LANDSAT DATA CONTINUITY MISSION (LDCM) ORBIT DETERMINATION

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Abstract: *The Landsat Data Continuity Mission (LDCM) will use many improvements in orbit determination (OD) capabilities compared to the previous Landsat missions. These changes include (1) processing Global Positioning System (GPS) point-solution data instead of radiometric data, (2) using FreeFlyer OD to estimate definitive ephemeris solutions, (3) applying a MySQL database for configuration control and storing trending data, (4) employing Quicklook and On-board Computer (OBC) services for near real-time monitoring of orbit and attitude performance, and (5) the automation capabilities of the entire Flight Dynamics System (FDS). This paper describes the automated FDS day-in-the-life operations, focusing on how OD, Quicklook OD and OBC monitoring fit into the flow, as well as the sources and transfer methods of environmental files, GPS telemetry, and real-time data. The LDCM OD performance expectations are validated using the current LDCM configuration with data from the Fermi Gamma-ray Space Telescope mission and Spacecraft/Operations Simulator telemetry.*

Keywords: *LDCM, orbit determination, flight dynamics, GPS, FreeFlyer.*

1. Introduction

The Landsat Data Continuity Mission (LDCM) is collaboration between the NASA Goddard Space Flight Center (GSFC) and the U.S. Geological Survey (USGS). The LDCM observatory is set to launch no earlier than February 11, 2013, and will become the 8th satellite in the Landsat Program of Earth-observing satellites. The LDCM observatory will be renamed Landsat-8 after launch and will join the aging Landsat-5 and Landsat-7 satellites [1] to collect and provide detailed remote sensing and land imagery data that will benefit the Earth science community and beyond. The LDCM observatory will operate in the low-Earth orbit regime, at an approximate equatorial altitude of 705 km, in a sun-synchronous orbit with an inclination of 98.2° ± 0.15°, and in a frozen orbit with eccentricity less than or equal to 0.00125.

Over the past 40 years, the previous Landsat-series missions began their mission "lives" supported by GSFC which processed radiometric navigation data using ground-based orbit determination (OD) to support all orbit estimation and prediction capabilities. Over the lifetime of a Landsat mission, operational responsibility of the mission progresses through various operations control centers. The Landsat-4 (decommissioned June 15, 2001 [2]), Landsat-5, and Landsat-7 (LS-7) missions use two-way Doppler data from the ground network and space network tracking stations to perform OD and to meet their 100 meter definitive 3-sigma accuracy requirement. After a commissioning phase, OD responsibility for these spacecraft transitions to USGS-owned operations centers with GSFC maintaining back-up capabilities. Landsat missions have been supported by a variety of commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) software to process the OD to meet the requirement, primarily using batch least squares OD, but more recently have employed Kalman filtering techniques. The early-mission OD data arcs were originally processed with the GOTS batch least-squares estimator, Goddard Trajectory Determination System (GTDS), in GSFC's Flight Dynamics Facility (FDF). In subsequent years, FDF used the COTS Extended Kalman Filter Real-Time Orbit Determination System (RTOD) to support the Landsat-4, Landsat-5, and Landsat-7 backup OD requirements. Orbit determination tools have also included the Satellite Tool Kit's Precision Orbit Determination System (STK/PODS). Recently, the Landsat-5 and Landsat-7 operations centers have transitioned to Analytical Graphics Inc.'s Orbit Determination Toolkit (ODTK) for Kalman-filter based OD products.

The upcoming mission, LDCM, has a greater OD accuracy than previous Landsat missions of 30 meter per axis 3-sigma definitive OD accuracy requirement (a total definitive position accuracy of 52 meters). To meet LDCM's accuracy requirement, the spacecraft is outfitted with General Dynamics' Viceroy Global Positioning System (GPS) receiver for on-board OD. The Viceroy receiver collects GPS pseudorange data to estimate a 3-D position fix using a low-fidelity orbit force model. The Viceroy receiver outputs point solution position and velocity estimates once per second. The on-board solution provides a continuous real-time OD capability that also supports ground-based instrument processing so that science data can be reduced on the ground. The previous Landsat missions process roughly five to seven 10-minute passes of radiometric data per day, which is a contrast to the near continuous GPS data provided for LDCM.

The Viceroy point-solutions are available for further ground-based estimation with better force models on the ground in the LDCM mission operations center (MOC) by the Flight Dynamics System (FDS). The pseudorange can also be processed on the ground. These data types will be processed in the FDS by COTS space mission analysis software FreeFlyer®, developed by a.i. solutions, Inc., using FreeFlyer Orbit Determination (FFOD).

The LDCM FDS is currently undergoing testing and is actively supporting the mission during the current pre-launch readiness testing period. Pre-launch evaluation to test the achievable OD accuracy has included the processing of GPS flight data from the Fermi Gamma-Ray Space Telescope, an active NASA mission, which flies in a lower, 540-km, circular orbit. The FGST also employs a Viceroy GPS receiver. Other test data includes simulated telemetry data from the LDCM Spacecraft/Operations Simulator (S/OS) provided during formal mission readiness tests by the LDCM spacecraft manufacturer, Orbital Sciences Corporation. The S/OS data was processed and evaluated with the FDS OD to further validate ground-based capabilities and estimate the achievable OD accuracy. Some of the S/OS data samples include maneuvers that will be seen during LDCM's lifetime, such as drag make-up and inclination adjustment maneuvers. The inclusion of these maneuvers in simulated telemetry assists in evaluating the ability of FFOD to estimate a good solution through these events.

This paper begins with an examination of the latest innovations of the OD capabilities being deployed for LDCM. Next, the day-in-the-life flow and automation capabilities of the FDS system are described, focusing on the OD, Quicklook, and OBC monitor services, which are subservices controlled by a continuously running automated Service Manager. Files such as telemetry and environmental files are delivered to the FDS via the Data Management System. Lastly, some results from the OD performance analysis and testing with the current LDCM configuration using real-mission Fermi Gamma-ray Space Telescope data and the LDCM dynamic Spacecraft/Operations Simulator telemetry are shown.

2. Innovations

A significant number of innovations are employed in the FDS for the OD of the LDCM. These features include processing GPS point solution data instead of radiometric data, which was used for previous Landsat missions, and employing FreeFlyer to perform orbit determination and estimate definitive ephemeris solutions with its extended Kalman Filter method. The MySQL database is used heavily by all the FreeFlyer scripts for configuration control and storing trending data. Finally, the OD services and real-time monitoring enabled by Quicklook and the OBC are described.

2.1. LDCM GPS Overview

The LDCM spacecraft is equipped with an on-board Viceroy GPS receiver that will provide near continuous point-solution and pseudorange telemetry to the ground via the Integrated Test and Operations System (ITOS). The GPS data are down-linked during each ground-station contact to the MOC at NASA GSFC for initial processing. With the initial processing by ITOS, the GPS point solution telemetry data is converted to a sequential print format; these are GPS point solution measurements represented as epochs, positions, and velocities in a text file.

