Error Parameters

Measurement Source	*Measurement Type*	*1-sigma Noise*
C-band Radar	Range	1.6 ft
	Azimuth	45 $arcsec$
	Elevation	45 $arcsec$
S-band Radar	Range	1.6 ft
	X-gimbal	45 $arcsec$
	Y-gimbal	45 $arcsec$
TDRSS	Range	10.5 ft
	Doppler Velocity	1.0 ft/s

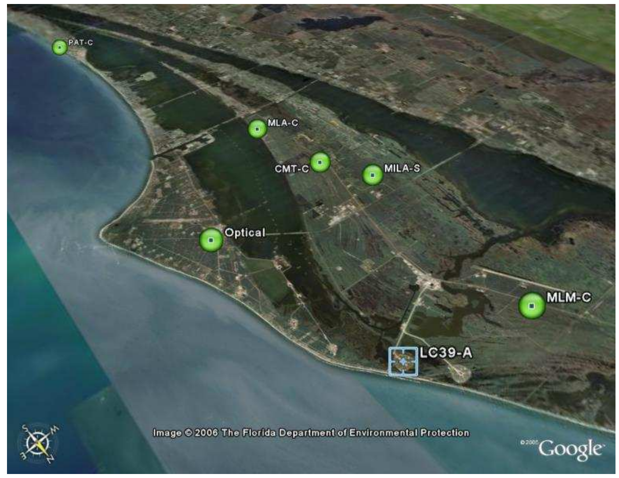
IV.C. Scenario

The ascent data from STS-121 was used as the baseline trajectory for the simulation. The radar site locations and handover times are taken from the raw data from that flight. C-band stations are located at Kennedy

Space Center (KSC) and Wallops Flight Facility (WFF), as shown in Figure 2(a). The of the KSC sites are shown in detail by Figure 2(b) and nominally handle the first 6.5 minutes of flight. TDRS satellites are simulated in geostationary orbits at longitudes of 41.4°W (TDRS-10) and 150.8°W (TDRS-7).



(a) Ascent Trajectory for Simulation



(b) KSC Tracking Sites for STS-121

Figure 2. STS-121 Ascent Simulation

V. Results

V.A. Nominal Radar Simulation

During normal operation, the vehicle is tracked with 2 Cband and 1 Sband radar through ascent with a Cband tracking handover to Wallops Island Flight Facility (WFF) at ∼390s MET. Figure 3 shows the RSS error in the estimated position along with the 1- RSS covariance during the simulation. Key mission events are shown for reference. Estimated position errors of 10-20 ft. in the early ascent and 50-100 ft. in the late ascent are typical values for shuttle tracking. A covariance drop at WFF handoff is clearly visible. This result gives confidence that the MATLAB simulation performs reasonably close to the MCC version.

V.B. Off-Nominal Radar Simulation

The HSTD uses a linear Kalman filter to estimate the navigation state, so an examination of the covariance matrix can give insight into the overall performance of the filter. The simulation was performed with various combinations of Sband, Cband, and TDRSS availability. Figure 4 shows the 1- RSS covariance for these runs on common axes for comparison. The nominal configuration (2 Cband, 1 Sband) is shown as a thick black curve with the other combinations in color.

V.B.1. No TDRSS Augmentation

Three off-nominal simulations were run without TDRSS augmentation, and all showed covariance values larger than the nominal. These are the typical downmode configurations for shuttle ground navigation. With 2 Cband and no Sband the covariance values increase by 25%. Similar results were found with 1 Cband and 1 Sband. With 1 Cband and no Sband the covariance values increase by 150%, reaching a maximum value of just over 250 ft.

V.B.2. TDRSS Augmentation

Four off-nominal simulations were run with TDRSS augmentation. Three of these show improved covariance over the nominal configuration. For the case of 2 Cband and 1 TDRS, covariance values show almost a 50% decrease. For the 2 Cband/1 TDRS and 1 Cband/2 TDRS cases, covariance values improve by almost 75%.

