Landsat Data Continuity Mission (LDCM) Flight Dynamics System (FDS)

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The Landsat Data Continuity Mission (LDCM) will be launched in January 2013 to continue the legacy of Landsat land imagery collection that has been on-going for the past 40 years. While the overall mission and science goals are designed to produce the SAME data over the years, the ground systems designed to support the mission objectives have evolved immensely. The LDCM Flight Dynamics System (FDS) currently being tested and deployed for operations is highly automated and well integrated with the other ground system elements. The FDS encompasses the full suite of flight dynamics functional areas, including orbit and attitude determination and prediction, orbit and attitude maneuver planning and execution, and planning product generation. The integration of the orbit, attitude, maneuver, and products functions allows a very smooth flow for daily operations support with minimal input needed from the operator. The system also provides a valuable real-time component that monitors the on-board orbit and attitude during every ground contact and will autonomously alert the Flight Operations Team (FOT) personnel when any violations are found. This paper provides an overview of the LDCM Flight Dynamics System and a detailed description of how it is used to support space operations. For the first time on a Goddard Space Flight Center (GSFC)-managed mission, the ground attitude and orbits systems are fully integrated into a cohesive package. The executive engine of the FDS permits three levels of automation: low, medium, and high. The high-level, which will be the standard mode for LDCM, represents nearly lights-out operations. The paper provides an in-depth look at these processes within the FDS in support of LDCM in all mission phases.

I. FDS Overview

For the past 40-years, Landsat satellites have collected Earth's continental data and enabled scientists to assess change in the Earth's landscape. The Landsat Data Continuity Mission (LDCM) is the next generation satellite supporting the Landsat science program, flying behind both current on-orbit missions, Landsat-5 and Landsat-7. LDCM is scheduled to launch in January 2013. LDCM will fly a 16-day ground track repeat cycle, Sun-synchronous, frozen orbit with a mean local time of the descending node ranging between 10:10 am and 10:15 am, requiring orbit maintenance maneuvers for both altitude and inclination station keeping.

This paper provides an overview of the newly developed and implemented LDCM Flight Dynamics System (FDS), a ground system designed with a goal of providing a framework of total automation. This system is fully capable of running continuously for a minimum of 72 hours, supporting all flight dynamics-related activities including autonomous maneuver planning and On-board Computer (OBC) performance monitoring. The FDS element was developed by a.i. solutions Inc. It is one element of a completely automated ground system for LDCM, developed under a NASA GSFC contract with Mission Operations Element (MOE) partners The Hammers Company, a.i. solutions Inc., and GMV Space Systems[1]. The Data Management System (DMS) component of the

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MOE automates the file transfers throughout the Mission Operations Center (MOC). The Integrated Telemetry Operations System (ITOS) provides telemetry, command, and control functions and provides FDS with sequential print files. The Mission Planning and Memory Management system is called FlexPlan; it receives many products from FDS to use for upload as well as for mission planning functions. MOE element Attention! provides remote monitoring and message alerts, and Archiva provides mission monitor and analysis functions.

II. Capabilities

The FDS provides complete ground system product generation for all ground-planning activities including antenna network planning, mission operations planning and scheduling, as well as detailed science planning and projection. The system also permits comprehensive validation of on-board orbit and attitude functioning on a near-continual basis, differencing the latest ground-determined solutions with the on-board determined solutions for both orbit and attitude during each real-time contact. This last component permits the FDS to help monitor the health and proper functioning of the spacecraft, making the FDS an active participant in measuring the OBC performance in an intelligent and autonomous fashion against ground-expected values.

The LDCM FDS is the first flight dynamics ground system developed for a GSFC-based mission to perform completely autonomous ground-based orbit and attitude determination, propagate the orbit, and perform both orbit and attitude maneuver targeting as needed. The FDS also creates command load inputs and maneuver-related products for FlexPlan ingestion. The FDS performs periodic ground-based assessment of the orbit and attitude throughout the day using additional sequential print data. Additionally, the FDS performs automated maneuver reconstruction and calibration, and completely plans for off-nadir image activities. The FDS is designed using a service oriented architecture like approach, and its functionality is provided using 8 SubServices (Figure 1) called from the high-level automation executive, the Service Manager.