Daily GPS telemetry data from ITOS is delivered via the Data Management System to the FDS for OD processing via FreeFlyer; and attitude sensor telemetry is used for attitude determination processing via the Multi-mission Three-Axis Stabilized Satellite (MTASS) attitude ground-system tool. Real-time (processed by OBC_Monitor), post-pass (processed by Quicklook) orbit and attitude telemetry, and post-maneuver telemetry data are also delivered and processed by the FDS. Figure 1 shows the ITOS to FDS interface.

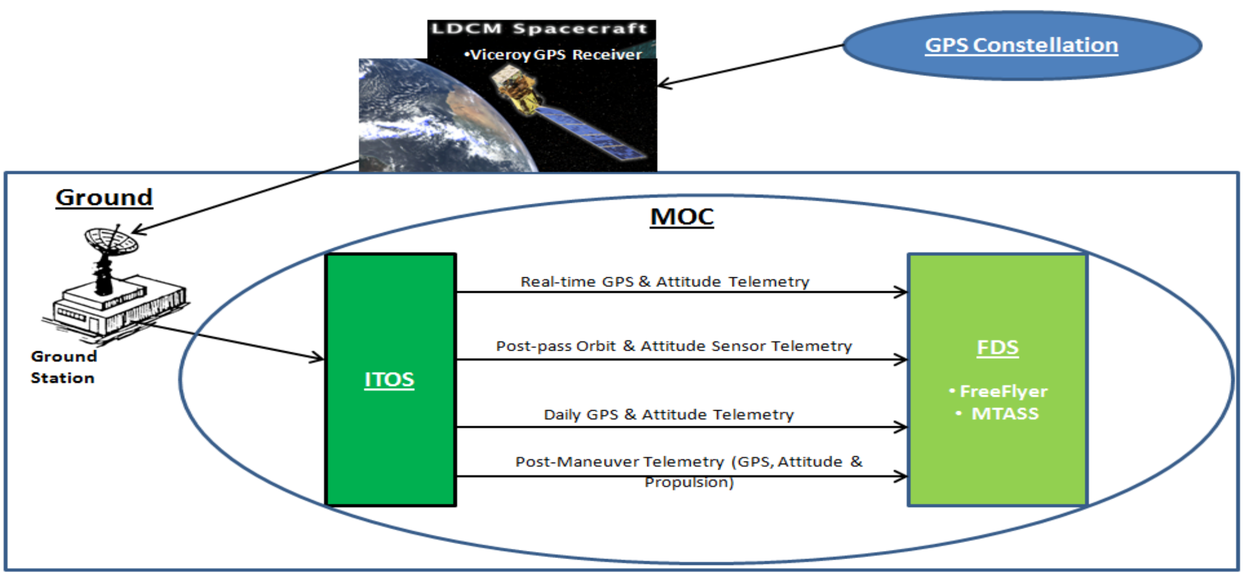


Figure 1. FDS Telemetry: ITOS to FDS Interface

2.2. FreeFlyer OD

The LDCM FDS uses a.i. solutions, Inc., FreeFlyer software, in the MOC to perform ground-based OD. FreeFlyer scripts (also known as "MissionPlans") have been designed to perform OD, target maneuvers, and produce planning products. FFOD uses the EKF method on the delivered GPS point-solution telemetry data as measurements to estimate position, velocity, and coefficient of drag (C_D) values during daily operations. FFOD outputs a definitive ephemeris and a corresponding state covariance file. Changes to velocity can also be modeled, making it possible to perform OD through maneuver events. The FFOD MissionPlan can be run manually or automated as an integral part of the "OD_Service," described in more detail in Section 2.4.

FFOD uses a Gaussian distribution to model the state error. Residual editing allows for rejection of measurements whose residuals exceed a tolerance, usually either 3-sigma or 6-sigma. The noise value that FFOD uses for the GPS Viceroy Receiver point solution accuracy is 15 meters in position and 7 cm/s in velocity (both 1-sigma). Position and velocity filter process noise covariances have been varied from looser (i.e., 1e-13 for position (km^2) and velocity (km^2/s^2) component noise) to tighter settings (i.e., 1e-17 for position and velocity component noise). The current process noise settings in the MOC are 1e-14 km^2 for the position components, 1e-16 km^2/s^2 for the velocity components, and 1e-08 for C_D. These settings may require further adjustment once the observatory gets on orbit.

2.3. MySQL

A MySQL database is used for configuration control and storing trending data. FreeFlyer scripts retrieve force modeling and estimation data, directory information and other default settings, and trending data stored in various MySQL tables. One of the key benefits of the MySQL database is that it allows the user to make changes in one location, instead of within individual FreeFlyer scripts. The database also enables the user to quickly view trends. The default settings table ('default'), spacecraft force model table ('spacecraft_info') and environmental files table ('services_requiredfiles') are called by every FreeFlyer script. In addition, automation flags and settings in the database are called from the service scripts.

The OD script in particular calls the 'orbit determination' table, where the estimated parameters are selected (i.e., position, velocity, and C_D), the GPS position and velocity receiver noise are applied, the OD parameter process noise values are tuned, and the maximum allowable residual sigma is set. The flag to estimate C_D is called from the 'orbit_determination' table, while the updated C_D value is stored in the 'spacecraft_info' table. The OD script also recognizes maneuvers within the OD data spans and retrieves maneuver related data from the 'maneuver_planning' table in order to process the OD through the delta-velocity events.

The 'trendingpreddef' table stores the comparison of the latest measured definitive ephemeris to the predictive ephemeris from three days prior to the current epoch. Using the three-day-old predictive ephemeris, the root-mean-square and root-sum-square statistical comparisons to the long definitive ephemeris are performed at 40 hours and 72 hours from the epoch of the predictive ephemeris. These direct performance metrics of the prediction accuracies are used for instrument planning. The ‘obcmonitor_plots’ table allows configurable (fixed) plot settings so the operator can see at a glance if tolerances are exceeding limits.

2.4. OD Service

The OD MissionPlan accepts start time, duration, telemetry data, and optionally an *a priori* covariance and *a priori* state or definitive ephemeris as inputs. The standard length of the OD sequential print data is 26 hours starting at 10:00:00.000 hours UTC on the previous day until 12:00:00.000 UTC the current day. The two hours in the beginning of the span allows the service to perform definitive overlap comparisons between the current and previous OD arc. The 26-hour OD arc fits the once-per-day tempo of generating new predictive products for planning the latest spacecraft operations. The *a priori* state can be retrieved through a filter “warm-start” by using the definitive state and covariance from the previous orbit estimation. If these fields are left blank, the solution will “cold-start” and initialize the spacecraft using the first state from the telemetry file. The warm-start is the nominal on-orbit mode for OD.

The OD MissionPlan features a console window with messages such as start time; which input files are read; whether the filter will cold or warm start; initial and final CD values; and percentage of point solutions accepted and rejected by the filter. A watch window also tallies a brief quality report showing the total number of measurements by component that were accepted by the filter , and a more in-depth quality report further detailing measurements rejected by the filter is an output file from the service. In addition to the quality report, the OD MissionPlan also outputs the definitive ephemeris, final state report, definitive covariance ephemeris, and plot. Figure 2 is screenshot of plots generated by the OD MissionPlan.