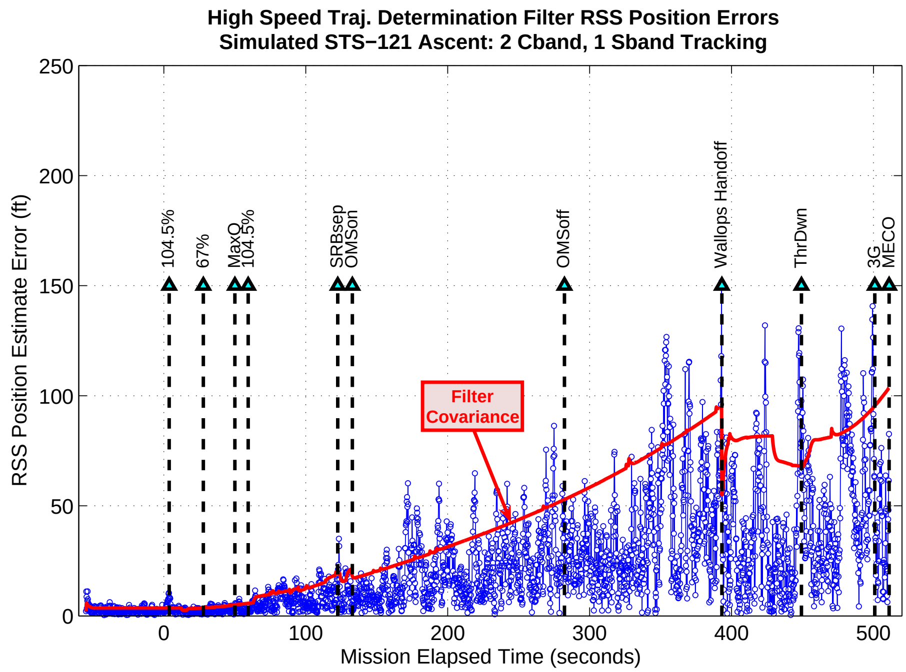


Figure 3. HSTD Nominal Simulation

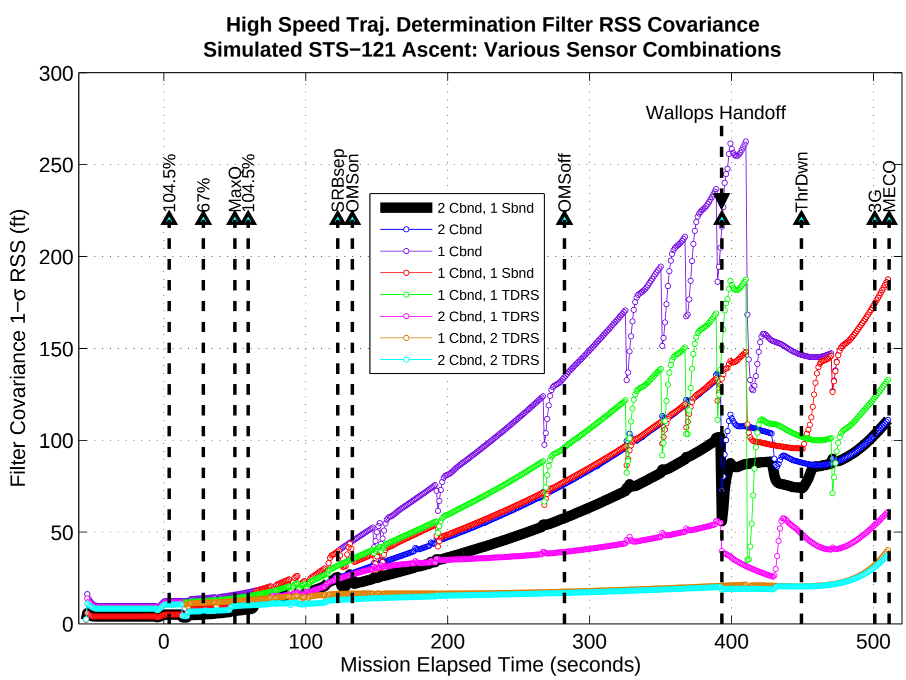


Figure 4. HSTD Covariance for Various Sensor Combinations

The 1 TDRS and 1 Cband covariance was 75% larger than the nominal, but still 30% smaller than 1 Cband alone.

