Flight Dynamics Analysis Branch

Fiscal Year 2008 End of Year Report

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Flight Dynamics Analysis Branch/Code 595
Greenbelt, Maryland 20771

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The contents of this report are based on inputs generously supplied by members of the Mission Engineering and System Analysis (MESA) Division’s Flight Dynamics Analysis Branch (FDAB) at NASA/Goddard Space Flight Center (GSFC).

Additional information concerning FDAB activities may be obtained through the following Branch management:

Thomas Stengle, Head
Flight Dynamics Analysis Branch, Code 595
(Thomas.H.Stengle@nasa.gov)

Mark Beckman, Associate Head
Flight Dynamics Analysis Branch, Code 595
(Randall.M.Beckman@nasa.gov)

Published copies of this report are available from:

Angela Cossentino
Flight Dynamics Analysis Branch
Code 595
NASA/Goddard Space Flight Center
Greenbelt, MD 20771
(Angela.T.Cossentino@nasa.gov)

This document will be available on the World Wide Web (WWW) at the Uniform Resource Locator (URL): http://fdab.gsfc.nasa.gov/

ABSTRACT

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2008. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based), spacecraft trajectory design and maneuver planning. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

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1.0 INTRODUCTION

This report is produced by members of the Flight Dynamics Analysis Branch (FDAB) at the Goddard Space Flight Center (GSFC). The Branch is responsible for providing analytic expertise in spacecraft navigation, trajectory design and control. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis and navigation. The Branch also provides the expertise to support a wide range of flight dynamics services, such as spacecraft mission design and on-orbit operations. An active technology development program is maintained, with special emphasis on developing new techniques and algorithms for autonomous navigation systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are:

- Trajectory analysis and control design
- Mission planning
- Estimation techniques
- Autonomous navigation
- Constellation and formation flying analysis
- Flight dynamics model development
- Spacecraft conjunction assessment
- Flight dynamics ground systems

The FDAB provides flight dynamics operations services through its Flight Dynamics Facility (FDF). This facility supported flight dynamics computations for more than twenty spacecraft in FY08. Operational services include orbit determination, acquisition data generation for the space and ground networks, tracking data evaluation and maneuver planning support. The FDF also supports Expendable Launch Vehicle (ELV) operations, International Space Station (ISS) orbit determination and Space Transportation System (STS) flight operations.

The FDAB is a branch in the Mission Engineering and Systems Analysis (MESA) Division (Code 590). The MESA division is responsible for providing strong mission-enabling leadership for a broad range of advanced science and exploration missions. In addition, many planned future missions will rely on highly integrated observatories in which the spacecraft functions and performance cannot be separated from the instrument and science functions and performance. The MESA division has the charter and the critical mass of people and skills to provide leadership in these areas. Within the division, the FDAB's alliance with mission system engineers is a strong benefit to the infusion of flight dynamics technologies into new mission concepts, enabling the branch's mission designers to meet the needs of mission formulation study teams.

This document follows an outline similar to one used in past annual reports. It summarizes the major activities and accomplishments performed by the FDAB in support of flight projects and technology development initiatives in Fiscal Year (FY) 2008. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year. The FDAB engineers that were involved in the various analysis activities within the Branch during FY2008 prepared this document. Where applicable, these staff members are identified and can be contacted for additional information on their respective projects. Among the major highlights by engineers in the FDAB during FY2008 were:

- The branch provided successful support of GLAST launch and early orbit operations.
- LRO, LCROSS and SDO navigation and mission design activities maintained schedules for launch readiness in FY09.
- The FDF modernization program was initiated.
- MAVEN was selected (with the branch in the lead role for trajectory design) for the next Mars Scout mission.
- The ARTEMIS mission to the moon (with branch navigation and trajectory design support) was approved.

2.0 FLIGHT PROJECT SUPPORT

2.1 DEVELOPMENT MISSIONS

2.1.1 Constellation Program Navigation Support

http://www.nasa.gov/mission_pages/constellation/main/index.html

The Constellation Program Office at Johnson Space Center (JSC) has the responsibility for developing the next human space transportation system that will be used to extend a human presence throughout the solar system. The program includes multiple project offices and technical teams at all ten NASA centers and at contract organizations around the nation. The Orion Project and Altair Project also are led from JSC. The Ares Project Office at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Ala., leads the design and development of the Ares I rocket and Ares V cargo launch vehicle. The Ground Operations Project at NASA's Kennedy Space Center in Florida will handle ground and launch operations for the vehicles.

The Flight Dynamics Analysis Branch provides navigation expertise and support to the Constellation Program Systems Engineering and Integration Office, including leadership of the Guidance, Navigation, and Control (GN&C) team within the Flight Performance Systems Integration Group. Some of the major activities led or supported by members of the FDAB included:

- The development of a “Navigation Standards” document for the Constellation Program was completed and the document was formally baselined by the program.
- A tiger team, led by the FDAB, studied possible implementation of the Global Positioning System (GPS) as a Range safety tracking source for Constellation Launch vehicles. The FDAB later provided assistance to the MSFC team developing GPS Metric Tracking requirements and preliminary designs.
- A FDAB member was co-lead of a Manual Control Study team, charged with evaluating the feasibility of implementing manual control of flight path angle and attitude during portions of ascent powered flight for the Orion/Ares I launch vehicle. The team recommended that a limited Manual Control capability should be implemented during second stage ascent.
- Interface requirements were developed for tracking services to be provided by the Space Communications and Navigation Office for Constellation missions.
- The GN&C team also worked closely with the Orion Project on a number of high profile activities, including a major mass reduction effort that was implemented, development of navigation and tracking requirements for the Orion Emergency Communications System, and a recent major change in the Orion Communications and Tracking System architecture resulting in re-work of many of the Orion communications and tracking requirements.
- A member of the FDAB co-led the Integrated Performance Team that was part of the nine month, ESMD led CxAT Lunar study. The study looked at possible lunar mission scenarios and compared them to the capabilities of the emerging Ares V

heavy lift launch vehicle and the Altair lunar lander design concepts. This culminated in a three day Lunar Capability Concept Review conducted at Johnson Space Center in June 2008, that gives the Constellation Program formal authority to proceed into “Phase A” for human lunar return, the first phase in preparing vehicle requirements.

- The GN&C Team also participated in the Preliminary Design Review activities for the Ares I launch vehicle, completed in September, 2008.

In additional to these activities, the GN&C team led navigation analysis activities as part of the fourth Integrated Design Analysis Cycle for the Program. The first analysis examined Earth based ground tracking of the Orion spacecraft in a Low Lunar Orbit. The second analysis examined the Earth return trajectory, and the utility of using GPS tracking for Navigation during the return from the moon.

[Technical contacts: Mike Moreau, Kevin Berry, Mike Maher, Russell Carpenter]

2.1.2 Fermi Gamma-ray Large Area Telescope (GLAST)

http://glast.gsfc.nasa.gov/

The Fermi GLAST was launched on June 11, 2008. The FDAB provided prelaunch analysis and on-orbit support during the Launch & Early Orbit (L&EO) phase of the mission. The Flight Dynamics Facility (FDF) provided orbit determination and Space Network (SN) acquisition data support for the first week of the mission. All Flight Dynamics operations were transitioned to the MOC on June 18.

Fermi GLAST flies a redundant pair of Motorola Viceroy GPS receivers that provide the spacecraft with time, position, and velocity. Prior to Viceroy initialization and verification, FDF provided orbit determination solutions to the Mission Operations Center (MOC) based on Differenced One-Way Doppler (DOWD) tracking data acquired from the SN. The GLAST Omni antenna uses Left Hand Circular Polarization (LHCP) and Spread Spectrum, thus we were able to take advantage of using the TDRS Multiple Access Return (MAR) link for DOWD. The DOWD orbit solutions were accurate to better than 20 meters. See Section 2.2.2 for more details on DOWD.

The FDAB provided technical support to the Flight Operations Team (FOT) by tuning the Kalman filter and smoother in Orbit Determination Tool Kit (ODTK), a COTS product provided by Analytical Graphics Incorporated (AGI). The Viceroy receiver specifications indicate that the point solutions are accurate to 30 m (1σ) and 20 cm/s (1σ). By processing the Viceroy telemetry in ODTK, the smoother provided accuracies to 1.67 m (1σ) and 0.17 cm/s (1σ). Filter-smoothing the Viceroy data in the MOC was critical to allow the FOT to perform accurate 42-day predictions for mission planning.

The Viceroy receiver exhibited infrequent anomalous behavior. On occasion, the timetag reported by the Viceroy would show a discontinuity of as much as 111 µs. A Flight Review Board (FRB) team including FDAB personnel was formed to investigate the anomaly. The FRB determined that the timing errors were caused by occasional bit synchronization errors of the GPS data message in one of the 12 Viceroy channels. General Dynamics developed a new Viceroy software image to correct the anomaly. The new software image was uploaded to Viceroy receiver A on August 20, 2008. Ten days later, a bit sync event was observed and the Project verified that the new software image corrected the anomaly.

[Technical contact: Mark Woodard]

2.1.3 Global Precipitation Measurement (GPM)

http://gpm.gsfc.nasa.gov/

GPM is an international cooperative constellation of precipitation measuring satellites. Designed to measure the global 4-dimensional variability of rainfall, latent heating and the micro-physics of the variability, this information will be used to improve the prediction of climate change, weather, fresh water resources and severe storms. To satisfy this requirement in a cost-effective manner, the GPM project envisions using resources from already or soon-to-be launched satellites with suitable instruments (radiometers) for rainfall measurement. The program also aims to improve predictions of the Earth's climate, the weather, and some components of the global water cycle. This article cites a few of the FDAB's analyses over the past year in preparation for the primary spacecraft Preliminary Design Review (PDR) to be held in November, '08.

The Attitude Control System development team requested assistance in analyzing star tracker selection and placement. FDAB personnel looked at Sun and Moon occultation for several combinations of fields of view (FOV) and orientations of star trackers before making a recommendation that was subsequently adopted.

Although the GPM core spacecraft is designed to demise upon reentry, FDAB personnel analyzed controlled reentry scenarios and provided feedback to the project with regard to impact on the mission lifetime, if such a course of action were ever decided upon. In addition to that, branch personnel repeatedly performed orbit lifetime analyses each time spacecraft drag models were updated or new solar flux predictions are released.

A late requirement to launch the GPM core spacecraft into an orbit with no shadow for at least one revolution sparked an analysis of launch windows and their resulting sunlight periods. Another recent requirement led to an analysis of flyovers of a ground site for on-board radar calibration opportunities. A ground station coverage analysis was also performed in order to provide candidate sites as a backup to the primary TDRS support.

These are just a few of the services provided by the Flight Dynamics Analysis Branch in support of the GPM project this year.

[Technical contact: Chad Mendelsohn]

2.1.4 Geostationary Operational Environmental Satellite (GOES)

http://www.goes.noaa.gov/

The FDAB GOES Team has been working since early 2007 to develop eccentricity control strategies for safely permitting the NOAA GOES spacecraft at the "GOES-EAST" location to share real estate with a Brazilian satellite. We successfully completed analysis that indicated a method for the GOES-12 spacecraft to co-exist with the Brazilian spacecraft by timing its regular East-West station keeping maneuvers to drive GOES-12 to a side of the control box opposite Brasilsat B1. Use of this method has begun and the early results look successful. A method for examining the role satellite inclination plays is still being studied.

A possible complication enters the control box sharing saga if one of the future GOES-(N-P) satellites is placed at the "GOES-EAST" location. These spacecraft perform a daily momentum unload maneuver that imparts a delta-V that can alter the strategy modeled for GOES-12. The ideal time to perform these momentum dumps to have a minimum effect on the orbit would be at either 00:00 or 12:00 Spacecraft Local Time (SLT). However, based on the preferred operational timeline, the desired time of day to dump momentum is 6:00 SLT. Doing dumps at 6:00 figured to be a problem. However, analysis showed that the direction that eccentricity evolves can be controlled by adjusting the time of each East-West station keeping maneuver.

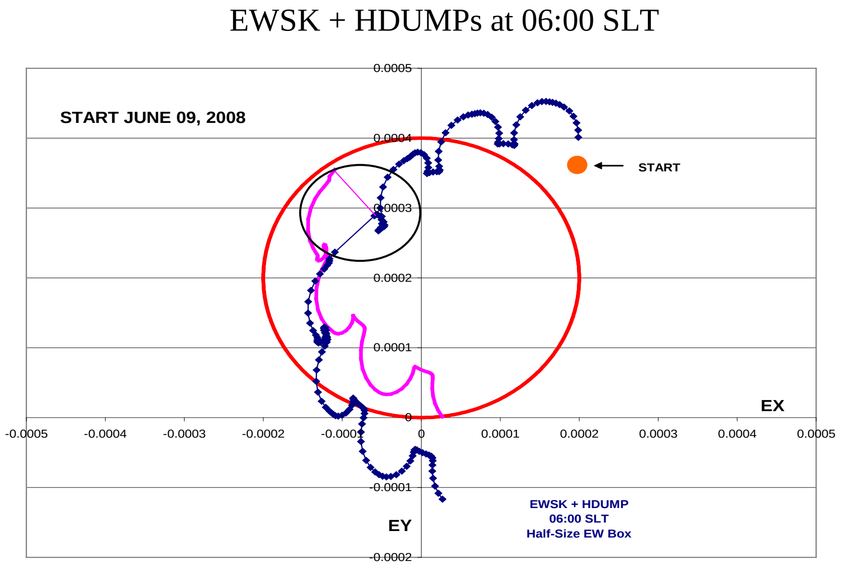

Figure 1. Effect of Change in East-West Stationkeeping

In Figure 1, the blue curve starting outside the red natural circle requires an E-W station keeping maneuver about 3 months after the start. The maneuver is shown as a straight line jump to somewhere on the small gray circle. If the maneuver time is not carefully chosen the eccentricity will evolve outside the natural circle (blue curve). Performing the maneuver at a different time of day would result in the eccentricity vector following the pink curve, thus staying within bounds for a longer time. Future adjustments in maneuver time can be just as effective.