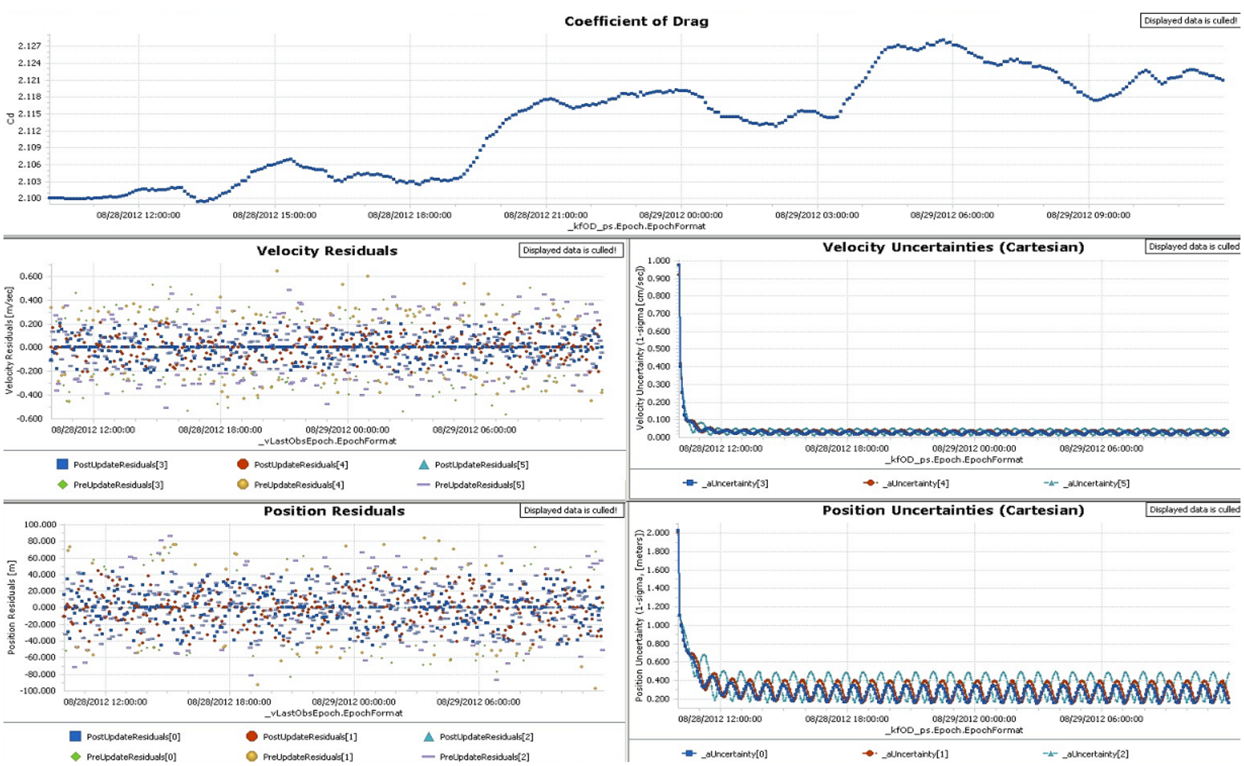


Figure 2. FreeFlyer OD MissionPlan Output screen

The OD_Service suite also contains the two-hour definitive-to-definitive overlap compare product comparing the previous day's definitive to the current day; which is a consistency check of the Kalman filter definitive solutions. Examples of plots output from the definitive-to-definitive overlap compare product including range, radial, cross-track and along-track separation plots are shown in Figure 3.

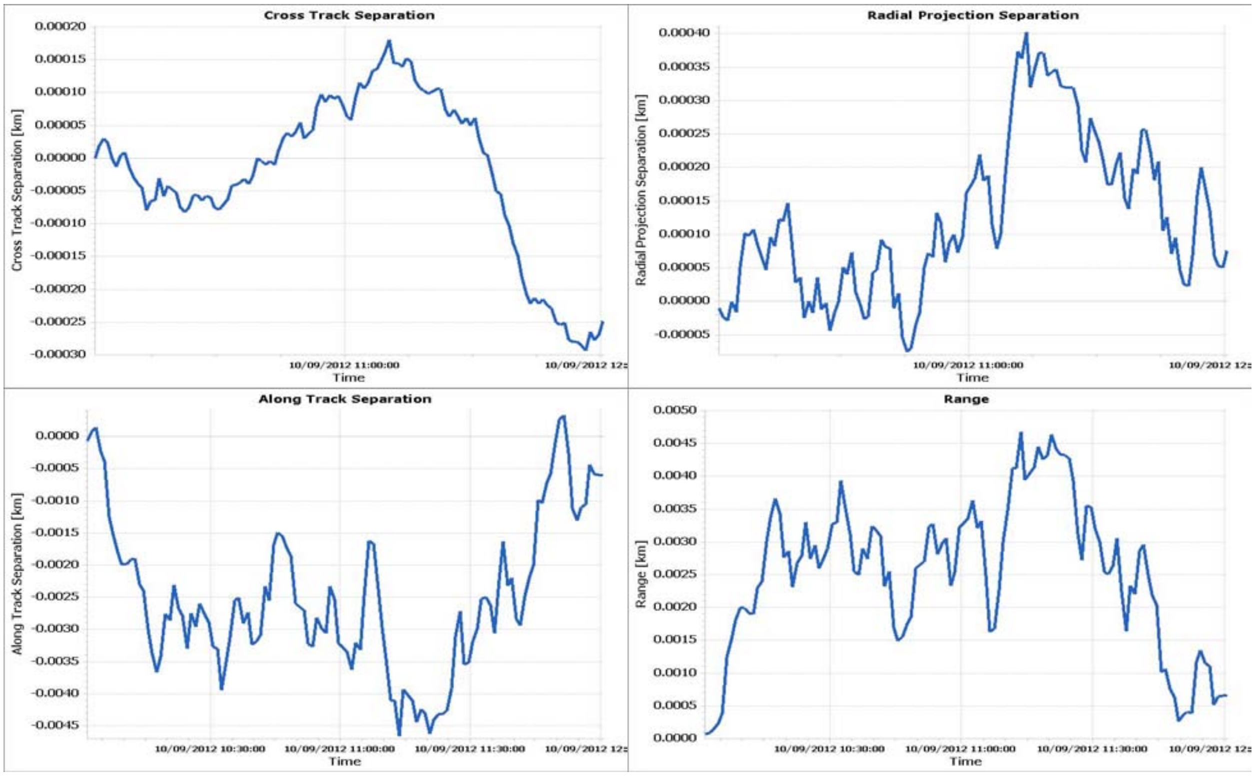


Figure 3. FreeFlyer Definitive-to-Definitive Overlap Compare Plots

The current, daily definitive solution appends to the mission-length definitive ephemeris to maintain a historical ephemeris for the mission, useful for mission analysis and trending. Lastly, the OD_Service differences the current definitive from the long definitive ephemeris and the 3-day-old predictive ephemeris for the predictive-to-definitive comparison to trend predictive performance metrics at 40-hours and 72-hours. Figure 4 is visual of the interaction between daily definitive ephemerides, the long definitive and the definitive-to-definitive and predictive-to-definitive overlap compares.