V.C. TDRSS Only After KSC LOS

In the case where WFF handoff does not occur after loss of signal from KSC, the filter uses only TDRSS range and Doppler measurements. The HSTD is set up as an overdetermined filter, so at this point the vehicle state is not directly observable and the filter must correlate measurements over time to produce an estimate. Figure 5 shows the RSS position errors and covariance for this case. Large attitude rate changes, such as the throttle-down maneuver, are not sensed by the filter. Covariance begins to grow exponentially and the filter eventually diverges. The UVW components for this same scenario are shown in Figure 6.

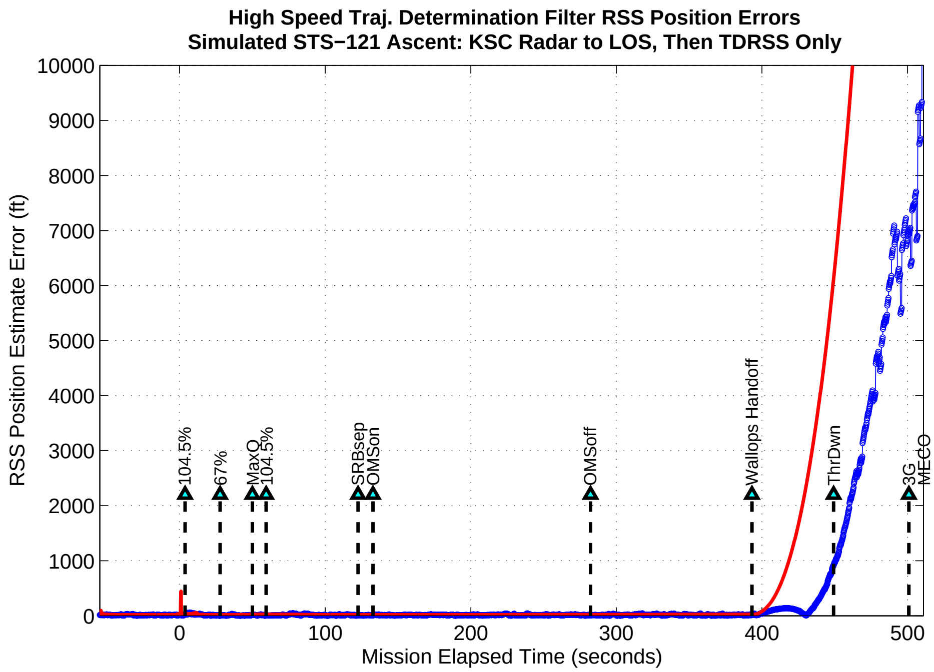


Figure 5. TDRSS Only After KSC Loss of Signal

V.D. GPS-Aided TDRSS After KSC LOS

As a precursor to future studies, the previous scenario (TDRSS only after the losing the KSC radars) was aided with GPS measurements at a rate of $0.2Hz$. Measurement errors are within the range of GPS accuracy before the loss of radar tracking. Afterward, the errors and the covariance show a ramp-up between GPS updates, as seen in Figure 7.

VI. Conclusions

TDRSS augmentation of the HSTD ground navigation filter appears to have no filter observability or mathematical issues that would prevent its effective use. This "first-look" study shows that replacing the nominal S-band tracking with that of one or more TDRSS satellites may be feasible from a ground navigation standpoint. TDRSS tracking alone appears to present difficulties for high-speed ascent tracking, but GPS aiding may be able to prevent filter divergence once radar data is lost. Further study is needed in the area of operational concerns (TDRSS availability, time-tagging, hardware, etc.).