[Technical contact: Robert DeFazio]

2.1.5 Interstellar Boundary Explorer (IBEX)

http://www.ibex.swri.edu/

IBEX will be a highly elliptical earth orbit (HEO) mission with the objective to discover the global interaction between the solar wind and the interstellar medium. This is a Goddard Principal Investigator (PI)-managed mission by Southwest Research Institute (SWRI) and the mission operations will be performed by Orbital Sciences Corporation (OSC). The FDAB was brought in as a consulting role and for the GSFC review boards. The flight dynamics support is to be performed by OSC and Applied Defense Solutions (ADS). ADS was given the responsibility to provide orbit determination (OD) and mission design of IBEX. Branch members supported the Mission Operations Review (MOR) in July 2008 and requested several actions by the IBEX team. One action focused on generating acquisition data, and performing end-to-end testing of the acquisition data, with the Universal Space Network (USN) and the Space Network (SN). The FDAB later realized that OSC/ADS did not have the interface to provide the powered flight state vectors required for the SN support during the High Earth Orbit (HEO) injection and perigee maneuvers. This required that the Flight Dynamics Facility (FDF) be brought in for the SN state vector support.

At the Flight Operations Review it was determined that because the coverage by the USN during Early orbit mission operations was lacking, that Santiago and Wallops Ground Network (GN) support be added to augment the USN and SN support. FDF agreed to provide the acquisition data for the added GN support.

[Technical contacts: Mike Maher, Sue Hoge, Lauri Newman, Dave Quinn]

2.1.6 James Webb Space Telescope (JWST)

http://www.jwst.nasa.gov/

FDAB is pleased to have played a role in helping the JWST pass its preliminary design review (PDR) and achieve confirmation. The JWST is a large, infrared-optimized space telescope designed to launch aboard an Ariane 5 launcher and to operate at the Sun-Earth/Moon L2 libration point. In 2007, our flight dynamics team played important roles in a variety of analyses. By combining automation techniques with advance targeting methods, our team was able to generate and analyze nearly 4000 JWST launch trajectories over the course of a few weeks, subsequently sifting through these to find the viable launch opportunities in 2013. We were instrumental in using Monte Carlo methods to analyze launch vehicle performance and dispersions that led to changes in the propellant allocation required to meet a launch window that reduced the risk of schedule slip.

In addition, we continued to champion 'flight dynamics as a subsystem' approach to our support to mission systems engineering. In the process we've provided valuable input to attitude control, sun-shield, propulsion, communications, command & data handling, and thermal subsystems. Working as an integral part of the Momentum Management Working Group (MMWG), our team developed a Kalman filter approach for orbit determination that accounts for the frequent stationkeeping and momentum unload maneuvers of the observatory and which models the 'sail-force' generated by solar radiation pressure on the sun-shield. These analyses have contributed to the design of the attitude control system and sun-shield and have figured into the propellant budget and thruster placement. By generating a project wide detailed reference trajectory that provides a high fidelity representation of the position and velocity of JWST from launch through 11 years of operations at L2, we've helped to eliminate disconnects in communications and commissioning requirements reducing risk and potentially reducing costs. In addition, our analysis of the powered flight trajectory and corresponding attitude is contributing to understanding the thermal loads during flight aboard the Ariane 5.

[Technical contact: Conrad Schiff]

2.1.7 Landsat Data Continuity Mission (LDCM)

http://ldcm.gsfc.nasa.gov/

The Landsat Data Continuity Mission (LDCM) is the eighth spacecraft in the Landsat series. Code 595 provided technical evaluations for the Source Evaluation Boards (SEBs) for both the LDCM spacecraft and the LDCM ground system. FDAB personnel also provided technical review of spacecraft and ground systems requirements documents and operations concepts. FDAB personnel presented LDCM flight dynamics requirements at the LDCM Systems Requirements Review (SRR) and participated in the Mission Design Review (MDR). FDAB also participated in technical discussions with the spacecraft builder, systems engineers, and scientists.

LDCM will fly a redundant pair of Motorola Viceroy GPS receivers that will provide orbit knowledge. The Viceroy will be initialized roughly 24 hours after launch. FDAB engineers are currently investigating the use of DOWD to provide reliable orbit estimates prior to Viceroy activation. The LDCM communications system will support S-band one-way Doppler service via TDRSS S-Band Single Access Return (SSAR) service.

[Technical contact: Mark Woodard]

2.1.8 Lunar CRater Observation and Sensing Satellite (LCROSS)

http://lcross.arc.nasa.gov/

The FDAB continued to provide significant trajectory design support for the Ames Research Center-managed LCROSS mission this fiscal year. LCROSS is a secondary payload, co-manifested with the GSFC-managed Lunar Reconnaissance Orbiter (LRO) mission, scheduled for launch in March 2009.

The primary LCROSS mission objective is to confirm the presence or absence of water ice in a permanently shadowed crater near a lunar polar region. Since ferrying water and other goods from Earth to the Moon is expensive and time consuming, finding natural resources, such as water ice, on the Moon could help expedite future lunar exploration.

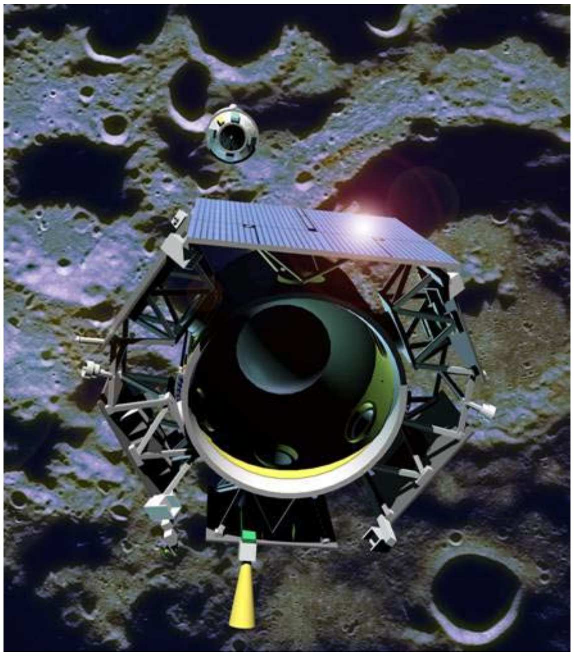

Figure 2. LCROSS in Lunar Flight

One unique aspect of the LCROSS mission concept is that the spacecraft carries the spent upper stage of the Atlas V launch vehicle, called the Earth Departure Upper Stage (EDUS), with it for most of its trajectory. Soon after launch, LRO separates from LCROSS. After separation from LRO, LCROSS, with the EDUS still attached, will perform a lunar swingby, go into a high ecliptic inclination orbit about the moon for 1.5 - 5 orbit periods, and then impact one of the lunar poles. Eight hours before impact, EDUS and LCROSS will separate. The EDUS will then impact the polar region while several LCROSS instruments, as well as selected ground and space assets, will analyze the impact plume for signs of water-ice. LCROSS, itself, still in view of the ground communication assets so that data can be transmitted back to Earth, will then also impact the Moon four minutes later.

[Technical contact: Steven Cooley]

2.1.9 Lunar Reconnaissance Orbiter (LRO)

http://lro.gsfc.nasa.gov

As the first mission in NASA's Vision for Space Exploration, the Lunar Reconnaissance Orbiter (LRO) is designed to spend a year in lunar orbit preparing for future human exploration of the Moon. The FDAB is responsible for all flight dynamics support (mission design and navigation) for LRO. The mission is currently scheduled to launch in 2009 on a United Launch Alliance (ULA) Atlas V vehicle.

The FDAB is responsible for providing target state vectors to ULA for each launch date. Several versions of this analysis were delivered during this fiscal year, and it will be updated again before launch. As part of the mission design efforts, the team has also put together a robust sequence of maneuvers that enable trajectory corrections, lunar orbit insertion, and orbit maintenance. The team has started training for mission operations support through a variety of simulations and mission rehearsals, including extensive contingency analyses. This process has included development of all the procedures to be used for operations, as documented in the team's handbook.

In addition, the portion of the team that supports navigation functions completed the development and testing of the first set of upgrades to the Goddard Trajectory Determination System (GTDS). These upgrades provide precision orbit determination capabilities for LRO on a daily basis. Another set of upgrades is currently being developed that will allow processing of the one-way forward laser ranging measurements from Earth. The Flight Dynamics Facility (FDF) team has also been supporting the certification efforts for the five new or upgraded ground tracking stations. The new White Sands 18-m antenna will be certified in the upcoming months, and the four upgraded Universal Space Network (USN) antennas have been certified as able to meet the challenging LRO ground tracking requirements.

All flight dynamics mission support for LRO will be provided from the FDF in Building 28. New hardware has been installed and tested that will be used for console support as well as the new interface with the LRO Mission Operations Center (MOC). Various sets of software have been developed and/or properly configured to support the maneuver planning and product generation efforts required in support of the mission. All of these interfaces have been tested during simulations and will continue to be tested and verified until launch.

The FDAB has been working with a team at Johnson Space Center (JSC) that has an interest in gaining experience in the areas of lunar mission design and navigation. A draft agreement is in place that will allow the JSC team to shadow the FDAB team during LRO support.

[Technical contact: Mark Beckman]

2.1.10 Magnetospheric Multi-Scale Mission (MMS)

http://mms.space.swri.edu
http://stp.gsfc.nasa.gov/missions/mms/mms.htm

The Magnetospheric Multi-Scale Mission (MMS) consists of four spinning spacecraft flying in a tetrahedral formation in highly elliptical earth orbits to study the phenomenon of magnetic reconnection on the dayside magnetopause and the nightside neutral sheet. A mission of this type presents many flight dynamics challenges. During FY08, MMS Phase B development and associated analyses proceeded with a System Design Review (SDR) in June and efforts continuing toward a PDR in May 2009 for the in-house mission.

Navigation work this year focused on supporting the development of the Interspacecraft Ranging and Alarm System (IRAS), a weak signal GPS receiver and a crosslink receiver/transmitter with GEONS embedded software for onboard orbit determination. Efforts included:

- Documenting covariance sampling techniques
- Defining statistical analysis techniques
- Analysis of solar radiation pressure model accuracy requirements
- Analysis of one-way forward Doppler to augment the GPS and crosslink measurements
- Analysis of crosslink message size reductions and associated reduction in the GEONS configuration from solving for all four satellites simultaneously to solving for the local satellite only
- Documentation of assumptions for intra-formation collision probability analysis
- Evaluation of the existing Collision Assessment Tool
- Analysis of the consistency of IRAS and GEONS measurement models
- Analysis of IRAS TRL6 test data
- Baseline testing to validate the crosslink simulator for IRAS
- Orbit determination sensitivity analysis of the commissioning phase
- Monte Carlo analysis of an MMS Phase 2b, 10 km formation maintenance maneuver which is expected to be the most stringent navigation scenario.

Mission design efforts involved launch window expansion around the days analyzed for the MDR; finite burn analysis of several propulsion thrust options; a comprehensive fuel budget estimate; analysis of eclipse periods relative to launch orbit and mission attitude conditions; contact analysis for antenna design and mission operations planning; launch vehicle-related analysis; development of a method for raising the apogee of all four MMS within the science and engineering constraints and off-nominal case analysis; analysis of the impact of maneuver timing, magnitude, and direction errors on the relative orbits; analytic and Monte Carlo analysis of the interspacecraft range, range-rate, and relative acceleration for IRAS operating limits; simulation of truth data for Constellation HiFi development testing and for IRAS TRL-6 testing; and formation stability analysis.