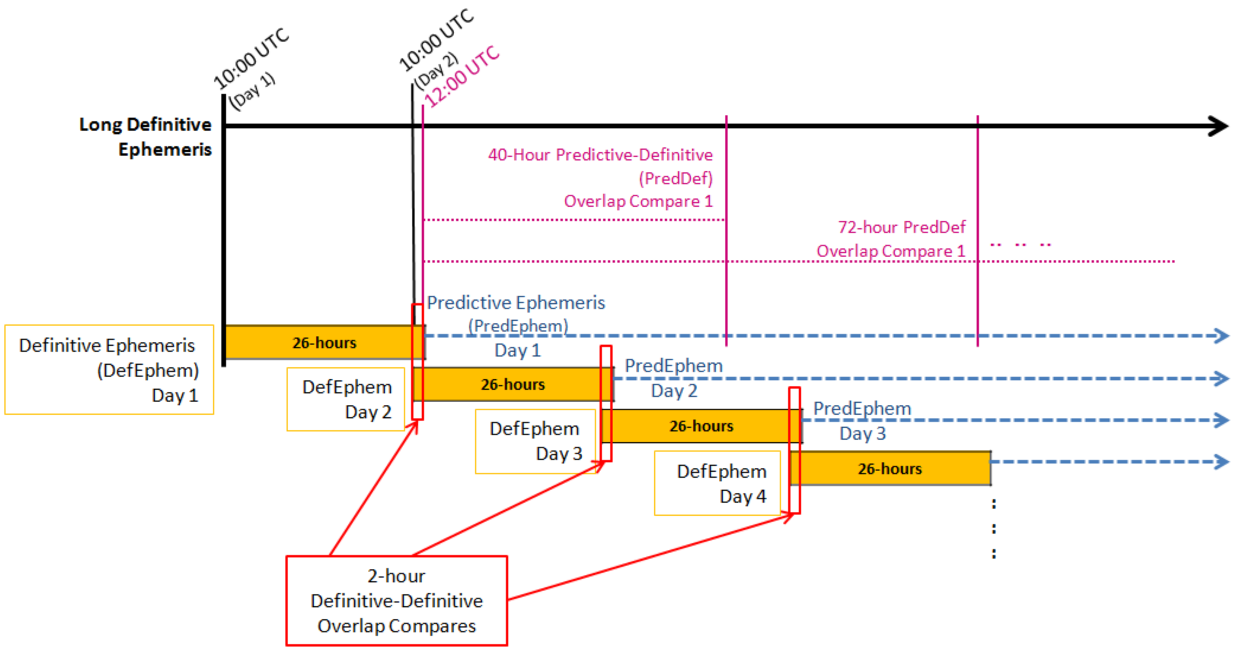


Figure 4. Definitive and Predictive Overlap Compares

2.5. Real-Time Monitoring: Quicklook & OBC_Monitor

In addition to the daily OD processing, the LDCM flight-dynamics support on the ground validates the on-board performance using the ground estimation of the orbit and attitude. It also uses this ground estimation to plan for needed orbit and attitude maneuvers as well as special slews required for instrument or sensor calibrations.

The OBC_Monitor Service is another unique feature of the LDCM FDS to provide near real-time monitoring of orbit and attitude performance. The OBC_Monitor is used to check the overall onboard orbit (and attitude) of the LDCM spacecraft for any obvious errors. The real-time pass telemetry is sent to ITOS in the MOC and sent directly to the FreeFlyer OBC_Monitor MissionPlan via a socket connection. The MissionPlan compares the on-board estimated orbit and attitude to the ground predicted orbit and attitude. If deviations are seen above user-selectable tolerances, then the flight-operations team (FOT) will be alerted to a possible issue via event messages e-mailed to the FOT. The OBC_Monitor generates four plots: (1) rotation angle differences; (2) radial, in-track and cross-track position differences; (3) real-time OBC quaternion; and (4) real-time OBC inertial position.

Quicklook OD is performed near real-time on smaller post-pass telemetry data sets than standard OD to provide a quick assessment of the current orbit. Typically performed on an as-needed basis, Quicklook is often used in the event the OBC_Monitor results indicate a discrepancy between the predicted ground and OBC orbit solution or some other anomaly. The start epoch and duration will vary based on the GPS telemetry set being processed. The Quicklook OD typically cold-starts with its initial state taken from the input telemetry data. It outputs a Quicklook definitive ephemeris to use as input into Quicklook attitude estimation.

The FDS system also performs Maneuver Calibration OD, which is similar to Quicklook and processes sections of GPS data over the pre- and post-maneuver period. This ephemeris can be used in maneuver calibration routines for measuring the achieved burn performance.

3. FDS Day-in-the-Life

The FDS has been designed to be fully automated for nominal day-in-the-life (DITL) operations, but all the scripts can also be executed in either partially or fully manual modes. The overall DITL flow begins with a daily delivery of the 26-hour GPS telemetry data to the FDS system. Files such as telemetry and environmental files are delivered to the FDS via the data management system (DMS). The DMS also delivers the output files produced from the DITL operations to proper locations within FDS, the MOC, and external parties. The DMS transfers event messages alerting the FDS and FOT of threshold violations.

The 'Service Manager' MissionPlan runs continuously, monitoring the system to detect new file delivery. The Service Manager is the executive hub of the automation processing, ensuring the processes kick off when data is available, and ensuring that there are no processing conflicts. With the arrival of the GPS telemetry file, the Service Manager calls the 'OD_Service' as the first in the sequence to process the telemetry data. 'OD_Service' processes the telemetry data and outputs a definitive ephemeris and definitive covariance. The MySQL database is also updated with the solved-for C_D. The 'OD_Service' merges the latest definitive ephemeris onto the mission-length definitive ephemeris; and performs definitive-to-definitive overlap compares and predictive-to-definitive compares for performance trending.

With the arrival of the definitive ephemeris to its delivered location, the Service_Manager calls the 'Plan_Service' to ingest the definitive ephemeris and covariance outputs and further propagates the spacecraft (while also monitoring and executing maneuver planning as necessary) to create a 7 day, or long 49-day (created once a week on Mondays) predictive ephemeris and products to be delivered to other teams in the MOC. The predictive ephemeris is used to generate the bulk of the daily products.

The 'AD_Service' (for attitude determination) also ingests the definitive ephemeris. Figure 5 is a simplified schematic of the overall daily flow for the FDS with emphasis on the OD and Plan Services. In addition to performing OD and making daily Plan_Service products, the 'OBC_Monitor' Service will run continuously during operations to perform automated real-time monitoring of the OBC attitude and orbit. On an as-needed basis, the FDS can perform automated OD on short segments of ITOS-provided GPS telemetry data via the 'Quicklook_O_Service' service. These innovative and new features permit the near real-time monitoring of the orbit and attitude performance of the spacecraft against ground predicted values. If there are deviations outside of expected offsets or user-selectable tolerances, the ground FDS will send a notice to the FOT via an alert message electronically for further investigation of developing problems. However, since these are real and near-real time products, they run independently of the flow diagram in Figure 5 below.