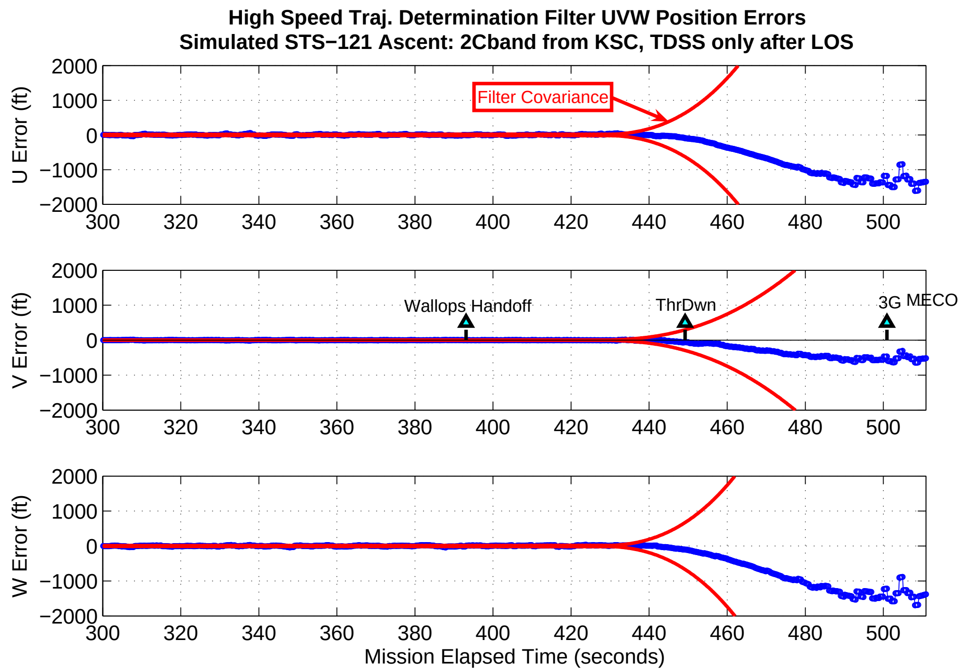


Figure 6. TDRSS Only After KSC Loss of Signal: Radial, Along-Track, Cross-Track Components

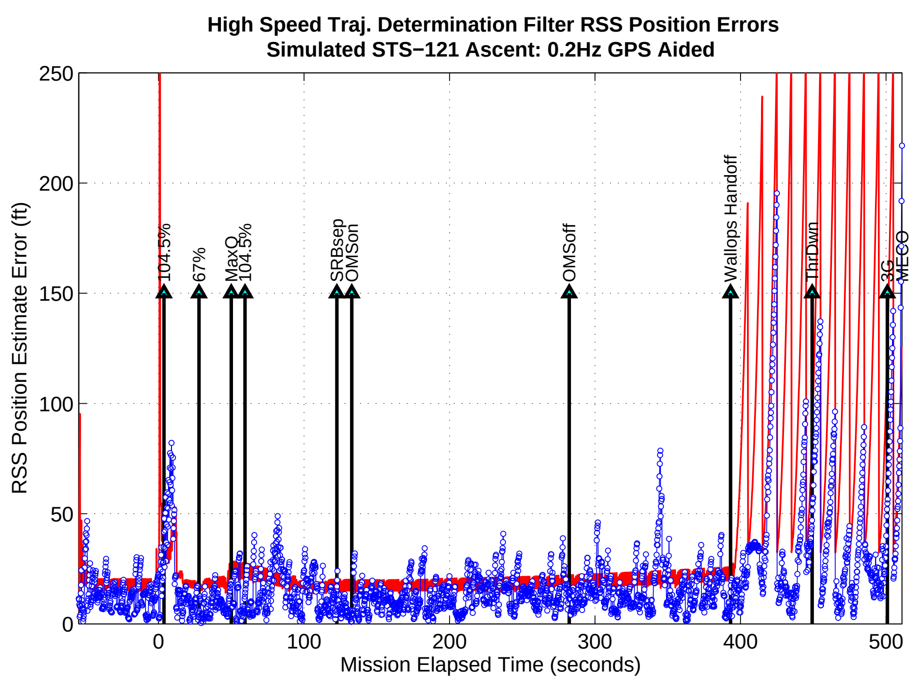


Figure 7. TDRSS and GPS After KSC Loss of Signal

References

[1] "OFT High Speed Trajectory Determination for Launch and Landing Phases," Tech. rep., Mission Planning and Analysis Division, NASA-JSC, Houston, TX, July 1977.

[2] Holt, G. N., *Generalized Approach to Navigation of Spacecraft Formations Using Multiple Sensors*, Ph.D. thesis, The University of Texas at Austin, Austin, TX, Aug. 2006.

[3] Phung, P. B., V. S. G. and Teles, J., "Tracking and Data Relay Satellite System (TDRSS) Range and Doppler System Observation Measurement and Modeling," Tech. rep., Goddard Space Flight Center, Greenbelt, MD, Sept. 1980.