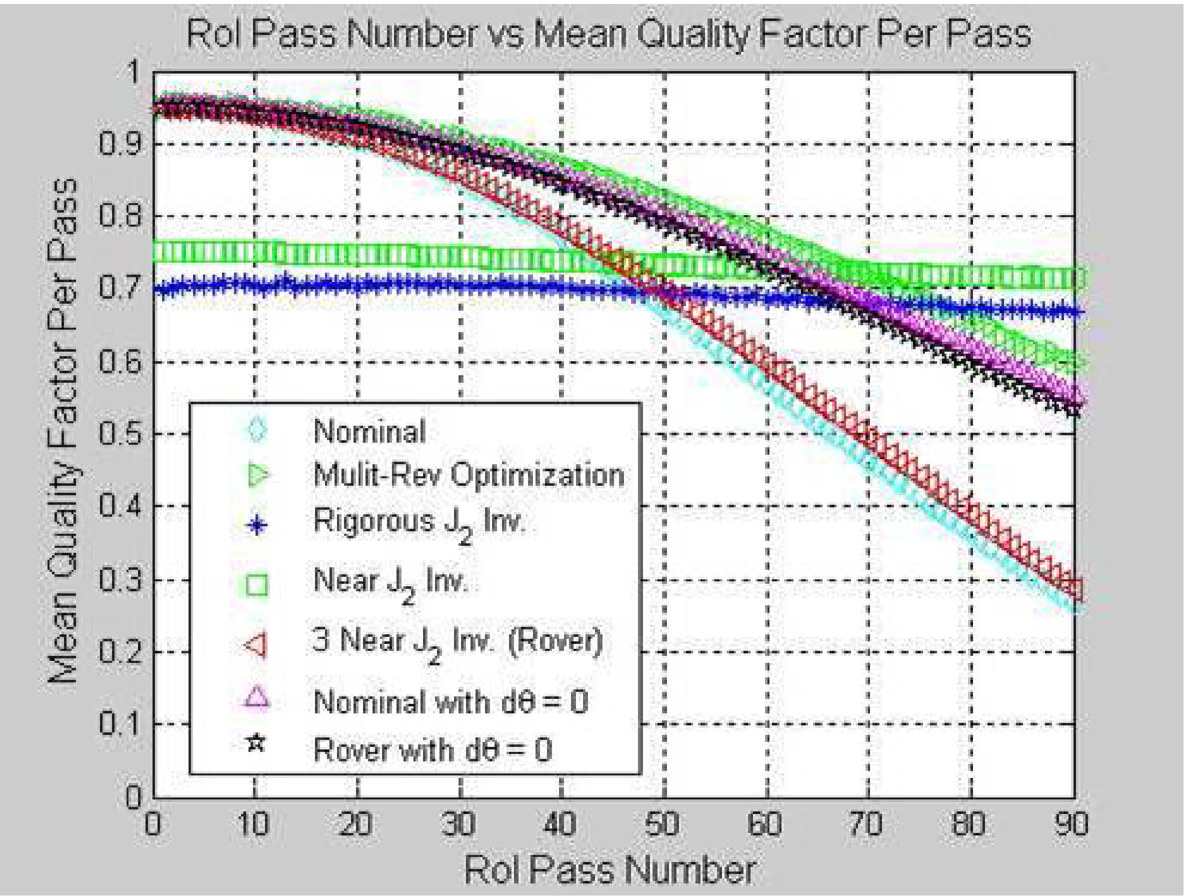

Figure 3. ROI Pass Number vs Mean Quality Factor Per Pass

Several design strategies that seek to improve the long-term stability properties of MMS formations were investigated. These techniques employ nonlinear programming to optimize a formation performance metric, subject to periodicity constraints. Neglecting error sources, these techniques reduce maneuver frequency by a factor of two. Figure 3 summarizes the stability properties of the various techniques analyzed, plotting how many passes through the Region of Interest the formation meets the Quality Factor requirement. It is not clear at this time if these design techniques provide a realizable improvement in stability in the presence of navigation and control errors.

[Technical contacts: Cheryl Gramling, Trevor Williams, Steven Hughes, Russell Carpenter]

2.1.11 Solar Dynamics Observatory (SDO)

http://sdo.gsfc.nasa.gov/

The SDO Flight Dynamics Team is marching toward an uncertain launch date, but is working on many fronts to be launch ready nonetheless. The MOC Flight Dynamics System (FDS) software is in the midst of what could be its final “cleanup” release. However, the slipping launch date has deferred some Ground System Readiness Testing that is highly desirable to insure launch readiness. We continued to train and support internal and Project simulations to exercise team members, software and operational procedures. For the Launch and Early Orbit (L&EO) phase, the orbit circularization profile was updated each time a significant change in the input conditions was noted. Currently, we are set to publish a Data Book for a June 23, 2009 launch of SDO. The orbit circularization profile consists of 7 principal orbit raising maneuvers carried out over 19 days. This effort will place SDO in a +/- 0.5 degree longitude control box about a longitude of 102 degrees West. The Data Book also contains predictions on eclipses, nodal crossing times, longitude drift, and spacecraft TDRS and ground station coverage for both line of sight and the SDO omni antennas in an attitude dependent mode.

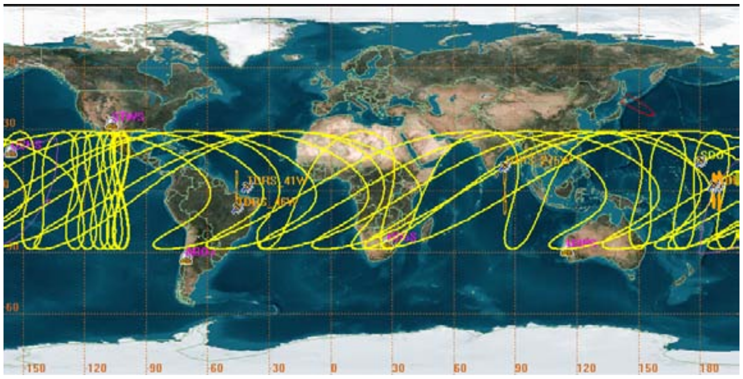

Figure 4. SDO Ground Track: Separation to 1st Station

Documentation updates during this reporting period included the *SDOGS / WS-1 Antenna S-Band Tracking Certification Plan*, the *SDO FDS Operational Handbook* and the *MOC/FDS to FDF Interface Agreement Document (IAD).* In addition, an MOA for SDO Conjunction Assessment was written to cover L&EO and the mission orbit.

The S-Band tracking service for the two newly constructed 18-meter SDO ground antennas at the White Sands Complex was certified by analysts in the GSFC Flight Dynamics Facility.

In the analysis area, inputs were updated to the link margin calculations for the ground antenna supporting SDO. Analysis by the SDO Attitude Control System team concluded that the gyros used to hold the spacecraft attitude during orbit raising maneuvers will be influenced by temperature. The MOC/FDS software will be modified to allow in-orbit calibration of the temperature dependence of these gyros. An attempt to gain insight into this issue during the recent SDO Thermal Vacuum testing proved inconclusive. In the orbit determination area, the use of Differenced One way Doppler data from two TDRSs in the initial orbit solution was studied showing promising results for this early but crucial computation.

[Technical contact: R. DeFazio]

2.1.12 Space Communications and Navigation (SCaN) Constellation Integration Project (SCIP)

SCIP was the Headquarters SCaN interface to the Constellation Project (CxP). The support of SCIP by the FDAB included routine support of weekly meetings by SCIP, and also the Constellation Project (CxP).

Multiple CxP Document Change Request (CR) reviews were supported over the past year. Most of the CxP Level-2 radiometric requirements were worked out between the SCAN(SCIP FDAB support) and the CxP Software and Avionics Integration Office (SAVIO) and are on the verge of being baselined. FDAB also participated in the development of the Level-2 SCaN Compatibility Test Set (CSTS) Requirements Document.

Major SCIP/CXP meetings FDAB supported were the the SCIP Quarterly Status meeting in October 2007, the Constellation Project (CxP) Integrated Stack Technical Interface Meeting (TIM) in November 2011.

SCIP has been dissolved by NASA HQ, although a subset of the former SCIP support has remained to support SCAN, as SCIP had done. As a result, contractor support was terminated, and only one FDAB member remains supporting part time. This SCaN CxP Interface support will continue into FY 2009 with potentially increased FDAB support.

[Technical contacts: Michael Maher & Karen Richon]

2.1.13 Tracking and Data Relay Satellite – K (TDRS-K)

In January 2008 Boeing Corporation was awarded the fixed-price contract for two Tracking and Data Relay Satellites (TDRS), adding TDRS-K and –L to the existing fleet of nine TDRS. The System Definition Review was held in July 2008 as the development continues to move forward toward a December 2008 Preliminary Design Review. Functionally, TDRS-K spacecraft will be equivalent to the second generation TDRS HIJ spacecraft, except that Multiple Access Return services on TDRS-K will perform ground based beamforming.

FDAB supported the development of the System Operations Concept, the Ground Segment Operations Concept, and the Multiple Access Beamforming Equipment

(MABE) preliminary design. An effort has also been underway between FDAB and Boeing to ensure that momentum wheel desaturation maneuvers and thruster flushing events on the TDRS-K spacecraft can be accurately modeled in the TDRS orbit determination performed at the Flight Dynamics Facility to meet the TDRS orbit prediction requirements for TDRS customers.

[Technical contact: Cheryl Gramling]

2.2 OPERATIONAL MISSIONS

2.2.1 Commercial and Foreign Entities Pilot Program

In FY08, the Flight Dynamics Analysis Branch assumed responsibility for support of the U.S. Strategic Command's (USSTRATCOM) Commercial and Foreign Entities (CFE) Program, which was previously supported from the Space Networks Project (Code 452). This work involves serving as a Liaison between USSTRATCOM and customers from commercial, foreign, and public entities who seek to obtain data and services from USSTRATCOM. For the past 30+ years, NASA Goddard has been designated to be the entry point for CFE customers to obtain USSTRATCOM services due to the provisions of the Space Act of 1958 which allows NASA to share data with those entities. The NASA Liaison assists CFE customers by making sure Form 1 requests are formatted properly and contain valid information, then passes those requests to USSTRATCOM for approval. If approved, the Liaison then coordinates routing of the data through the Networks Communication Center to the customer. Lauri Newman is the designated civil servant Liaison, and is supported by Honeywell in executing the day-to-day coordination.

In addition, the Air Force has been directed by Congress to put a new, expanded CFE program in place beginning in FY10. Lauri Newman has been working closely with Air Force Space Command to define what this program will look like and what opportunities exist for NASA to participate. Lt Col Charles Spillar visited Goddard in September 2008 to tour the facilities and learn more about NASA's current role in the CFE program and what NASA's capabilities are which could be utilized in the future. Goddard's close ties with the Air Force and USSTRATCOM personnel through the Conjunction Assessment and Space Protection areas in addition to the CFE support combine to build a strong, mutually-beneficial relationship between NASA and the military.

[Technical contact: Lauri Newman]

2.2.2 Differenced One-Way Doppler (DOWD)

DOWD is a subset of the one-way Doppler measurement available to SN customers for the determination of early orbit characteristics. A DOWD measurement is generated when a customer spacecraft with a wide-beam antenna system transmits a S-band one-way tracking signal (return link) to two TDRSs simultaneously. The configuration of S-band return links can be a combination of SSAR / MAR or SSAR / SSAR for the TDRS pair. The return link Doppler measurement, received by the two (preferably non-collocated) TDRSs, can be differenced and used as a type of observation to help determine the state of the user spacecraft. DOWD is typically used for any of three scenarios: as an early orbit determination method when a spacecraft's internal navigation methods are not fully functional during launch; for spacecraft that have no internal navigation methods and are not coherent; for spacecraft that possess non-TDRS compatible transponders or transceivers (non-TDRS compatible means not spread-spectrum).

The FDAB is working to create a DOWD Users' Guide. The purpose of this guide is to outline the technical implications and mission planning parameters of using DOWD via the Space Network (SN). The Users' Guide will describe the technical details of DOWD, discuss the inherent benefits and limitations of DOWD as well as describe the process of obtaining DOWD support from the SN. Additionally, the Users' Guide will examine the communications equipment requirements for DOWD and present the past performance of DOWD based on previous operational use.

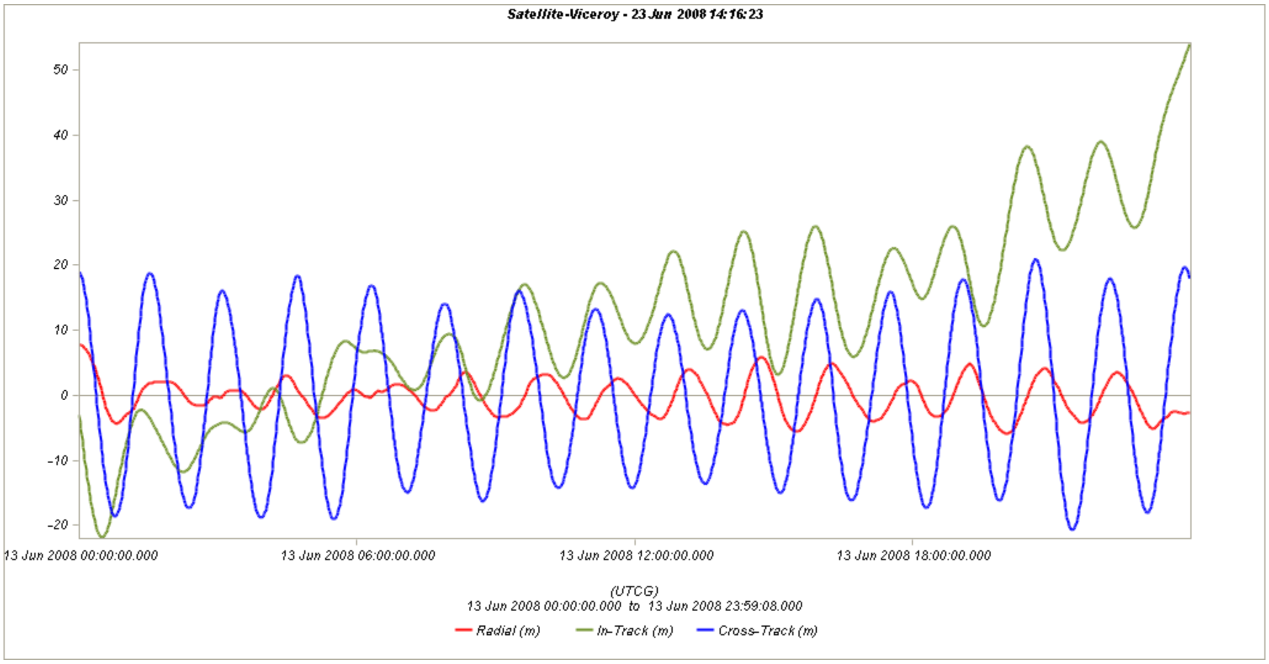

Figure 5. Computed Residuals between GPS and FDF Orbit Determination Solutions

DOWD was most recently used to support the launch of the Fermi Gamma-ray Large Area Telescope (Fermi GLAST) on June 11, 2008. GLAST carries two Motorola Viceroy GPS receivers that provide the spacecraft with positioning, navigation, and timing (PNT). However, the GPS receivers were not initialized immediately before or after launch so they could not be used for PNT during launch and early orbit. DOWD was used as an early orbit OD tool as well as a verification method once the GPS receivers were initialized. Figure 5 shows a plot of the radial, in-track, and cross-track differences between the definitive DOWD and Viceroy (GPS) solutions for 1 day (June 13). The total RMS difference between the 2 solutions was surprisingly good, roughly 20 meters, indicating that DOWD is a very good option if you can get the TDRSS time.