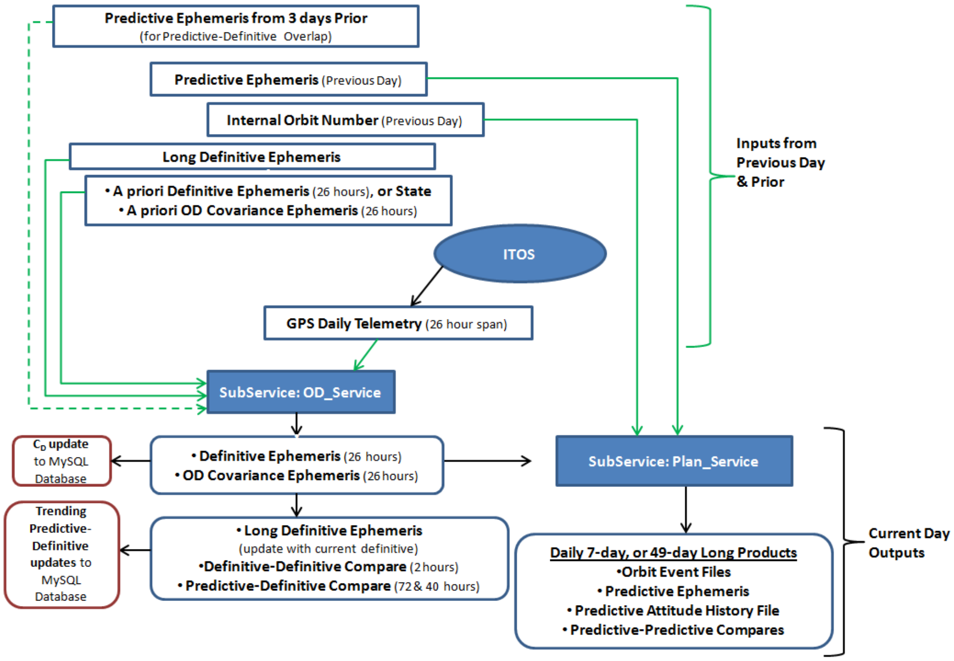


Figure 5. FDS Day-in-the-Life flow (Focusing on OD and Plan Services)

4. OD Performance Analysis

The FDS DITL automation is currently being run daily in the MOC to simulate on-orbit support. FreeFlyer simulated telemetry is mainly used, but Spacecraft/Operations Simulator (S/OS) telemetry is made available for frequent ground readiness testing.

Further analysis was also performed to validate the performance of FreeFlyer OD including processing (1) truth data, (2) flight mission data, and (3) simulator data. These three data sets used for testing are described below and representative cases are shown in the subsequent sections:

1) Truth Data

Uses a truth ephemeris to create OD measurements and subsequently estimate the orbit from the resultant point solution measurements. A series of trials varying the noise on the actual measurements; and adjusting the process noise and sigma editing limits on the filter were performed.

2) Validation Using Real Flight Mission Data

Two consecutive 48-hour length telemetry arcs from FGST flight mission data were also tested. FGST also uses a General Dynamics Viceroy receiver to produce point solutions observations at a rate of 1 Hz, but this data was edited down to 10 seconds.

3) Ground Readiness Test Data

Four sample sets of S/OS Telemetry data were processed from Mission Readiness Tests #1 and #4 (MRT 1, MRT 4), including data arcs approximately 26-hours in length and shorter samples with a drag make-up maneuver and one with an inclination maneuver.

Position and velocity uncertainty, residual plots showing pre- and post-Update Residuals, and drag (C_D) estimation plots are among the outputs examined from the OD service.

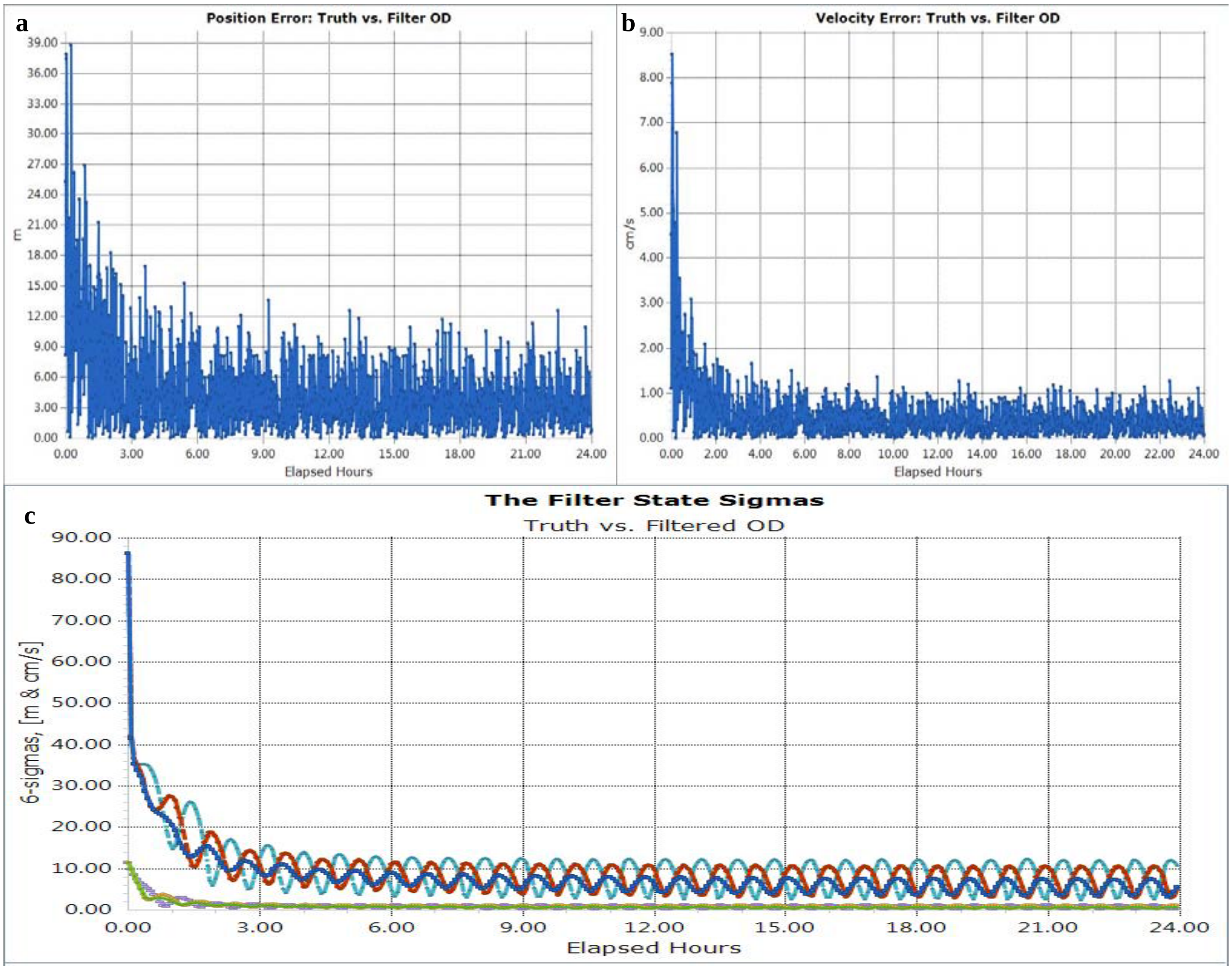
The truth study focused on testing the sigma editing limits and varying the GPS Receiver measurement noises. The Fermi Gamma-ray Space Telescope validation extensively tested the filter tuning (process noise settings) and the corners of acceptable performance. The process noise settings were adjusted to find the envelope of acceptable filter performance and to determine the so called best-case. The ground readiness test built upon acceptable settings found in the previous studies and extensive DITL testing in the MOC. Table 1 summarizes the analysis cases presented in this section.