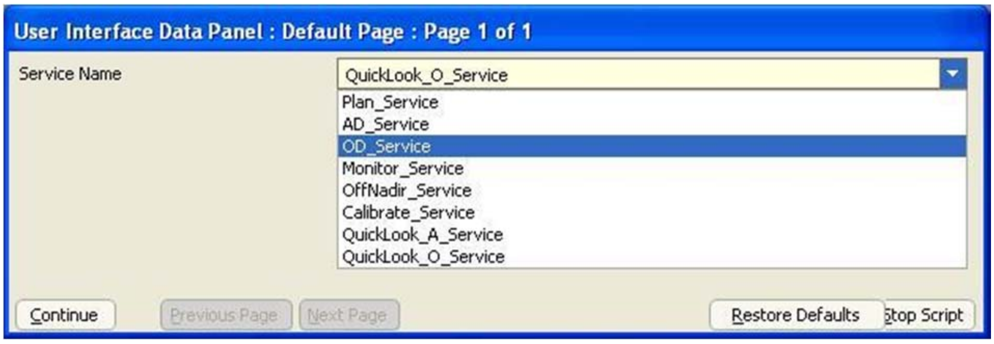

Figure 1. FDS Services

The FDS has 3 major components, shown below in Figure 2: the Commercial off-the-shelf flight dynamics software FreeFlyer® developed by ai Solutions Inc., the GSFC Government off-the-shelf software Multi-Mission Three- Axis Stabilized Satellite (MTASS) tailored for LDCM, and a MySQL database that contains all the settings for force modeling, estimation, propulsion, fuzzy logic control, file naming, and automation dependencies.

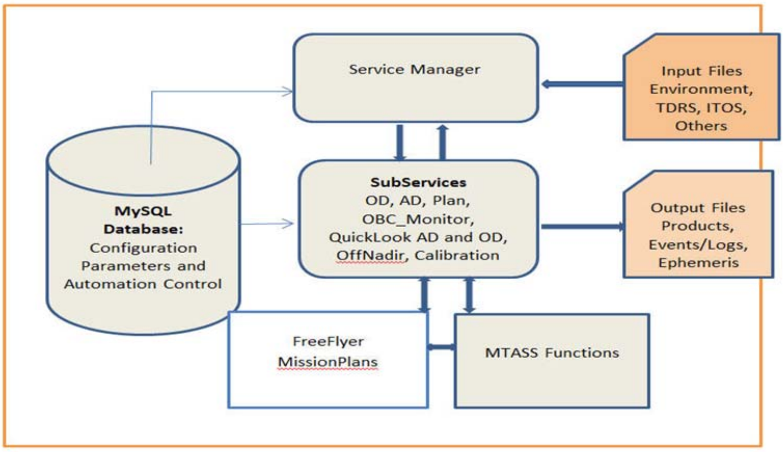

Figure 2. FDS Components

III. Testing in the MOC

The LDCM FDS has been installed in the LDCM MOC since January 2010. A continuous Day in the Life (DITL) simulation has been performed since January 2011, providing invaluable opportunities for evaluating system performance and response under a variety of conditions including formal mission testing periods. This daily simulation has largely been enabled by the extensive automation capabilities that permit the system to run continuously without operator intervention. The system is also capable of generating simulated GPS and attitude data on a regular schedule via FreeFlyer® and MTASS scripts, thus emulating the real operations of the spacecraft. The internal simulators can be turned off when the actual spacecraft simulators are used in formal spacecraft testing.