[Technical contacts: Michael Maher, Dennis Woodfork, Mark Woodard]

2.2.3 Earth Science Mission Operations (ESMO) Support

The Flight Dynamics (FD) team has supported the Earth Science Mission Operations (ESMO) division for mission operations and in many diverse analysis areas for multiple Earth Science missions. Three Earth Observing System (EOS) Mission Operations Working Group (MOWG) meetings were supported by the FD team (Lille, France in October 2007, Greenbelt, MD in March 2008 and Langley, VA in October 2008), in addition to an Aura Science Team Meeting in Columbia, MD in October 2008. The FD team presented analysis results and future EOS mission operations plans at each of these meetings comprised of representatives from all the Afternoon Constellation (AC) member missions.

Afternoon Constellation Maneuvers: EOS Drag Make-Up (DMU) maneuver planning was designed to position Aqua, Aura, & Terra so that routine orbit maintenance maneuvers were not required during the Beijing Olympics (a science request for uninterrupted pollution monitoring). The FD team planned, supported, and calibrated the following orbit maintenance maneuvers in FY 2008: 4 Aqua DMUs, 3 Aura DMUs, 3 Terra DMUs and 3 Terra Inclination maneuvers. A wave-off for a planned Aura DMU was necessary because of predicted conjunctions with both Aura maneuver options presented; the DMU was re-planned for the following week.

EOS Inclination Plan: The EOS 2009 Inclination plan analyses were also presented at the two MOWGs. Several conflicting new "desires" for Mean Local Time (MLT)/solar beta angle constraints were analyzed to try to meet all the new requests. It was found that all mission "desires" could not be simultaneously satisfied with one inclination plan and ESMO management had to prioritize the requests. The FD team also generated and provided analysis information to the PARASOL mission for review of Aqua 9-maneuver inclination plans (post-March MOWG) and received approval from PARASOL and the other Afternoon Constellation (AC) members. The FD team delivered the Spring 2009 Inclination Series ephemerides with and without solid Earth tide effects modeled, but recommended the latter be used for AC planning purposes.

Solid-Earth Tide Effects on MLT Prediction: The accuracy of long-term, MLT predictions was found to be significantly affected by the un-modeled effects of solid-Earth tide (SET) in the operational version of the EOS maneuver planning software (FreeFlyer). A beta version of FreeFlyer with SET effects modeled was tested using historical EOS ephemerides. This testing showed that the error in long-term MLT prediction was greatly reduced when SET perturbation effects were included. This improvement will permit better launch vehicle targeting information for future Constellation members

Backup EOS Operations Center (BEOC): A backup EOS operations center is now required and the FD team has supported the operations concept phase, requirements phase, and specification phase. The team also provided a final equipment list that was used for purchasing the FD BEOC hardware. The final FD recommendations were reviewed and approved by an ESMO BEOC implementation team.

Risk Mitigation Maneuvers: Task personnel supported a close approach of Aura with a piece of debris (object #01399) by planning a risk mitigation maneuver (RMM) on Thursday June 26, 2008. Intensive tracking of the object was performed early in the week, but the predicted miss distances continued to decrease and the probability of collision continued to increase to the largest historical values seen on the EOS missions. A 2-second Aura RMM was performed, since additional information showed that the threat continued to be significant. Task personnel supported another close approach of Aura with a piece of rocket debris by planning a RMM. The maneuver was waved-off after additional information showed that the threat had subsided.

Aura Re-phasing: A request from the Aura Microwave Limb Sounder (MLS) principal investigator (PI) was analyzed to assess the improvement in co-located viewing opportunities and estimated viewing durations with a CloudSat (CS) nadir-pointing instrument by reducing the relative separation between Aura and CS. Several iterations were required to insure that the PI viewing requirements were achieved with the proposed FD plan. An Aura re-phasing plan was analyzed by the FD team and presented at the Pasadena Mission Operations Working Group (MOWG) meeting and the team received approval of the Aura rephasing plan from the attendees. The plan was then presented to ESMO, Code 300, and HQ and approved by the review board. The re-phasing was accomplished by stopping routine Aura drag make-up (DMU) maneuvers until the desired phasing with CS was achieved. The elimination of DMU maneuvers resulted in a lower Aura altitude, which decreased the orbital period, allowing Aura to “catch-up” with CS. An Aura DMU (orbit-raising) maneuver was then performed on May 7, 2008 to stop the Aura drift toward CS and return Aura to the proper altitude.

Aura MLS instrument attitude and orbit accuracy analysis: The Aura MLS PI contacted ESMO regarding improvements in attitude and orbit accuracy beyond the original mission requirements. The improvement could provide more accurate hurricane predictions, especially in the modeling of early hurricane formation. The FD team performed an analysis to determine the accuracy of overlap compares between on-bard computer (OBC) and definitive ephemerides and found that the desired radial component accuracy was close to the new constraint proposed. However, the onboard, along-track component error (not specified in the initial MLS request) would lead to excessive attitude pointing errors, based on their stated attitude constraint. A FD plan was proposed to increase the frequency of Flight Dynamics Facility (FDF) definitive orbit generation and EOS FD predictive orbit products to reduce the induced attitude determination error from along-track orbit error. Improvements to the onboard attitude determination accuracy were also investigated and preliminary analysis indicates that improved attitude sensor calibration along with thermal distortion modeling may be required to meet the new MLS requirement.

Glory analysis**:** Glory had initially requested entry into the AC, but budget considerations caused several other options to be explored. A “No Propulsion Option” below the AC was investigated, with the implications on coincident viewing opportunities with AC constituents analyzed. This option was later dropped and the FD team also provided inputs for Glory launch and early orbit operations, analysis/approval of proposed launch vehicle parameters from an AC safety perspective, final ICD review comments, and reviewed a Glory Configuration Change Request (CCR) regarding their request to move closer to the Parasol control box by 15 seconds from a Constellation safety perspective.

EOS De-Commissioning: The FD team began analysis/specification of the Terra de-commissioning plan. A controlled re-entry is not required (or possible) with this spacecraft. Multiple meetings were conducted to define the goals, requirements, and spacecraft operational constraints during the “safing” of the spacecraft, in accordance with NASA guidelines.

Lifetime predictions for Aqua and Aura were also generated using the FD institutional maneuver planning software with the decay phase modeled using the Johnson Spaceflight Center (JSC) Debris Assessment Software (DAS). Preliminary analysis indicates that both missions have sufficient fuel to remain operational past 2016, if required.

Constellation Coordination System (CCS)**:** The CCS is managed by the FD team and serves as the center for exchange of operational products (e.g. ephemerides) by the AC constituents. A new version (V 4.1) was delivered this year and requirements for V 4.2 and V 5.0 were also approved by ESMO management.

Anomaly Support: The FD team assisted with analysis of unrelated Solid State Recorder (SSR) anomalies on Aqua and Aura and explored the potential for the FDS system to be used to help replacing missing data. An alternate method to recover the data was found, but the FD team supported two Aura control mode transition simulations for a Fault Management Unit (FMU) reset contingency and successfully provided the necessary FD quaternions for simulated transition back to Fine Point Mode (FPM).

[Technical contact**:** David Tracewell]

2.2.4 GOES Operational Support

The FDAB provides support to the GOES Project at GSFC and to NOAA in a number of areas related to both preparation for upcoming launches and support of in-orbit GOES spacecraft. The launch in-waiting is GOES-O, currently scheduled for the first quarter of 2009. Boeing Satellite Systems is responsible for Flight Dynamics operations during the first 24 days of the mission. The FDAB provides consultation and backup support to the Project, as well, as, working a few prime requirements related to collision avoidance assessment, acquisition data generation and delivery, and backup orbit determination. From Launch +25 days to Launch + 96 days, the FDAB assumes the prime role for orbit determination and acquisition data until NOAA achieves Image Navigation and Registration startup.

The in-orbit GOES fleet has encountered several anomalies and problem situations during this reporting period. In December, 2007, a leaking thruster sent GOES-12 into safe hold several times. FDAB personnel were called in to perform DIRA (gyro) calibration on several occasions before the anomaly was characterized and corrected. The FDF GOES Team received a letter of commendation from NOAA for their role in supporting this anomaly resolution.

The GOES-13 spacecraft had an anomaly in August, 2008 when a malfunctioning thruster caused a move back to Normal On-Orbit mode during the annual North-South maneuver. As a result of the aborted maneuver the target inclination was not achieved and an increase in longitude drift rate took GOES-13 out of its control box and into close proximity with other geosynchronous spacecraft. The FDAB worked with NOAA and USSTRATCOMM to get an accurate assessment of the predicted close approach between GOES-13 and several communications spacecraft. Before the autumn eclipse period began in late August, NOAA maneuvered GOES-13 to reverse its drift back toward its control box. The stopping maneuver will occur after the eclipse period ends.

[Technical contact: Robert DeFazio]

2.2.5 NASA Robotic Conjunction Assessment Process:

Over the course of the past year, the Conjunction Assessment (CA) program initially implemented by FDAB to support the Earth Science Constellation missions has been expanded to support all of NASA's unmanned (robotic) missions as part of the Space Systems Protection Mission Support Office (Code 590.1). A new requirement (NPR 8715.6a) was signed in August 2007 requiring all NASA missions with maneuver capability that fly within 200 km of GEO or have perigees less than 2000 km to perform routine Conjunction Assessment. In response, the mission set supported by the CA Team has grown to support 24 spacecraft, including the TDRS constellation, as well as GLAST, Jason, OSTM/Jason-2, TOPEX, and TRMM.

To date, supported assets have had to perform eight debris avoidance maneuvers to mitigate the threat of collision. Table 1 lists relevant data for each of the maneuvers. The most notable was the Aura vs. 1399 conjunction in June 2008, which reached a Probability of Collision of 1 in 2 and a miss distance of 11 m.

Table 1: Risk Mitigation Maneuvers Performed by the ESC

Asset	Secondary	Maneuver Date	Minimum Total Miss (m)	P_c
Terra	14222 (SCOUT G-1)	21-Oct, 2005	37	6.82E-2
TDRS	21019	02-Jan, 2006		
PARASOL	81257 (Analyst SAT)	16-Jan, 2007	43	1.51E-3
SAC-C	14345 (SL-8 DEB)	16-Feb, 2007	57	3.40E-6
Terra	31410 (FENGYUN 1C DEB)	22-Jun, 2007	18	1.58E-1
CloudSat	28893 (SINAH 1)	04-Jul, 2007	38	2.24E-2
Aura	1399 (SNAPSHOT Heat Shield)	26-Jun, 2008	11	4.80E-1
CloudSat	8542 (Delta I Debris)	20-Jul, 2008	90	1.77E-3

[Technical contact: Lauri Newman]

2.2.5 TDRS Mission Analysis

NASA's Tracking and Data Relay Satellite System fleet of spacecraft spans a considerable time period from 1983 to the present. All the TDRSs that reached mission orbit are still operational although several have diminished capacity. There is concern about those spacecraft that are perhaps a single failure away from not only losing operational usefulness, but running the risk of dying in place. If that should happen, those massive spacecraft would become a hazard to operational satellites in the geostationary belt. The TDRS Project has commissioned some mission analysis to help determine if there is a method to lessen this risk.

A team of TDRS Project analysts has been working to develop a strategy that would use a form of eccentricity control to maneuver the riskiest TDRSs and eventually the entire fleet into orbits that reduce the risk of a collision in place. The FDAB was tasked to help evaluate a process where regular East-West station keeping maneuvers would be used to adjust the orbital eccentricity and argument of perigee as a means to minimize the time the TDRSs in question spend in the geostationary region. A range of eccentricities and arguments of perigee was determined that could keep a TDRS at least 50 kilometers away from the geostationary ring for a time period that could approach 15 years. The role of spacecraft orbit inclination was also examined and used as an input for selecting a viable eccentricity and argument of perigee pair.