Table 1. OD Validation Analysis Cases

Parameter	Truth vs. Filter		S/OS Runs	FGST		
	Truth	Filter		Lower Edge	Best Case	Upper Edge
Data Sampling, Measurement frequency	1/minute		1/second	Edited down from 1/second to 1/10-seconds		
Maximum Allowable Residual Sigma setting	Varied from 1 to 1000		3 or 6	3 or 6		
GPS Position (X, Y, Z) Receiver Noise (km)	Varied from 5 to 30	0.015	0.015	0.01	0.01	0.01
GPS Velocity (VX, VY, VZ) Receiver Noise (cm/s)	Varied from 5 to 15	7				
Measurement Weight Sigma's (m and cm/s)	50 m & 2 cm/s					
Position (X, Y, Z) Component Process Noise (km^2)	10^{-14}	10^{-14}	10^{-14}	10^{-13}	10^{-14}	10^{-17}
Velocity (VX, VY, VZ) Component Process Noises (km^2/s^2)	10^{-17}	10^{-16}	10^{-16}	10^{-13}	10^{-16}	10^{-17}
C_D Process Noise	10^{-09}	Varied from10^{-07} to 10^{-09}				

4.1. Truth Data

In this study, the measurement noises and the maximum allowable sigma noises were varied as shown in Table 1. First a truth ephemeris was generated; then point solutions measurements were simulated from the truth ephemeris; lastly, the OD filter processed these measurements. Outliers appear for cases with high position and velocity noise as would be expected. The total position and velocity error results and the filter covariance errors appear in Figure 6. The settings for the case appearing in Table 1 include the filter measurement noise set to 15 m and 7 cm/s; and the filter process noise for position 1e-14 km; velocity 1e-16 km^2/s^2; and C_D 1e-08, truth measurement noise of 30 meters and 5 cm/s and a maximum allowable residual sigma set to 6-sigma.



3-sigma Filter Legend: X-component; Y-component; Z-component; VX-component; VY-component; VZ-component

Figure 6. Truth Study Case (Zoomed in views, some initial points are off the scale): a. 6-sigma Position Errors; b. 6-sigma Velocity Errors; c. 6-sigma Filter State Sigmas for Position and Velocity components

4.2. Validation Using Real Flight Mission Data

To validate the LDCM FDS, GPS point solution telemetry arcs (48-hour length) from the Fermi mission for the month of March 2011 were analyzed. March 2011 was a month marked with high and rapid variations in solar activity. The National Oceanographic and Atmospheric Administration (NOAA) measured the geomagnetic Ap index, which is an indicator of solar storm activity, as 53 for March 1, 2011, but the index drops rapidly to 43, 23, and 19 for the following 3 days, which makes it a particularly interesting period to study. The Fermi Gamma-ray Space Telescope orbits the Earth with an altitude of 540 km and inclination of 28.5^{o}. The circular orbit for the LDCM orbit possesses an altitude of 705 km and an inclination of 98.2^{o}. The Fermi orbit is lower than that of the LDCM observatory and, therefore, passes through a more atmospherically dense region than the LDCM observatory.

Navigation data from the Fermi mission was filtered and smoothed using ODTK as a reference solution. The FreeFlyer OD settings and modeling were made to match as closely as possible to the modeling of the flight configuration of the Fermi mission. Consecutive 48-hour telemetry arcs were processed with 24-hour overlaps between runs. The first solution on March 1 had a cold-start (i.e. no a priori inputs) and the following (on March 2) was warm-started with the previous day's results. The 24-hour definitive overlaps between consecutive solutions in the Fermi study are sub-meter levels, showing consistency between successive definitive solutions.

The pre- and post-update residuals and uncertainties, or sigmas, in position and velocity for the March 1, 2011 solution are shown in Figure 7 for the first 8 hours of the 48-hour data span. The solution converges within the first 4 hours as seen when the data uncertainty plots settle. This 6-sigma maximum allowable residual solution had a high amount of data acceptance (99.8%).