IV. Automation Operations

The automation scheme permits running 3 different schemas, or strings, on each machine, one called "operations" or OPS, the second called "TEST", and the third called "MODEL". The OPS configuration will be the operational version. The TEST and MODEL schemas permit special testing or analyses without any interference with concurrent operations, safeguarding operational support while permitting the access to operational configurations and tools for analysis. Each schema can use different password-protection privileges, further safeguarding the operational schema. The automation can be fully enabled on the TEST and MODEL environments, as well.

The LDCM FDS automation is split into 8 main functional areas, as shown above in Figure 1. The executive of the automation is the "Service Manager", a FreeFlyer® Mission Plan that runs continually when enabled. The FDS Service Manager is in control of the autonomous FDS. The Service Manager calls the appropriate SubServices, which are collections of FreeFlyer® Mission Plans to support specific flight dynamics functions. Individual FreeFlyer® Mission Plans provide core functional processing, e.g. Orbit Determination (OD) based on Global Positioning System (GPS) Point Solution (PS) data.

The Service Manager was designed around the central operations concept of performing the estimation of the orbit and attitude once per day, shown below in Figure 3. Once the definitive orbit has been re-estimated, the Service Manager will control the propagation of the state via the Plan_Service, and determine whether a station keeping maneuver is needed using the MySQL database of constraint limits for both the ground track control error (via drag make-up maneuvers) as well as the control of the mean local time (via inclination maneuvers). If a maneuver is required during the prediction span, the fuzzy logic models for orbit control scheduling are applied to determine when the maneuver can be performed – day of week and hour of day. The Plan_Service will create the predictive ephemeris and associated products to include any planned maneuvers within the span.

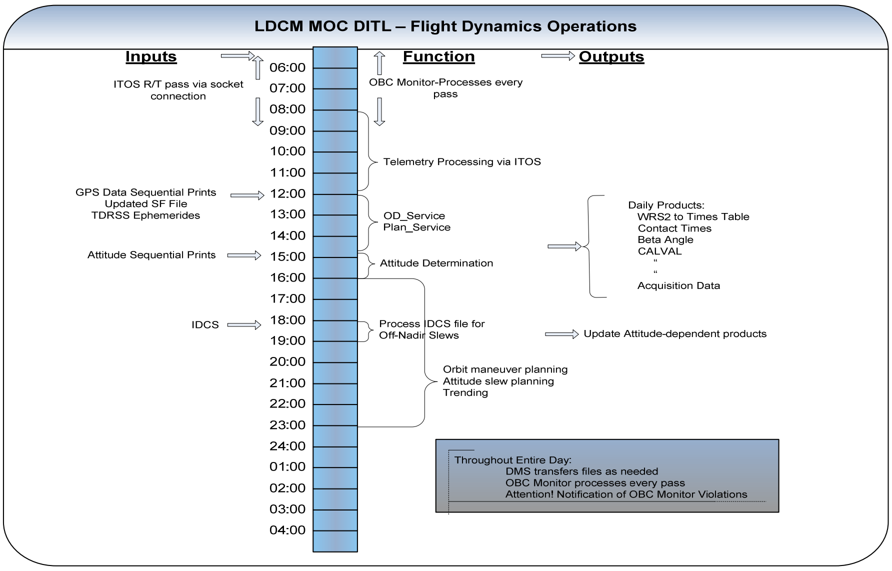

Figure 3. Typical Daily Flight Dynamics Support in LDCM MOC

The Service Manager monitors the system continuously for key file updates that will kick off the FDS new OD, AD, and update of the maneuver plan and product generation. The Service Manager is a new innovation in flight dynamics automation as it successfully manages creating updated products on a schedule and updates the estimation for the current day as soon as the sequential print data is available from the ITOS area. It also manages all other special automation features in the FDS, such as monitoring event messages, file ages and availability, and logging.