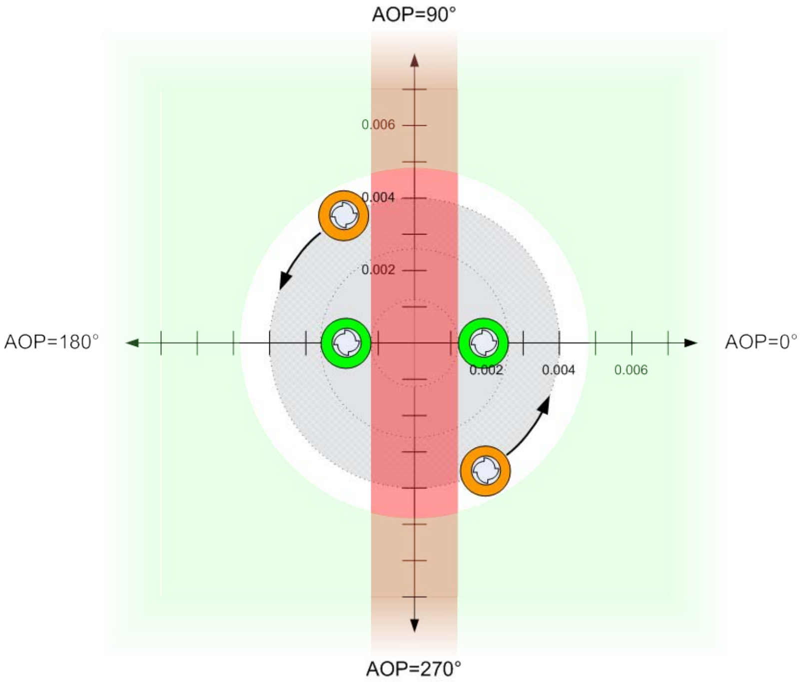

Figure 6. Orbit Placement for TDRS to Reduce Hazard Risk (diagram by Rob Cherney, Orbital)

Figure 6 is a polar plot showing eccentricity in the radial direction, and AOP as an azimuth angle increasing in a counterclockwise sense. The small green and orange circles represent nominal 1-year cycles in eccentricity and AOP for different starting positions. These circles will tend to move counterclockwise along a given eccentricity contour with a period of about 56 years. In the diagram above, the red zone represents the area where closest approach to the geostationary ring will be within 50 km. A TDRS located at the green circles where the eccentricity is ~0.001 with the “best “possible choice of an AOP would enter the red zone rather quickly. However, the orange circles represent TDRSs kept at an eccentricity of ~0.004 with appropriate AOPs and should avoid the red zone for many years, even following a failure. Analysis of this solution to reduce risk from a failed TDRS is near completion and will be the subject of a TDRS Project report.

[Technical contact: Robert DeFazio]

2.2.6 Tracking and Data Relay Satellite System (TDRSS) Navigation Improvements

Error on the ephemeris for the Tracking and Data Relay Satellite (TDRS) is the leading contributor to error in the orbit solution for users of the TDRS System. Both the TDRS and the user orbit solutions are determined from user services radiometric tracking data; therefore, improvements in the overall generation of the tracking data will improve the orbit solutions for both the TDRS and TDRS user. Specific improvements to the generation of radiometric tracking data and the Central Time and Frequency Standard in the ground segment were developed by FDAB and presented to GSFC and HQ Space Network managers whom agreed to the need. Additionally, a broadcast navigation beacon signal is under study to provide GPS differential corrections, TDRS ephemerides, and TDRSS health and status information via Multiple Access Forward services to easily disseminate up-to-date state information to TDRSS and GPS users. Near-real-time estimates of the TDRS orbits would be provided by FDF based on the higher quality radiometrics, thus realizing significant accuracy improvements in the TDRS orbit available to the user. These improvements have been worked through the modernization efforts of the Space Network Ground Segment and the TDRS-K project.

Alternate tracking data types that use the highly accessible Multiple Access Return service to eliminate biases and add relative dynamics are being analyzed through a study under GSFC Code 450 funded by Space Communications and Navigation (SCaN) Office at HQ. A Technical Readiness Level (TRL)-6/7 demonstration is planned for November 2008 to fully examine the impacts of the new radiometric tracking data.

[Technical contact: Cheryl Gramling]

2.3 FLIGHT DYNAMICS FACILITY (FDF)

2.3.1 FDF Overview

http://fdf.gsfc.nasa.gov/

The FDF supported fourteen Expendable Launch Vehicle (ELV) launches, three STS missions, and performed launch and early orbit support for two new missions in FY08. The FDF continued to support approximately 25 spacecraft on a routine basis and provided tracking system engineering support for the LRO and SDO ground stations.

Two members of the FDF contractor support team received Space Flight Awareness (SFA) awards and attended the launch of STS 122 and STS 124. Members of the FDF contractor support team presented a paper at the AIAA conference in August 2008. The paper dealt with orbit determination during emergency support for the THEMIS mission and TDRS. A paper discussing the 'Evolution and Re-engineering of NASA's Flight Dynamics Facility' was presented at the SpaceOps conference in June 2008.

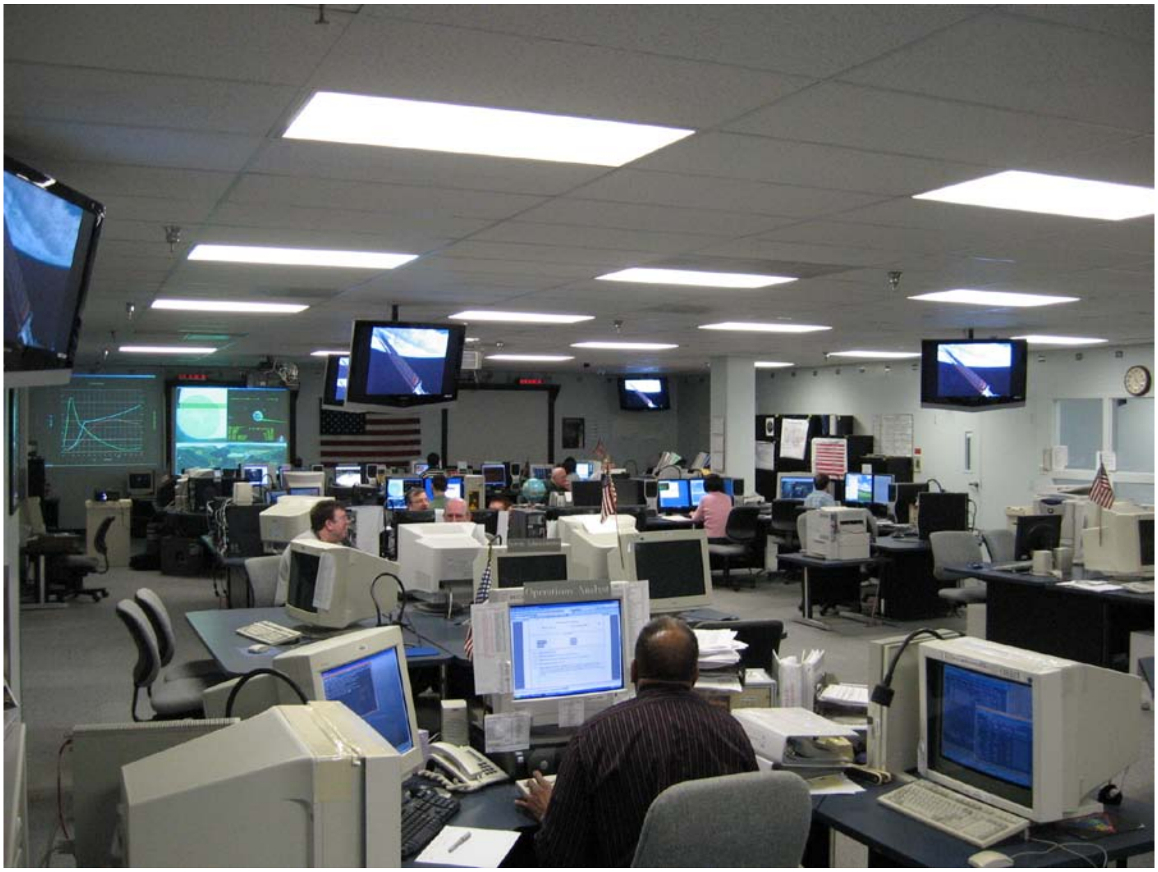

Figure 7. Flight Dynamics Facility Operations During STS 122

The FDF modernization requirements and design effort began in 2008 and Phase 1 development is expected to begin in 2009. This is a five year effort to implement a

Goddard Mission Services Evolution Center (GMSEC) based architecture within the facility.

The FDF opened it's doors during GSFC's Launchfest day on September 13, 2008. Approximately 1200 people from the public came through the FDF and were shown demonstrations of FDF's Space Transportation System support, ELV support, orbit determination support, and LRO trajectory planning.

[Technical contact: Sue Hoge]

2.3.2 FDF Software Maintenance

Work continued on the upgrades to the Acquisition Data Generator (ADG) software. This software is used in the FDF to generate the acquisition data for the spacecraft and ELVs that are supported by the FDF.   These updates include replacement of ORACLE forms with a JAVA-based Graphical User Interface (GUI) that is more user friendly. The new GUI uses GMSEC to communicate with the ADG GMSEC daemons. Operations testing on the new ADG is expected to begin in January of 2009, with installation into operations prior to the end of calendar year 2009.

Software modifications to the Goddard Trajectory Determination System (GTDS) for support of the LRO mission were completed and operations tested. This new version of GTDS is to be moved into operations before the end of calendar year 2008. Additional modifications to GTDS are being made for the processing of the laser data that the FDF is expected to receive as part of the LRO support.

Software modification and testing was completed on the Flight Dynamics Product Center software. This software allows the retirement of the FORMATS software and provides a more robust interface with the FDF Product Center.

[Technical contact: Sue Hoge]

2.3.3 Sustaining Engineering Activities

Facility sustaining activities during 2008 included the installation of Restricted IONet connections. This new operations network connection will allow the FDF to communicate directly with spacecraft Mission Operations Centers (MOC) that are connected to the Restricted IONet.   The FDF now has direct connection into three operations networks – Open IONet, Restricted IONet, and Closed IONet.

Roaming profiles for support personnel were implemented in 2008. It provides greater flexibility when using the operations support areas within the FDF by allowing the analyst to perform work from any desktop located in the operations areas.

The General Operations Room (GOR) within the FDF was reconfigured to provide for better layout of support areas and to accommodate the collision assessment analysts. FDF system security was improved by discontinuing the use of anonymous FTP for the exchange of data with outside entities. Users that previously used anonymous FTP were migrated to their own user accounts.

In preparation for development to be done in Phase 1 of the FDF modernization, a new Itanium server was installed for use by the developers on the Open IONet. This is the first Itanium server available to FDF developers and will enable them to take advantage of Itanium-related features during Phase 1.

[Technical contact: Sue Hoge]

2.3.4 FDF Modernization

The purpose of the FDF Architecture Upgrade is to modernize the FDF in such a way that it is properly positioned to continue to perform support for existing missions and bring new missions into the portfolio more cost effectively. Technology and the nature of mission support have and will continue to advance; the FDF must keep pace continuing its role as the center of expertise and provider of choice for mission support.

The upgraded FDF will consist of at least a new front end communications system, a restructured Oracle data base, and a GMSEC messaging bus. GMSEC adapted modular data processors, enhanced analysis and support applications, and adapted legacy applications will process and store data and provide services and product generation.

The GMSEC publish and subscribe messaging system will be used as a method for standardized communications and data exchange between applications and systems while emphasizing flexibility in support. Current support is very individualized for the analysts and missions. Incorporating GMSEC in the upgrade activities will facilitate making support consistent across the facility, and will help expose the processes to facility level control and monitoring. It will also help enable consistent data flow within and outside the facility. The intent will be for GMSEC to be the medium for data exchange, however, if bandwidth is an issue for large transfers, GMSEC can be used to broker the exchange over other methods.

The FDF Upgrade will be implemented in three phases. A pre-phase activity will focus on the development of an Operations Concept and high-level requirements and architecture / design. Phase-I will comprise the bulk of the implementation – focusing on the new front-end communications processor, data handlers, and re-engineering the database schema. Incorporating FDF legacy applications into the GMSEC architecture will comprise the Phase-II effort. Part of this effort will be carried out under a Space Act Agreement with a.i.-solutions, Inc. as our partner. Phase-III activity will cover the development of data distribution and delivery applications and methodologies.

We are currently well into the pre-phase activity, having completed the Operations Concept document. The high-level requirements definition and analysis activity is nearly complete with a review scheduled in early October 2008. Activities associated with the Space Act Agreement are also underway. The GMSEC test-bed has already been configured and the Concept Design Document will be delivered at the end of September.

[Technical contacts: Sue Hoge, Rodger Abel]

2.3.5 Expendable Launch Vehicle (ELV) Support

The FDAB Flight Dynamics Facility ELV Support Task successfully supported 14 missions in FY08. Mission support includes generation and transmission of pre-mission acquisition data and planning products, and real-time acquisition updates based on processing of inertial guidance data and tracking data during flight. The missions supported are listed below:

ELV LAUNCH LOG (FY08)

2007

- September 14 - H II/Selene
- October 11 - Atlas V AV-011/WGS-F1
- November 11 - Delta IV DSP-23
- December 10 - Atlas V AV-015/ NROL-24

2008

- January 15 - Sea Launch SL-36/Thuraya
- March 13 - Atlas V AV-006/ NROL-28
- March 19 - Sea Launch SL-32/DirecTV 11
- April 14 - Atlas V AV-014/ICO-G1
- May 21 - Sea Launch SL-30/Galaxy-18
- June 20 - Delta II OSTM (JASON II)
- July 16 - Sea Launch SL-34/Echostar XI
- July 18 - MDA MDA/DST (FTX-03)
- August 13 - Textron Minuteman - III
- August 22 - ALV-X1 SOAREX

[Technical contact: Frank Vaughn]

2.3.6 FDF Orbit Maneuver Support

The FDF Operations Orbit Maneuver Task provides support to a complement of three legacy NASA libration point missions: WIND SOHO and ACE. Task personnel, under

Project direction, monitor the orbits of these missions, plan and calibrate station keeping maneuvers and supply any requested products related to these missions. Typically, 3-4 station keeping maneuvers are performed annually for each mission. Task personnel have provided maneuver plans that lead to post-maneuver calibration errors that are usually less than 1 percent. This is achieved by careful monitoring of each orbit and retargeting upcoming maneuvers when necessary. In this reporting period, no significant anomalies during orbit maneuvers were noted.