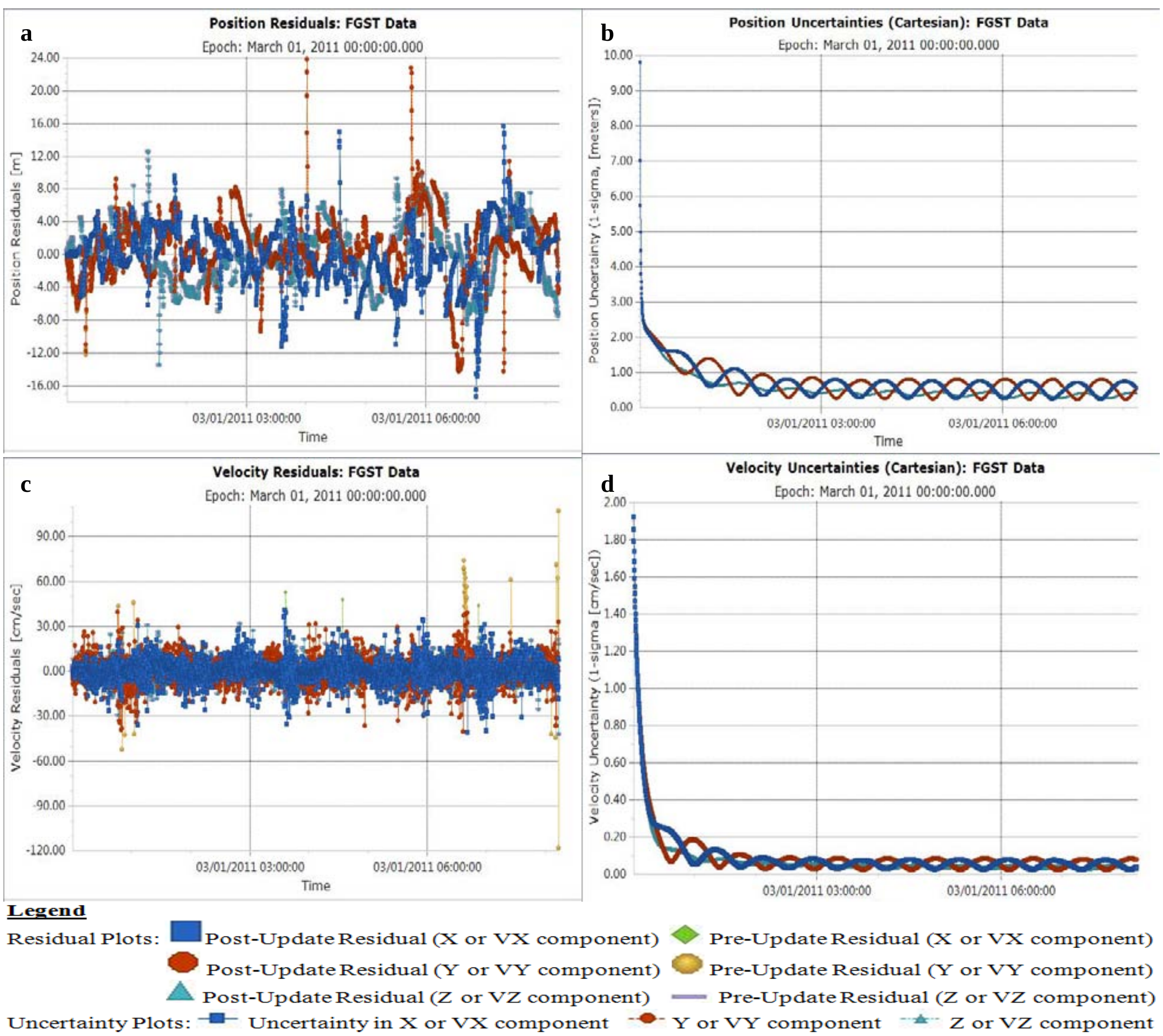


Figure 7. FGST, "Cold-Start" Epoch March 01, 2011: a. Position Residuals (6-sigma); b. Position Uncertainty (1-sigma); c. Velocity Residuals (6-sigma); and d. Velocity Uncertainty (1-sigma)

4.3. Ground Readiness Test Data

The testing of FreeFlyer OD is ongoing in the MOC with daily runs of internally simulated telemetry for the DITL. However, during formal testing the high fidelity dynamic simulator telemetry is also generated via the S/OS provided by Orbital Sciences Corporation, the builder of the LDCM spacecraft. Two sample sets of S/OS Telemetry data from Mission Readiness Tests #1 and #4 are shown in the following figures.

The MRT 1 sample does not contain maneuvers. The following plots in Figure 8 shows the first 8 hours of filtering for a non-maneuver data samples for a data arc spanning a duration of approximately 26-hours (February 13, 2012 01:11:50.999 to February 14, 2012 03:42:26.999) with 1 measurement every second. Convergence occurs within the first 4 hours. Data acceptance is 98% for this dense set; the maximum uncertainties are 14.36 m in position, and 1.92 cm/s in velocity.

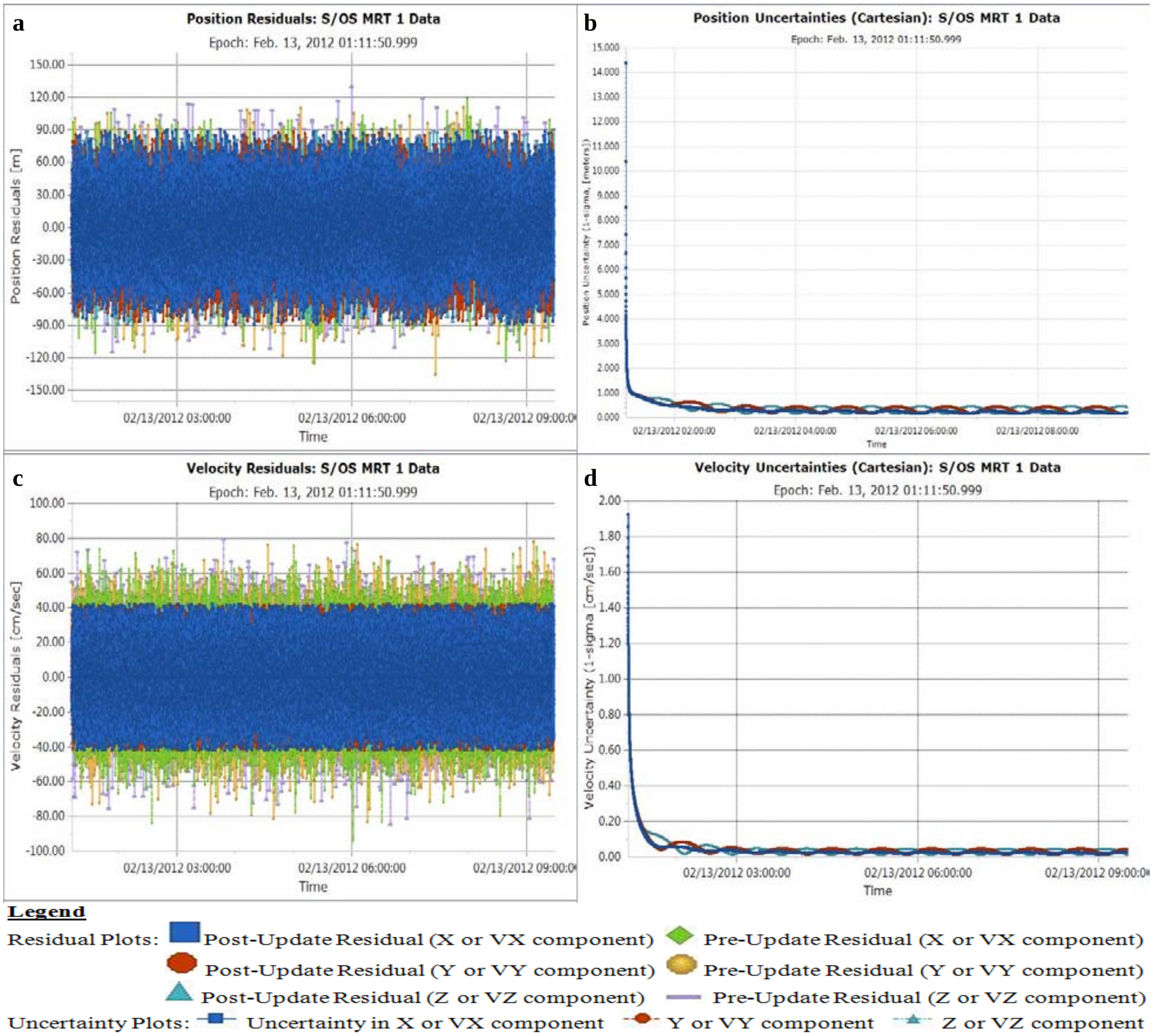


Figure 8. MRT 1 Daily Telemetry, Epoch February 13, 2012 01:11:50.999: a. Position Residuals (6-sigma); b. Position Uncertainty (1-sigma); c. Velocity Residuals (6-sigma); and d. Velocity Uncertainty (1-sigma)

The MRT 4 samples included maneuvers. A drag-makeup maneuver was modeled in the first sample. The telemetry arc was approximately 2.5 hours starting on April 16, 2012 15:34:00.000 with a 1.1-second burn and a total delta-velocity of 0.047 m/s. The inclination maneuver is modeled in the second sample of approximately 3.5 hours of data starting April 17, 2012 14:09:01.999 with a larger 82-second burn and a total velocity of change of 6.963 m/s. The filter was able to solve through and converge after both types of burns. The filter adjusts by widening its covariance to continue to process through the maneuver. The inclination maneuver is a much larger burn performed out-of-plane and a less frequent orbit adjust than the drag-makeup maneuver. Figure 9 shows the residual and uncertainty errors for the inclination maneuver case; note the uncertainty increases about 2 hours into the data (16:00:00.000 UTC) when the inclination maneuver occurs. This increase allows the filter to adapt to the maneuver and re-estimate the satellite trajectory. Within the last hour and half the filter recovers and converges.