The Service Manager is largely file dependent, awaiting the availability of new files before starting subsequent processing. It is in an endless while loop, checking to see if new files are available for performing any service. It also checks to see if all the environment files are current, and whether it has been issued any directives (such as STOP), and checks for special alert messages or "event" files. The Service Manager constantly monitors several locations for updated files. When new files arrive, they are compared with data contained in the "SavePoint Files". These are essential files that are used by the Service Manager to determine its last known configuration of the FDS. During each cycle, the Service Manager compares the most recent input file to the information in the SavePoint file; if the input file is different from the SavePoint file, then the associated subservice is started. The SavePoint files are all located in one directory. Table 1 below summarizes the expected update cycle for each service, as well as the trigger the FDS is looking for to start the service.

Table 1. Service Manager's Functional Support

Service	Expected Update	Plan Trigger
OD_Service	Once per day for last 26 hours of definitive data	Availability of new daily GPS sequential print file (~12:00 UTC)
Plan_Service	Once per day for a 49-day prediction (if executed on Mondays) or 7 days (if executed on Tues-Sun)	Availability of new definitive ephemeris (after OD_Service completes)
AD_Service	Once per day for last 26 hours of definitive data	Availability of new daily attitude sequential print file (~ 15:00 UTC)
QuickLook_OD	Postpass GPS Telemetry Data	As scheduled in MySQL (selectable)
QuickLook_AD	Postpass Attitude Telemetry Data	As scheduled in MySQL (selectable)
OBC_Monitor	Every real-time pass	Availability of open socket connection during real-time pass
Off-Nadir Service	Once per day or near real-time slew requests via Collection Activity Planning Element (CAPE) file	Off-nadir requests included in daily plan service update; additionally near real-time requests are also process automatically as received by FDS

Service	Expected Update	Plan Trigger
Calibrate Service	Once per maneuver	At user prompt after availability of post-maneuver propulsion sequential print file and post-maneuver GPS file along with maneuver in MySQL database

The FDS properly de-conflicts the ordering of the daily support, for example, ensuring that the Plan_Service does not run before the OD_Service. The FDS properly orders all services even if the triggers for the service start are simultaneous.

The operations tempo is to repeat all of the functioning on a daily basis. The OD and AD will be repeated once daily on non-maneuver days. The maneuver planning will be re-executed each day, and orbital constraints will be evaluated. Since the maneuver planning process is so frequent, the orbital control will be performed with highly accurate predictions over the medium term. Any needed attitude slews will also be incorporated in the prediction process, which is a combination of both orbital and attitude planning. This process will be discussed further below in the Plan_Service overview.

V. Detailed Overview by Function

A. Daily Orbit and Attitude Determination (OD and AD Services).

OD for LDCM will be performed once per day using a 26-hour GPS point solution (PS) telemetry file. The file will be directed to the FDS, sent by ITOS via DMS at approximately 12:00 UTC. The data will start on the previous day at 10:00 UTC and end at 12:00 UTC on the current day. Automation scripts will be enabled by the ITOS area to create the sequential print data (telemetry data converted to text files) for FDS. The expected rate of data in the file is 1 Hz.

Once the data arrives at FDS, the Service Manager will automatically detect it via the file naming convention and by comparing the Start and Stop date on the file. The Service Manager will compare these fields to the last known GPS telemetry file that it has previously stored. The last configuration for the OD process should be the GPS telemetry file that began 2 days prior to the current day (used in the previous day's OD processing). Once the newly available GPS telemetry file is available, the ServiceManager will trigger the OD processing, saving the configuration and checking against it continually to see if a more current file has arrived to trigger subsequent processing.

The *a priori* for the OD_Service is a vector extracted from the previous day's definitive ephemeris. If there is a matching definitive previous day's covariance file, it will be used in the process as well. If the ephemeris is not available, the OD_Service will use the first GPS state from the new telemetry file, and will not use the covariance file from the previous day as it will not be appropriate, and the filter startup will be a cold-start. The service uses a Kalman filter to perform the OD to ensure that the definitive accuracy is high throughout the entire data set. The performance statistics are then generated by comparing the current day's ephemeris to the previous day's ephemeris over the 2-hour overlap period. A tolerance is set for this; any large deviations will send an alert from FDS to DMS, and subsequently to Attention!, to alert the FOT. The orbital statistics are also logged into a quality report, and all the OD plots are saved in the archive. The output from the OD_Service is the definitive ephemeris file. This file is sent to the central repository and is also available as an input to the Plan_Service and the AD_Service.