Requests for orbit products related to maneuver support are provided by the task. Long range orbit ephemerides are generated for future maneuver planning and generation of Spacecraft, Planet, Instruments, C-Matrix and Events (SPICE) files for loading studies at the Deep Space Network. If the science teams associated with these missions require any special products, the task will try to meet these requests within resource limitations. A recent product generated by the task is a monthly ACE orbit ephemeris for delivery to NOAA via the ACE Mission Operations Center (MOC).

Delivery of orbit maneuver products by the task is being modified to use the Flight Dynamics Product Center (FDPC). Projects receiving data products will connect to a secure server and pull in their products using predetermined file names and directory structure. To date, the WIND maneuver command sheets are being tested for delivery through the FDPC.

Finally, the task has been training several new maneuver analysts to provide a broader base of experienced support personnel.

[Technical contact: Bob DeFazio]

2.3.7 Human Space Flight Support

The Flight Dynamics Facility continued its support of human space flight with several missions over the past year. Four space shuttle missions were completed over the past year: STS-120, STS-122, STS-123, and STS-124. These four missions continued the construction and supply of the International Space Station (ISS), including deliveries of the Harmony Module and both European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) laboratories. During shuttle missions, the FDF provides acquisition data and planning product support to the Ground and Space Networks, TDRS vector support to the Johnson Space Center (JSC), and tracking data evaluation services. In addition, the FDF is prepared to resume primary orbit determination responsibilities in case the Emergency Mission Control Center (EMCC) is activated.

In addition, the FDF continued similar support of ISS flight operations, including support of several other visiting vehicles. During this time period, FDF supported two Soyuz missions, including early orbit acquisition data generation, orbit determination, and tracking data evaluation services. The FDF also supported the first Autonomous Transfer Vehicle (ATV), an ESA vehicle designed to supply the ISS. This complex mission successfully completed a thorough test of its capabilities during this first flight.

When Hurricane Ike hit Houston in September, the ISS Backup Control Center (BCC) was activated. During ISS BCC activation, the FDF is responsible for ISS orbit determination and ephemeris updates. The FDF successfully provided this data to the Trajectory Operations Officers (TOPO) in the BCC while JSC was closed.

[Technical contact: Rivers Lamb]

2.3.5 Metric Tracking Data Evaluation

The Metric Tracking Data Evaluation (MTDE) task supports both the NASA space and ground tracking networks and many of the spacecraft missions operated or supported by NASA including the International Space Station. A primary task of the MTDE is to evaluate statistically significant samples of metric tracking data from the networks to ensure that the tracking systems are delivering accurate measurements for the location of the spacecraft. These measurements are used by both FDF and other centers to determine and predict the orbits of operational spacecraft including the Space Shuttle and all the TDRSS spacecraft. Figure 8 is a sample of the products MTDE produces weekly to ensure tracking accuracy. An additional effort for this support is to provide data quality estimation during the launch and early orbit period for many NASA and NASA supported satellite missions.

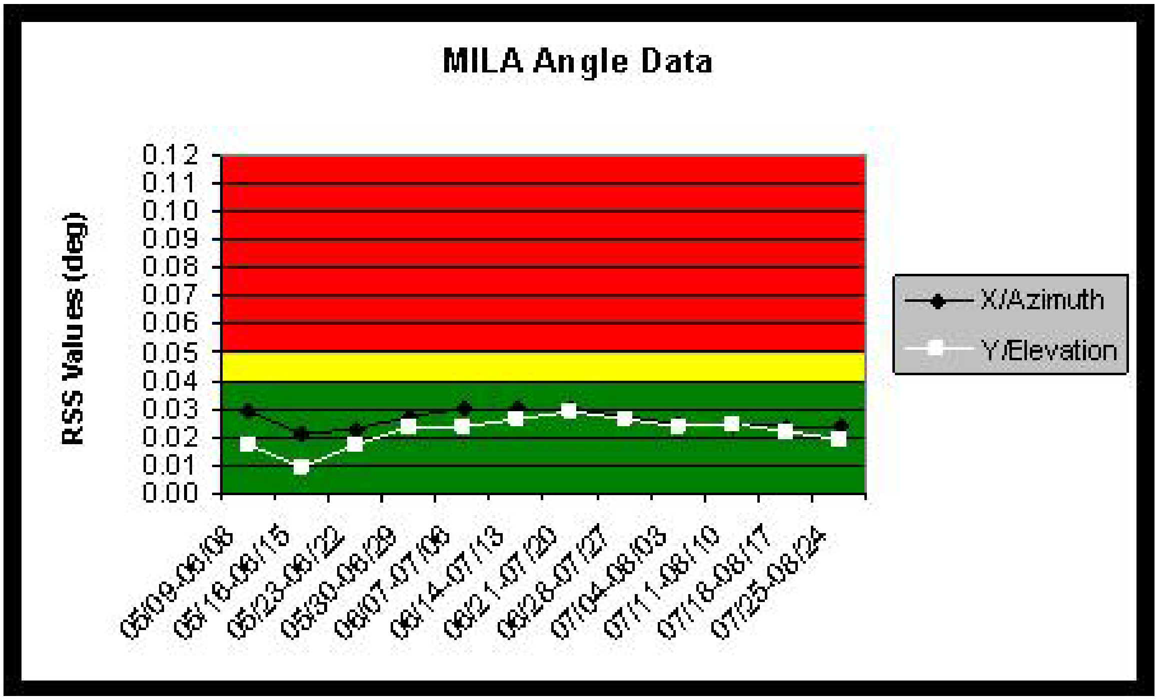

Figure 8. Sample of Metric Tracking Data Evaluation Product Used to Ensure the Accuracy of the Tracking Data Provided by the Network

A second major effort under the MTDE task is to certify that new or reconditioned tracking stations can meet the tracking data accuracies required by space missions. During this reporting period MTDE has certified stations that will be tracking the Lunar Reconnaissance Orbiter (LRO) mission. These tracking stations are located in Australia, Hawaii, and in Europe. The nature of the LRO mission required that the MTDE task certify that these stations could measure the spacecraft velocity as it orbits the moon to within an accuracy of 3 millimeters per second. Also during this reporting period the Bilateration Ranging Transponders (BRTS) that are used to determine the orbit of the TDRS spacecraft were replaced. MTDE certified the accuracy of each new transponder as it was installed and continues to monitor the accuracy each day. In addition to LRO and BRTS, MTDE certified the new ground stations at White Sands New Mexico that will support the Solar Dynamics Observer and the antenna at the University of Alaska. MTDE is currently certifying the newly installed Australian TDRSS Facility antenna.

In support of individual spacecraft missions, the MTDE task routinely measures the slow but inevitable drift of the spacecraft radio frequency while they orbit the earth by evaluating the tracking data provided by the tracking stations. These measurements are made and provided each month for use by satellite mission control centers. With this information the satellite control centers can instruct the tracking stations to use the correct frequency needed to communicate with the spacecraft.

[Technical contact: Kevin Berry]

2.3.6 Orbit Operations

In the past year, the FDF Orbit Operations Team supported over 60 missions, of which 2 were decommissioned during the year, 9 are receiving pre-launch support, and 12 were only supported for a short time during the year. These missions included low Earth orbit (LEO), High Earth orbit (HEO), libration point missions, geosynchronous Earth orbit (GEO) missions, and two spacecraft in heliocentric orbit. For some spacecraft, the support was to provide acquisition data only, but others included orbit determination, tracking data evaluation, and responding to requests for special products. Several hundred separate products are provided by FDF Orbit Operations each month.

For manned spaceflight operations, the Orbit Operations Team supported Space Transportation System (STS) missions 120, 122, 123, 124, and will support 125, the Hubble Space Telescope (HST) Servicing Mission 4. This support includes tracking data evaluation and providing acquisition data. The Autonomous Transfer Vehicle (ATV) launch on March 8, 2008 and subsequent activities were also supported. That mission had to be replanned immediately following its launch due to a partial thruster failure. Following the replan, it was successfully controlled to the high degree required for an International Space Station (ISS) attached payload. Orbit Operations will assist in its planned reentry later this year.

For unmanned spaceflight operations, Orbit Operations successfully supported Gamma-ray Large Area Space Telescope (GLAST) from its launch on June 11, 2008, providing orbit determination and station acquisition data support until the GLAST onboard orbit determination system was performing satisfactorily. Orbit Operations provided backup orbit determination support for the Ocean Surface Topography Mission (OSTM) / Jason-2 spacecraft, launched on June 30, 2008. The group also supported the Advanced Land Observing Satellite (ALOS) / Tracking Data Relay Satellite – 10 (TDRS-10) Ka-band on-orbit data exchange tests on May 28-29 and June 4-5 of 2008. Support was also provided to the POLAR end of mission activities prior to its decommissioning on April 28, 2008. The Bilateration Ranging Transponder System (BRTS) replacement was supported, monitoring the data received and the solutions using those data to assure the new BRTS are functioning properly.

The Orbit Operations support also included preparing the paper “Orbit Determination During Spacecraft Emergencies with Sparse Tracking Data THEMIS and TDRS-3 Lessons Learned” for the AIAA/AAS Astrodynamics Specialist Conference of August 2008.

[Technical contacts: Chad Mendelsohn, Dennis Woodfork, Sue Hoge]

3.0 STUDY MISSION SUPPORT

3.1 ARTEMIS

ARTEMIS is the follow-on to the highly successful THEMIS mission using the same spacecraft to explore Earth-moon and lunar regions. THEMIS is comprised of 5 spacecraft each in an increasing elliptical Earth orbit. The outer two spacecraft, called P1 and P2, will enter the Earth's shadow in the next year which would result in the battery completely discharging, thus disabling the mission. In order to extend the mission and to continue the successful investigation of the magnetosphere, The THEMIS P1 and P2 spacecraft will be moved into new orbits both near the moon at locations called the LaGrange points (also called libration points). From this vantage location, they will perform science observations before they are both transferred into lunar elliptical orbits. Once they depart the Earth orbit, they will be renamed ARTEMIS.

The Flight Dynamics Analysis Branch at GSFC will play an important role in the transfer of these spacecraft into their new locations. The FDAB will provide all the navigation and maneuver design including both pre-departure analysis, maneuver modeling, error analysis, attitude support, and operational support from FDAB's Flight Dynamics Facility. The depart date begins in late summer of 2009 and the transfer takes approximately a year to complete. This transfer involves the use of weak stability boundaries to minimize the amount of fuel required to insert into the final lunar orbit. To overcome the fuel required for a direct transfer, lunar gravity assists are incorporated into a weak stability transfer design. Once in the libration orbit (P1 at the farther Earth-Moon L2 locations and P2 at the closer Earth-Moon L2 location) they will be transfered into an elliptical lunar orbit to extend the science investigation of the Earth and moon environment.

[Technical contact: David Folta]

3.2 Comet Nucleus Sample Return (CNSR) Concept Study

The objective of the Comet Nucleus Sample Return (CNSR) concept study is to produce a documented plan for a mission to return a sub-surface sample from an inactive comet. The spacecraft concept is a carrier/lander combination with automated rendezvous and landing capabilities and a robotic arm for docking and sample transfer, based on the Orbital Express architecture. The role of the Flight Dynamics Analysis Branch (FDAB) in this study includes evaluation of potential targets with respect to launch vehicle and spacecraft propulsion requirements, mission duration, length of the return leg, and Earth re-entry conditions.

In this second year of the study, the FDAB provided the project team with a trajectory analysis report, detailing the results of trajectory analysis and design performed during FY07, including the selection of comet Wilson-Harrington from a list of 97 potential targets as the primary science target, development of an end-to-end, chemically-fueled, multiple gravity-assist trajectory, and a preliminary launch window analysis. Results of a rudimentary low-thrust analysis were also presented, but detailed low-thrust analysis was performed by Glenn Research Center (GRC) using the Mission Analysis for Low-Thrust Optimization (MALTO) trajectory analysis software developed by the Jet Propulsion Laboratory. The GRC-developed trajectory was selected as the baseline since it delivered better performance in terms of shorter mission duration and higher returned payload. The FDAB work turned to refining the chemical trajectory and evaluating the possibility of sending the carrier spacecraft to rendezvous with another target after releasing the sample return vehicle at Earth. The FDAB also supported three CNSR-related studies in the Integrated Design Center (IDC). The first study was conducted in mid-April 2008 in the Instrument Design Laboratory (IDL) to develop the harpoon sampling system conceptual design. The second study was conducted in late-April 2008 to develop the CNSR lander conceptual design. The third study was conducted in mid-May 2008 to develop the CNSR carrier spacecraft conceptual design.

Evolving science goals are refocusing this effort on the concept of a multiple asteroid rendezvous/sample return mission. The FDAB began developing preliminary trajectories for this concept in May 2008 and the work is ongoing.

[Technical contact: Frank Vaughn]

3.3 DESTINY – Dark Energy Space Telescope

http://beyondeinstein.nasa.gov/
http://nasascience.nasa.gov/missions/jdem/

The Dark Energy Space Telescope (DESTINY) is one of several mission concepts vying to be selected as the Joint Dark Energy Mission (JDEM), part of NASA's Beyond Einstein program. JDEM, a collaborative effort between NASA and the Department of Energy, will study "dark energy" - a mysterious substance that physicists theorize comprises over 70% of Universe.

DESTINY will study dark energy by examining Type 1a supernovae from an orbit around the Sun-Earth L2 libration point. During FY08, Flight Dynamics Engineers supported the DESTINY proposal effort by providing analysis of the ΔV budget required to fulfill mission requirements. In doing this, an automated script using Matlab and Satellite Tool Kit™ was developed to examine the solution space of libration point orbits for a given launch day. This automated script will be extremely useful for future libration point mission studies. In addition to the ΔV budget, a full lifecycle (Phase A through End-of-Life) cost estimate was prepared.