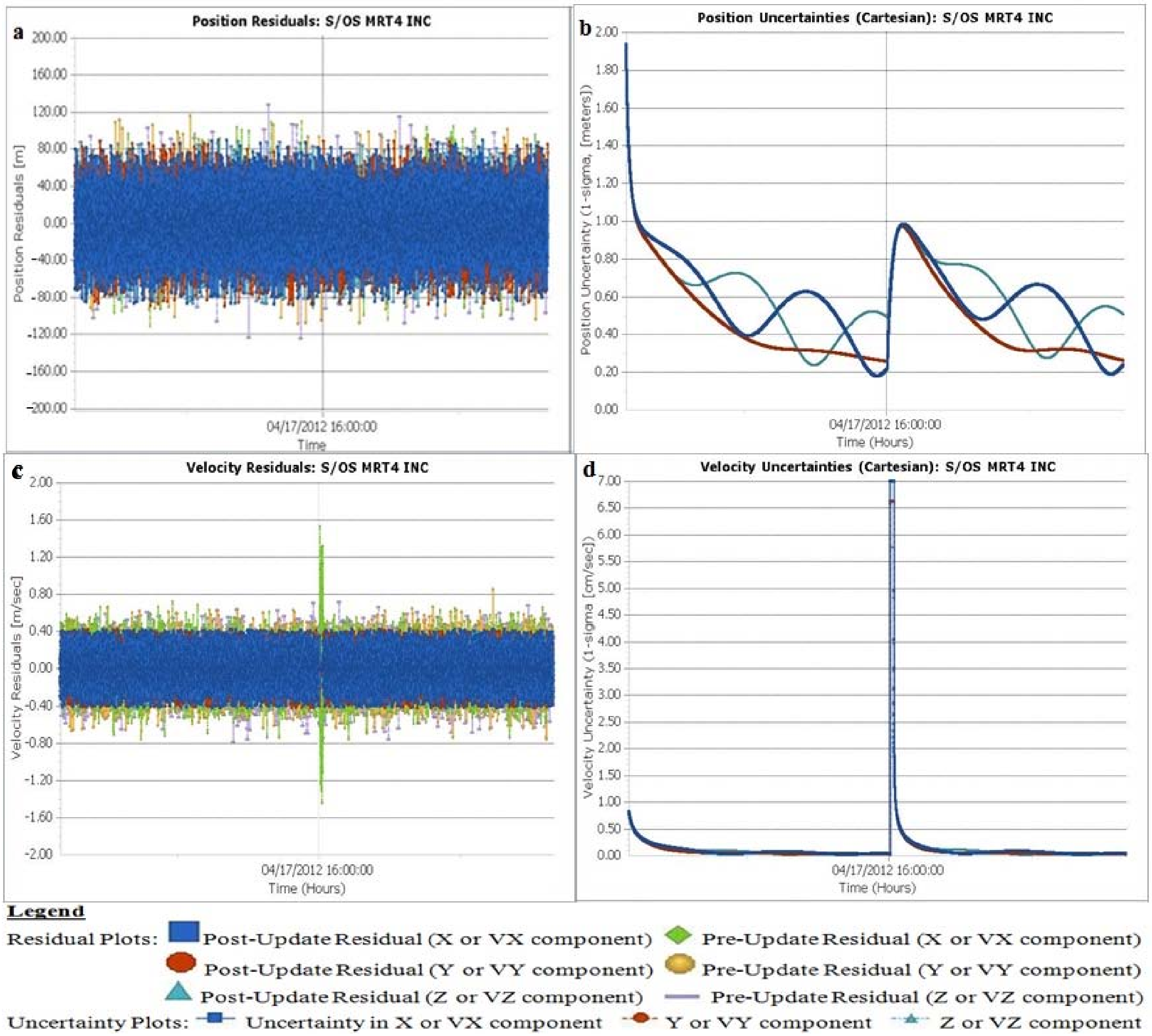


Figure 9. MRT 4 Inclination Maneuver, Epoch: April 17, 2012 14:09:01.999 with 82 second Inclination burn at 16:00:00.000: a. Position Residuals (6-sigma); b. Position Uncertainty (1-sigma); c. Velocity Residuals (6-sigma); and d. Velocity Uncertainty (1-sigma)

The LDCM's OD was validated using various data types from FreeFlyer simulated data (truth vs. filter study); to current S/OS with and without maneuvers; and real-mission data from FGST. The results all show that the residuals converge within a few hours, worst case and that the errors fall well within the 30 meters per axis, 3-sigma accuracy.

5. Conclusion

The FDS ground system deploys modern OD capabilities for the LDCM mission, using near-continuous GPS Point Solution data to provide improved accuracy as well as near real-time orbit solutions for health monitoring and providing a first alert system should the spacecraft undergo significant orbital deviation. The routine functions of the system are highly automated, ensuring standardized and accurate processing at all times. This includes OD processing required for daily planning, OD performed for maneuver reconstruction and calibration, and real-time OD process monitoring ensuring that the spacecraft and the ground results are within tolerances at all times. Should the real-time OD processing indicate that LDCM has deviated from its projected path more than expected the FOT will be notified via email with system event messages. The incorporation of the MySQL data base to the flight dynamics support provides a central location for mission configuration data, and a repository for storing mission trending data in one location.

The capabilities of the FDS FFOD have permitted extensive prelaunch validation of processes and procedures with the continuous DITL simulation running on the system pre-mission to simulate the on-orbit support. The FDS FFOD has been fully validated using multiple types of test data, and its extensive use during the pre-launch time period has provided a good deal of operational experience for the FD team.

6. List of Acronyms

COTS	Commercial off-the-shelf
DITL	Day-in-the-Life
DMS	Data Management System
EKF	Extended Kalman Filter
FDF	Flight Dynamics Facility
FDS	Flight Dynamics System
FFOD	FreeFlyer Orbit Determination
FGST	Fermi Gamma-ray Space Telescope
FOT	Flight Operations Team
GSFC	Goddard Space Flight Center
GPS	Global Positioning System
GOTS	Government off-the-shelf
GTDS	Goddard Trajectory Determination System
ITOS	Integrated Test and Operations System
LDCM	Landsat Data Continuity Mission
MOC	Mission Operations Center
MRT	Mission Readiness Test
MTASS	Multi-mission Three-Axis Stabilized Satellite
OBC	On-board Computer
OD	Orbit Determination
S/OS	Spacecraft/Operations Simulator
USGS	United States Geological Survey

7. References

[1] LDCM website, “Landsat overview,” http://www.nasa.gov/mission_pages/landsat/overview/index.html.

[2] Landsat website, “Landsat Missions Timeline,” http://landsat.usgs.gov/.