The AD_Service will also run once every 24 hours after the OD_Service (and the Plan_Service). The AD_Service requires the availability of the definitive ephemeris and the daily attitude telemetry file to begin. The newly updated predictive ephemeris from today's Plan_Service run is not required. If available, the AD_Service will also utilize the previous day's Attitude History Files (AHF) and extended Kalman filter (EKF) files. The attitude data is provided at 10 Hz. This large volume of data requires that the data be processed in sections to prevent memory overflows. The data is processed in 2-hour sections, with the sections combined into one overall definitive AHF using a Kalman filter and a Smoother. Detailed statistics on the AD processing are logged. The definitive attitude is then compared to the previous day's AHF throughout the overlap period, and the offsets are logged. If necessary, alerts are sent to the FOT via Attention!

B. QuickLook Services (OD and AD QuickLook Service)

The OD and AD QuickLook Services are features in the FDS that allow for autonomous updates of the attitude and orbit determination results at times other than the daily update time periods. This feature allows for a periodic update of the ground assessment of the attitude and orbit determination, enabled by the frequent provision of post-pass attitude and orbit sequential print data from the MOE ITOS system. Additionally, this feature is useful in investigating a recent anomaly that might have resulted in the issuance of an alert sent by the FDS, such as an alert sent by the OBC_Monitor Service. This service can be run by the user at the GUI or can be set to trigger autonomously at a user-defined interval.

C. Plan_Service

Maneuver planning on-orbit is performed automatically within the Plan_Service. This is an exciting new innovation for an FDS system as the system can perform all on-orbit maneuver planning processing including the attitude slews required to perform the orbit maintenance maneuvers as well as any attitude slews required for instrument calibration.

The data flow for the Plan_Service is shown below in Figure 4. Once the definitive ephemeris is available as output from the OD_Service, the ServiceManager detects the new definitive ephemeris and kicks off the Plan_Service. A seed vector from the end of the definitive ephemeris is stepped forward in time and orbit control constraints are examined. If a drag makeup (DMU) or inclination maneuver is needed within the span of the product to keep LDCM within its orbital constraints, the Plan_Service iterates on the maneuver planning process until a good solution is found for both nominal and low drag conditions. Likewise, if multiple maneuvers are required to maintain LDCM within the stationkeeping box, all of the maneuvers are planned and put into the predictive products to ensure proper forecasting of the maneuvers. The maneuver targeting process is rapid and robust, quickly converging on proper targeting conditions. The FDS also stores the seeds found during the maneuver targeting process to use as initial seeds for subsequent burn planning.

FDS applies attitude slews required as part of the targeting process to properly align the thrusters in the correct direction for the orbit maneuvers. This includes the automatic targeting of the correct inclination maneuver yaw angle to minimize the in-plane burn component of the maneuver to avoid creating a need for a Ground Track Error correction maneuver (or DMU) following the inclination maneuver. This information is processed in combination with MTASS. MTASS produces the desired slew target attitude for uplink to the spacecraft. The Plan_Service also checks for any planned instrument calibration slews in the MTASS slew repository. These slews are planned off-line by the FOT and the Calibration Validation team. Once the slews are approved and planned, they are committed to the repository where they are picked up automatically by the Plan_Service for inclusion in the uplink product as well as in an attitude prediction file. The attitude prediction is then used by the Plan_Service to create all the predictive products including those that are attitude dependent. If no orbit maneuvers or attitude slews are necessary, then the nominal attitude profile will be output by MTASS and given back to the Plan_Service to create the predicted products.