Future efforts will be to continue providing Flight Dynamics engineering expertise as the DESTINY team prepares its proposal to respond to a JDEM announcement of opportunity that is expected to be released some time in early FY09.

[Technical contact: Michael Mesarch]

3.4 Enceladus

The FDAB provided mission design support for an Internal Research and Development (IRAD) study led by NASA GSFC. The objective was to make frequent flybys of Saturn's moon, Enceladus. A number of mission design options were considered and analyzed. The mission design option with two Venus and two Earth flybys and no deterministic maneuvers was baselined to maximize the payload mass delivered to Enceladus. The post-Saturn orbit insertion orbit required deterministic maneuvers and a series of Titan flybys to achieve the mission orbit which allowed for frequent Enceladus flybys.

[Technical contact: Greg Marr]

3.5 EAGLE

This was a very challenging IRAD study requiring many mission design reformulations as the science objectives evolved. When the study began last year, the goal was to visit the asteroid Apophis which astronomers had found to be on course for a close encounter with Earth in 2029, and possible impact in 2036. As the study moved forward, it became clear that a flight to Apophis was not feasible under the $450M cost cap of a Discovery mission. Since a secondary objective would use analysis of the spacecraft orbit to estimate the value of the Solar J2 gravitational term (which in turn would allow deeper understanding about the internal structure of the Sun) it was decided to make this a primary objective and look at sending spacecraft elsewhere to accomplish it. We began by looking at the asteroid Phaethon (as well as many others) which, like Apophis proved too expensive to get to. We then looked at sending a pair of spacecraft to Venus, one of which would go into orbit about Venus, the other would use a gravity assist at Venus and Earth to go on to Mars, where it would enter orbit. With two such spacecraft, triangulated tracking could reveal the Solar J2 and allow the science objective to be met. Finally, the project was renamed EAGLE as the objectives were shifted again to a high latitude laser altimetry experiment about Europa, the second inner most Galilean moon of Jupiter. In this formulation, several approaches were considered including everything from a direct entry into Europa orbit to orbiting and departing both Ganymede and Callisto (Jupiter’s outer most Galilean moons) before finally arriving at Europa. At this time, the study remains on hold pending a decision from NASA HQ as to how to proceed.

[Technical contact: Dave Quinn]

3.6 Integrated Design Center (IDC)

http://imdc.gsfc.nasa.gov/

The Integrated Design Center (IDC) (formerly the Integrated Mission Design Center) is a human and technology resource dedicated to innovation in the development of advanced space mission design concepts to increase scientific value for NASA and its customers.

The IDC provides specific engineering analysis and services for mission design in the Mission Design Laboratory (MDL), and for instrument design in the Instrument Design Laboratory (IDL), and provides end-to-end spacecraft, instrument, and mission design products.

The Flight Dynamics Analysis Branch (FDAB) provides engineering expertise in the areas of trajectory design, navigation, and control. The trajectory and navigation engineers from the FDAB incorporate a wide range of experience in trajectory regimes from low-Earth orbit to interplanetary, and utilize that experience in the mission design process to develop end-to-end mission design concepts, usually in less than a week.

A total of 20 mission studies covering a wide range of mission types were supported by FDAB engineers. Most missions utilized proven concepts, but a few required new technology concepts to achieve the science goals. The mission concepts utilized low and high Earth orbits (including Sun-synchronous and geosynchronous), Sun-Earth L2 orbits, Heliocentric drift-away orbits, Lunar orbits, orbits of Saturn's moon, Enceladus, and rendezvous orbits with cometary bodies. Spacecraft concepts included single spacecraft, formation flying/constellation, and orbiter/lander designs.

[Technical contacts: Frank Vaughin and Michael Mesarch]

3.7 International X-Ray Observatory (IXO)

http://ixo.gsfc.nasa.gov/
https://conxproj.gsfc.nasa.gov/

The International X-Ray Observatory (IXO) is a joint mission including participation from NASA, the European Space Agency (ESA), & the Japanese Aerospace Exploration Agency (JAXA). The IXO mission will incorporate the joint experience gained from NASA's Constellation-X (Con-X) and the ESA/JAXA X-ray Evolving Universe Spectroscopy (XEUS) mission concept into a single mission. IXO will perform high resolution X-ray spectroscopy with 100 times the throughput of previous X-ray observatory missions.

After launch, IXO will operate from an orbit around the Sun-Earth L2 libration point. Flight Dynamics support during FY08 was focused on the Con-X (prior to the collaborative agreement) visit to the Mission Design Laboratory (MDL) during July of 2008. During the MDL study, Flight Dynamics engineers re-evaluated the ΔV budget and again discussed the ΔV implications related to maneuvering Con-X into an L2 orbit that stays within the Earth's magnetosheath to shield the observatory from high energy cosmic particles. Additional work included providing a qualitative evaluation of the navigation concept given Con-X's momentum unloading strategy. The decision was made to proceed with a sequential orbit determination architecture given the expectation that Con-X expects to unload momentum roughly every 3 days. Further analysis of the orbit determination architecture will leverage the experience gained through similar work done for the James Webb Space Telescope (JWST) mission which employs a similar architecture due to frequent momentum unloads in its L2 libration point orbit. Finally, a full lifecycle cost estimate was prepared during the MDL study for Con-X.

Future efforts will include working with GSFC IXO team to understand the new roles and responsibilities in this new international collaborative effort.

[Technical contact: Michael Mesarch]

3.8 MAVEN: The next MARS Mission

The Mars Scout 2013 program is the second in a series of Mars Scout missions. This GSFC managed mission named the Mars Atmosphere and Volatile Evolution (MAVEN) is supported by the Flight Dynamics Analysis Branch, who is designated as the lead for Navigation and Mission Design. Over the past year, the FDAB has provided analysis and guidance on the launch period, heliocentric transfer orbit, Mars insertion, navigation, relay analysis, and mission orbit maintenance. We also worked with the spacecraft contractor (Lockheed Martin) on spacecraft and ground support design. MAVEN is a direct type-II transfer trajectory using a Bi-propulsion system to insert into a 35 hour capture orbit from which the 4.5 hour mission orbit is met. MAVEN will depart Earth on an EELV between November 18 and December 7, 2013 and achieve Mars Orbit Insertion (MOI) on September 16, 2014 (for 11/18 launch). The primary mission science orbit is a 75° inclination, 4.5 hour period, 150 km periapsis altitude. Over a 1-year period, it will obtain detailed measurements of the upper atmosphere, ionosphere, planetary corona, solar wind, solar EUV and SEPs, thus defining the interactions between the Sun and Mars. MAVEN performs five “Deep Dip Campaigns” to altitudes near 125 km during the 1-year mission. Each campaign is 5 days in duration and captures previously unobtainable science measurements. The year-long support culminated in a concept proposal and a site visit at Lockheed-Martin’s Denver facility. In September 2008 MAVEN was selected as the next Mars Scout mission.

[Technical contact: David Folta]

3.9 New Worlds Observer (NWO)

http://newworlds.colorado.edu/

The Flight Dynamics Branch provided mission design and operations planning support to the proposal mission New Worlds Observer (NWO), an exo-planet and general astrophysics mission flying in the vicinity of the Sun-Earth L2 libration point. The two-spacecraft mission consists of a 4-m telescope in a traditional L2 libration point orbit, and a 50-m diameter Starshade spacecraft which flies in formation with the Telescope, at ~80,000 km distance. The Starshade spacecraft will fly between the NWO telescope and the target star when exo-planet observations are being made; it blocks the light from the star in such a way that the telescope can search for planets orbiting the star. The Starshade is the workhorse of the two, changing its orbit approximately every two weeks to get into position for the next exo-planet star target; this is accomplished using a low thrust solar electric propulsion system with approximately 10 km/sec of delta-v capability. The NWO telescope will be performing other astrophysics observations, during this period, only pointing towards the target star when the Starshade is in position. At this time, the Starshade uses a bipropellant propulsion system to maintain its position along this line of sight between the star and telescope to within +/-1 m, maneuvering every 20 minutes during the entire exo-planet observation period.

The NWO mission presents many interesting challenges in the flight dynamics area. During the past year, FDAB has supported two GSFC Integrated Design Center studies, one for the instrument and one for the mission itself. Some of the issues supported for NWO include the redesign of the reference Telescope L2 trajectory, which was nearly coplanar with the ecliptic plane and thus experienced many shadow periods; determining the feasibility of the Starshade Spacecraft trajectory with respect to the two propulsion systems; orbit determination and navigation feasibility, in particular for the constantly maneuvering Starshade; momentum unloading frequency and magnitude for both spacecraft due to non-trivial solar radiation pressure perturbations on these two large-area spacecraft; and mission operations concepts for launch through the 5-year lifetime for the Starshade and the 10-year goal for the Telescope.

Branch members Dave Folta and Karen Richon provided NWO with trajectory analysis, with an initial feasibility analysis of the formation flying concept, which included a high-fidelity example of the Starshade trajectory demonstrating a targeting method for the low thrust retargeting maneuvers. Analysis is being performed by the FDAB to redesign the reference orbit and to refine the Starshade trajectory to demonstrate the feasibility of meeting the science requirements with the current concept in preparation for the Non-Advocacy Review in November 2008 and the submission to the National Science Foundation Decadal review next year.

[Technical contact: Karen Richon]

3.10 OSIRIS

GSFC, working with our University of Arizona, Lockheed Martin, and other industry partners, developed the flight dynamics concept for the proposed Origins Spectral Interpretation, Resource Identification and Security (OSIRIS) mission. OSIRIS was one of three missions selected for additional Phase A study as part of NASA's 2006 Discovery Program announcement of opportunity. The primary objective of the mission was to rendezvous with near-Earth asteroid, RQ36, and return a sample of the asteroid surface to Earth for in-depth study.

Figure 9. OSIRIS Sample Return Mission

Another objective of the mission was to improve our understanding of the non-Keplerian orbital evolution of potentially hazardous near-Earth objects. This enhanced understanding of asteroid orbit dynamics would be needed for any future effort to deflect dangerous asteroids away from the Earth.

The Phase A study activities culminated in a site visit and formal presentation to the NASA Headquarters review committee on August 20, 2007.

[Technical contacts: Steven Cooley, Russell Carpenter]

3.11 UnPressurized Cargo (UPC) Exploration Carriers

The UnPressurized Cargo (UPC) is the use of available area in the Orion Service Module (SM) by the Explorations Systems Project at NASA's Goddard Space Flight Center. The overall objective of the study was to determine the feasibility of utilizing Orion's SM-UPC capability for the ISS Design Reference Mission for scientific and technology type payloads, and the required interface accommodations to the SM. This capability, collectively referred to as UPC Exploration Carriers, accommodates two modes of UPC payload operations, Free-Flyer and Attached Payloads.

Supporting the Free-Flyer study, the FDAB provided analysis for both chemical and low-thrust propulsion systems that allowed mission design to LEO, GEO, Elliptical orbits, and also lunar and libration orbits. Trajectory design analysis was performed to provide data for both the feasibility of such missions as well as for the system engineering design parameters (fuel, mass, communication and tracking, power, etc). Several mission types were investigated and by using a low-thrust system similar to the ESA Smart-1 program, a lunar mission was found to be achievable. Trades were

performed and a Mission design Lab (MDL) study was supported to find a preliminary design. Analysis covered the LEO considerations of orbit maintenance and orbits achievable based on Delta-V (DV) and fuel volume requirements. The lunar mission (and libration orbit mission) used advanced approaches of gravity assist to a near Earth weak stability boundary transfer to minimize the required DV for lunar orbit insertion.
The Free-Flyer consists of a small sub-satellite that is deployed (ejected) from the SM into ISS LEO orbit (~400km at 51.6°) and is completely independent of Orion. The GSFC mission design team conducted a point design for a Lunar Orbiter as a bounding case, capable of carrying a 50 kg payload injected into a stable lunar orbit with a mission life of 2-3 yrs on station. A Solar Electric Propulsion system was selected over a chemical system in order to maximize payload mass. However, chemical propulsion is a better option for LEO type orbits and offers a payload mass of approximately 100 kg in ISS inclination and altitude with an estimated mission life of 5 years.

[Technical contact: David Folta]

3.12 Planetary Probe IRAD

The FDAB provided mission design support for an IRAD led by NASA GSFC. The objective was to deliver an interplanetary probe and orbiter using the same launch vehicle. A number of mission design options were considered and analyzed. The FDAB determined the nominal trajectories required to meet a series of changing mission requirements. The FDAB was instrumental in organizing an experienced team of personnel necessary for the support of this effort.

[Technical contact: Greg Marr]

4.0 TECHNOLOGY DEVELOPMENT

4.1 Advanced Navigation Technologies

(http://techtransfer.gsfc.nasa.gov/ft-tech-GEONS.html)

The advanced navigation team (Code 595 personnel supported by a.i.-solutions, Inc) completed two new releases of the Goddard Enhanced Onboard Navigation System (GEONS) software[1]. GEONS provides autonomous navigation capabilities using a variety of measurement types for spacecraft in any region of space, and is publicly available from the GSFC Innovative Partnerships Program Office. Release 2.10 contains a variety of enhancements, including a coupled first- and second-order Gauss-Markov clock model (see below), and implementation of TDRSS Augmentation Service for Satellites (TASS) differential corrections of the GPS ephemeredes. Release 2.11 adds major new enhancements supporting the MMS mission, as well as the capability to process the Improved Clock and Ephemeris information now broadcast by the GPS system.