The seamless approach of the Plan_Service also permits using fully-planned or partially-planned maneuvers in the daily processing. Once a maneuver is within 3 weeks of a DMU and/or inclination (INC) maneuver, the maneuver epoch is chosen and fixed in the MySQL database by the FOT as a partially-planned maneuver. This will ensure that the proper allocation is made in the network scheduling to cover the forecasted maneuver. The daily Plan_Service will continue to iterate the size of the DMU or size of the yaw angle for the inclination maneuver in each daily run. Once the maneuver is 2-3 days out, the maneuver parameters will be fixed, and the maneuver will be “fully planned”. Subsequent Plan_Service runs will pick up the fully planned maneuvers within the forecast period and apply the maneuver as fully planned without retargeting.

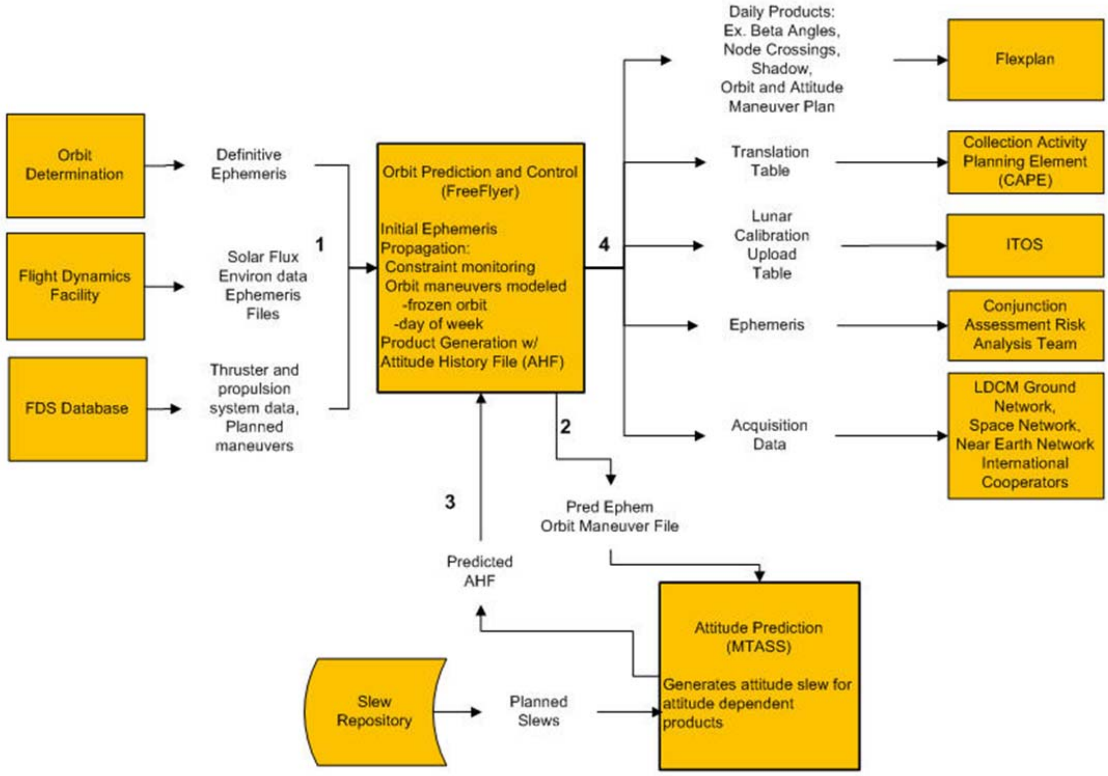

Figure 4. Plan_Service Process Flow

VI. Attitude Slews

Attitude maneuvers can be planned in several different ways, each also in innovative upgrades from past FDS ground systems. The CAPE slew requests will be processed upon receipt and a new attitude profile and associated attitude-dependent products will be created. The CAPE file contains any off-nadir slew requests for special target imaging. Other types of attitude maneuvers require additional coordination between the Flight Operations Team (FOT) FDS and Calibration/Validation (CAL/VAL) team members. Should a member of the CAL/VAL team request a solar slew calibration, for example, the details of the slew will be decided, and the FOT will setup the slew through the FDS and input the slew in the slew repository. The slew will remain in the repository until it is no longer within the span of the predictive products. The FDS can accommodate slews for solar calibrations, Earth calibrations, stellar calibrations, and lunar calibrations.

At the core of attitude slew planning, the FDS uses an MTASS subcomponent called AttPred to string together the series of attitude control segments, which consists of the slew segments from the nominal attitude to the required slew and special events such as star scan or lunar field rastering, and return to the nominal attitude. All of the slew types are shown in Table 2 below. Figure 5 shows how each slew is ordered, with the initial slew out, specialized slew target between time 3 and time 4, and slew back to the nominal attitude. The resulting slew profile is output for modeling the predicted attitude (and associated products), the slew parameters are output to FlexPlan for generation of the uplink parameters to execute the maneuvers.

Two of the slews are automatically supported: the orbit maneuver slew produced within the maneuver planning process in FreeFlyer®, and the CAPE Off-Nadir Slew Request, which is generated outside of the FDS and delivered via DMS. These requests will be ingested by FDS automation in FreeFlyer® and passed to the AttPred slew planner. The CAPE Off-Nadir slew can be supported on demand upon receipt to support quick scene requests on other than standard schedules. The slew request will be received by FDS, automatically ingested, the slew planned, and the products sent to FlexPlan and ITOS to support the near-term slew request.

As opposed to the automatically FDS ingested slews discussed above (maneuver and CAPE slews), the instrument calibration and sensor calibration slew requests require a human in the initial setup loop to manually plan the slew via the LDCM SlewPlanner under the MTASS special LDCM Utilities subpanel, see Table 2 below. Once planned, the slews are committed to a slew repository, where they will be picked up by FDS during planning and product generation each day that the slew is within the predictive product span.

Slew planning can be validated with tools available under the LDCM Slew Planning Menu, with a view of the predicted attitude history file (predicted attitude), viewing the slew event file, and checking constraints across the predicted attitude file.

Table 2. FDS Slews Supported

Slew Type	Event Frame	Offset
CAPE Off-Nadir	Yaw Steering Frame	Roll Slew, < 15 degrees
Orbit Adjust Slews: *Drag Makeup Maneuver* *Ascent* *Collision Avoidance* *Inclination* *De-orbit*	Velocity-Normal-Binormal (VNB)	Thruster alignment (in VNB) + Yaw 0 deg 0 deg 0 deg 90 deg 180 deg
Earth Calibration	Yaw Steering Frame	Offset = Yaw Slew, +/- 90 deg
Solar Calibration	Solar Cal, Spacecraft –Y to Sun	Offset = 0 deg
Lunar Calibration	Lunar Cal, Spacecraft +Z to Moon	Offset = initial offset + scan table sequence of rolls/pitches
Stellar Calibration	GCI	RA & Dec of Star + scan table sequence of rolls/pitches
Sensor Calibration	VNB	Various “slew-hold-slew back” about body axes (x, y, z)

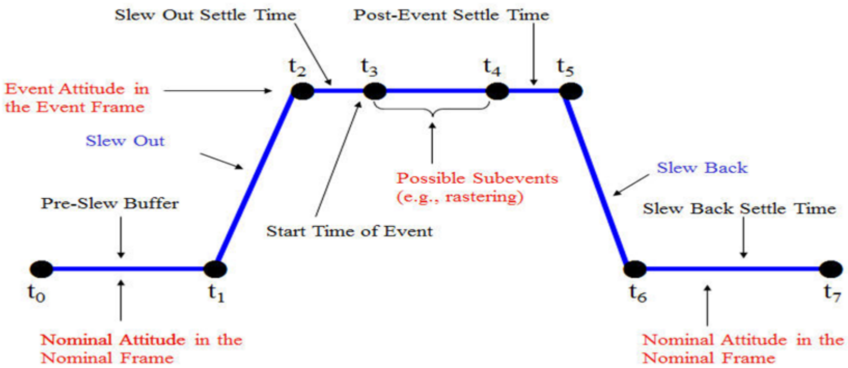

Figure 5. Slew Components

VII. Real-time Monitoring

The FDS OBC_Monitor SubService is another significant improvement in satellite support for GSFC. It is designed to run continuously, checking the OBC performance at every opportunity during a real-time connection via a telemetry socket. This process does not interfere with any of the daily definitive and predictive processing. This process is shown below in Figure 6. Should the OBC performance exceed a user-defined tolerance set in the database, an alert to Attention! will be issued, and the FOT members will be alerted to a possible anomaly on-board that requires further investigation. Since this process is totally automated, it will run regardless of the hour or day, keeping watch over the OBC values. It may be the first alert to a developing issue on-board.

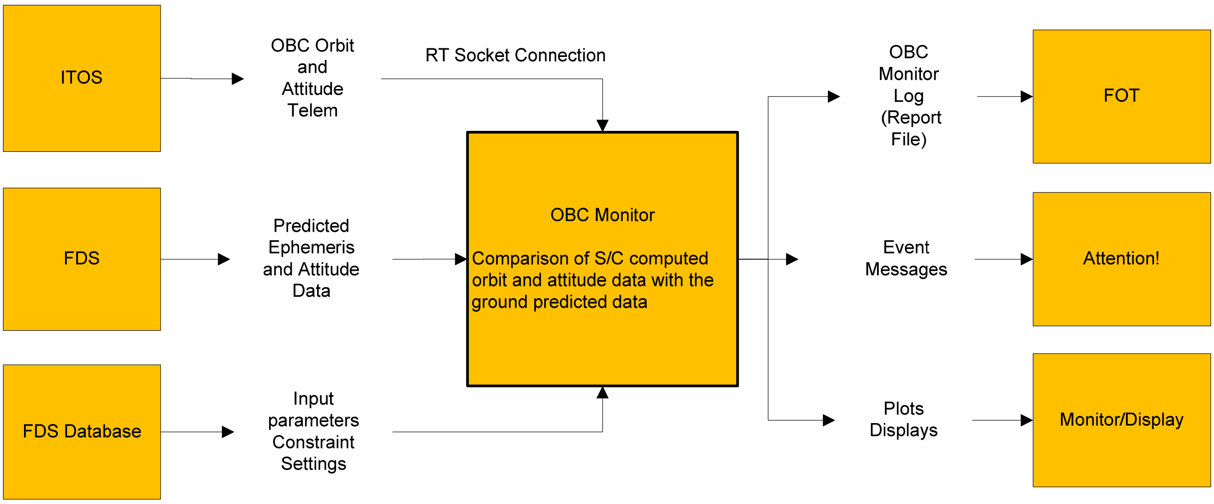

Figure 6. OBC Monitor Process Flow

VIII. Conclusions

The LDCM FDS has made giant strides in integrating orbit and attitude functions for the first time in a single automation system. The FDS is a configurable, highly automated system that provides a flexible approach to operations. The system architecture permits parallel analysis work with the same automation tools as operations, while protecting operations from the analysis projects.

The maneuver planning for on-orbit stationkeeping is robust and accurate, fully planning all required stationkeeping maneuvers without assistance. This automation will ensure that the orbital control for LDCM will be properly performed with a minimal amount of effort from the FOT. Further, the constant replanning of the maneuvers allows the maneuvers to be closely monitored and properly forecasted.

The FDS configuration permits a high integrity level of configuration control, permitting standardization of processes and error tolerance checking. This configuration control will isolate the impact of user error should it occur, and help to standardize the process by which the FDS functions are performed.

The FDS is also a highly graphical system, permitting the user to see the current trending, and emergence of new trends as they develop. This will aid in the user's intuition and provide rapid integration of the maneuver planning concepts and implementation, and estimation understanding.

References

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