Russell Carpenter presented work by himself and T. Lee (a.i.-solutions), “A Stable Clock Error Model Using Coupled First and Second-Order Gauss-Markov Processes,” as Paper AAS08-109 at the AAS Space Flight Mechanics meeting in Galveston, Texas. This paper addresses long data outages that may occur in applications of global navigation satellite system technology to orbit determination for missions that spend significant fractions of their orbits above the navigation satellite constellation(s). Current clock error models based on the random walk idealization may not be suitable in these circumstances, since the covariance of the clock errors may become large enough to overflow flight computer arithmetic. This paper describes a model (now available in GEONS) that is stable, but which approximates the existing models over short time horizons is desirable.

The team also performed numerous advanced onboard and ground navigation studies for Project Constellation. These studies examined the sensitivities to DSN and GPS tracking for both low lunar orbit and cislunar transfer scenarios. The team studied options including two- and three-way Doppler from 6- and 8-station enhancements to the current DSN, as well as data from standard and weak-signal-tracking GPS receivers. This work showed that weak-signal GPS tracking significantly reduces requirements for ground-station coverage, contingent upon the accuracy to which unmodeled accelerations on the spacecraft are present.

[Technical contact: Russell Carpenter]

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[1] GEONS was formerly an acronym for “GPS Enhanced Onboard Navigation System,” but since its capabilities have grown to such numerous non-GPS data types, the team felt that a more generally descriptive name was more appropriate.

4.2 Relative Navigation Sensors (RNS)

http://www.nasa.gov/mission_pages/hubble/servicing/SM4/main/SCRS_FS_HTML.html

The upcoming Hubble Space Telescope (HST) Servicing Mission 4 (SM4) includes a Relative Navigation Sensor (RNS) payload which uses three cameras and an avionics package to record images, and estimate in real-time the relative position and attitude (aka "pose") during the Shuttle capture and deployment of the telescope. Code 595 staff act as Principal Investigator, and pose application development lead for this payload.

In the course of developing the preliminary mission concept and spacecraft design for the Hubble Robotic Servicing and De-orbit Mission (HRSDM), it became evident that in order to successfully rendezvous and dock with an uncontrolled HST the design must incorporate an autonomous means for real-time estimation of the position and attitude of HST relative to the servicing vehicle. Several challenges associated with executing autonomous rendezvous and docking (AR&D) with an uncontrolled spacecraft were identified during HRSDM including execution of pose estimation processes on available space flight processing hardware and assessing the level of pose accuracy that was attainable. Pose estimation commonly maps two (e.g., optical/IR cameras) or three (e.g., lidar) sources of dimensional image information into relative position and orientation (or attitude). This mapping shares many characteristics with the field of image processing including a characteristic need for computing power to process the sensor images at the pixel level in a real time fashion. As such, RNS seeks to demonstrate that pose estimation can be accomplished on space qualified processing hardware at rates similar to those required for AR&D.

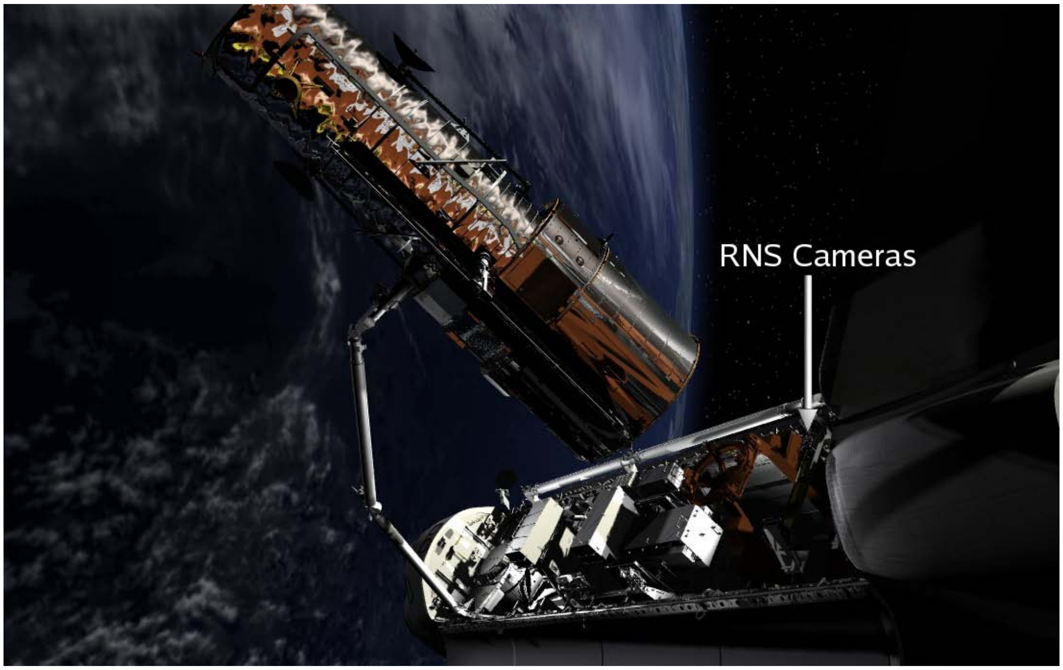


Figure 10. RNS Flight Experiment

After cancellation of HRSDM, hardware and software developed under HRSDM has been utilized and enhanced to assemble a payload called RNS, hosted in the Shuttle cargo bay, which will make real-time pose estimates on approach to and departure from HST during SM4. The objectives of RNS are: 1) to image the new Soft Capture Mechanism after its installation on HST; 2) to demonstrate the feasibility of generating real-time, on-board pose estimates under orbital lighting conditions; and 3) to evaluate the performance of a comprehensive pose estimation system on orbit for the purpose of assessing its adequacy for providing inputs to a relative state estimation process during AR&D operations with an uncontrolled HST. Of course, these objectives are subject to limitations including the facts that HST will remain controlled during the entire SM4, and RNS will neither specify nor control the Shuttle trajectory or attitude relative to HST.

The RNS payload consists of short, medium, and long range cameras, the Integrated Control Electronics (ICE), which includes two Mass Storage Modules which use commercial hard drives to store on-orbit imagery, and an innovative new reconfigurable flight computer called the SpaceCube, which hosts Command and Data Handling, Camera Automatic Gain Control, and Pose Applications.

[Technical contact: Bo Naasz]

4.3 The CAVE: Goddard Space Flight Center's Flight Dynamics 3-D Immersive Visualization Environment

The Goddard Flight Dynamics CAVE is an immersive stereographic (3-D) visualization environment, which permits analysts to interact with and visualize complex shapes. The name, CAVE, is a recursive acronym for "CAVE Automatic Visualization Environment". While the Goddard CAVE was originally intended for mission design and engineering (astrodynamics research, launch and critical operational support, and spacecraft design and anomaly investigation), there is the potential to extend this resource to other areas of Goddard research and operations, including space and Earth science. The CAVE is located in Building 28, room N210 next to the Flight Dynamics Analysis Branch's Flight Dynamics Facility (FDF). Figure 11 shows an analyst viewing the MMS spacecraft in the CAVE.

Figure 11. MMS Model in the CAVE

Code 590 constructed, manages, and operates the CAVE. Designed by Christie Digital Systems and SGI, the CAVE is a four-channel design (3 walls and a floor) with a tracking and control system used for simulations. The custom designed structure incorporates mirrors and projector mounts, Mirage S+4K projectors (38-DSP104-x6), four 96” by 128” soft display screens and a rigid 128” by 96” floor screen. The approximate viewing footprint is 12’x12’x12’. It uses four graphics pipes in a Linux based visualization system with a resolution of 1440 x 1050. A tracking headset, command wand, and wireless eyewear allow the user to command and control the visualizations. It is multiplexed for active stereo using hardware compositors to combine the pipes. The skeletal structure shown in figure 12 is approximately 30’ wide, 25’ deep, and 15’ high.

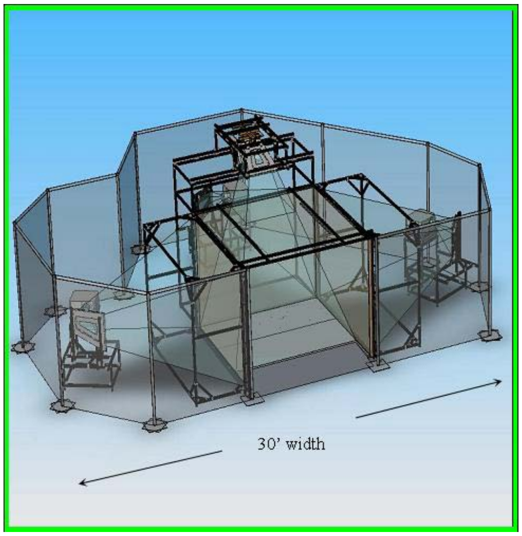


Figure 12. CAVE Structure

With advanced capabilities in computer systems and graphics, the CAVE enhances present research and technology development at GSFC and creates a multiple use visual computing environment. For example one can investigate mechanical and propulsion designs before spacecraft are built and design trajectories using advanced methods such as invariant manifolds. Eventually, Code 590 engineers hope to establish interfaces between the CAVE and the FDF as well as other operations facilities in order to view near real-time events, such as lunar orbit insertion maneuvers and lunar landing. Another benefit is to create a Community Visualization Environment by linking the GSFC CAVE with other computing systems at other NASA centers and universities.

[Technical contact: David Folta]

5.0 BRANCH INFRASTRUCTURE

5.1 Creation of First-Guess Utilities to Support Development of Lunar Architectures

The FDAB, in conjunction with Professor emeritus David Richardson of the University of Cincinnati, continued the development effort to create first-guess utilities for cislunar, libration point, and other multi-body orbits in order to increase both the efficiency and capability of the mission design process. The utilities will be used to help develop possible lunar architecture concepts.

The knowledge of the properties of multi-body orbits such as those within cislunar space is necessary for the development of an exploration infrastructure. For example, the use of Halo orbits, which are periodic solutions of the circular restricted three body problem (CRTBP), can be used to obtain communication and navigation capabilities for satellites and/or lunar structures on the far side of the moon. The ability to thoroughly characterize the entire family of these Halo orbits, as well as numerous other types of orbits, will result in a much more capable and efficient mission design process.

[Technical contact: Steven Cooley]

5.2 Flight Dynamics Support Services (FDSS) Contract

A Request for Information (RFI) and Sources Sought Synopsis was released on March 24, 2008. The synopsis detailed the intent to consolidate all Goddard flight dynamics work under a single Code 595 managed contract. Current flight dynamics work being performed under the Mission Operations Mission Services (MOMS) and Multi-Disciplinary Engineering and Technology Services (METS) contracts would be transitioned to this new contract. The Procurement Strategy Meeting (PSM) was held for FDSS on August 11, 2008.

The FDSS will be a $95M (contract cap) 5-year Indefinite Delivery/Indefinite Quantity (IDIQ) Award Fee contract. The goal for a release of the draft Request for Proposal (RFP) is late October 2008. The most optimistic date for selection and award of the new contract are mid-March and mid-May 2009 respectively.

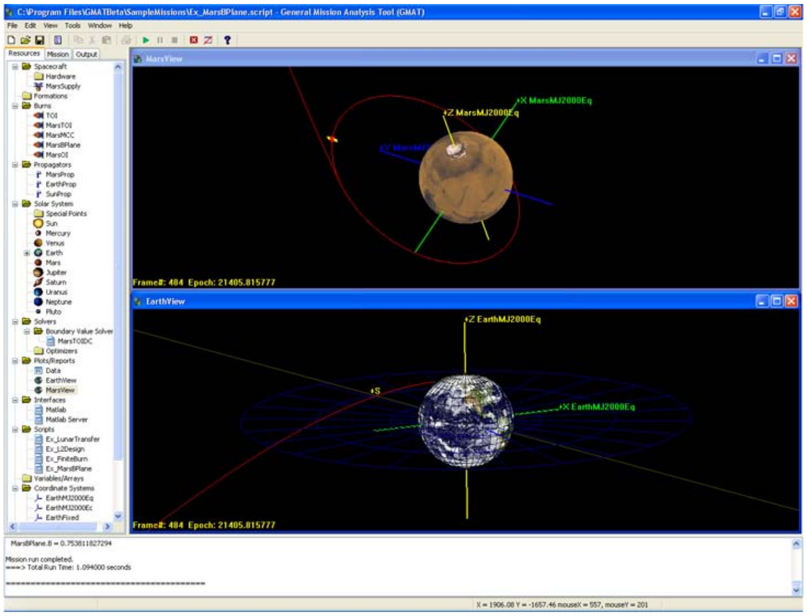
[Technical contact: Mark Beckman]

5.3 General Mission Analysis Tool (GMAT)

http://gmat.gsfc.nasa.gov/

The General Mission Analysis Tool (GMAT) is an open-source, multi-platform mission analysis and trajectory optimization system. Analysts currently use GMAT to design spacecraft trajectories, optimize maneuvers, visualize and communicate mission parameters, and understand a mission's trade space. For more information or to obtain GMAT, go to http://gmat.gsfc.nasa.gov/.

The GMAT project has had an exciting year. We’ve begun a new partnership with the Air Force Research Lab (AFRL), implemented many new features, and begun design and prototyping for major new orbit determination functionality.



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MarsBPlane.B = 0.753811827294

Mission run completed.
===> Total Run Time: 1.094000 seconds

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Figure 13. GMAT User Interface

The GMAT development team has worked hard this year to implement perhaps the most complex and useful new feature which we call GMAT functions. GMAT functions are like subroutines in FORTRAN, except in GMAT the user writes them in GMAT’s MATLAB-like script language. GMAT functions allow users to isolate complex or repeated calculations in text files and share them with other users. For example, a user can write a function that optimizes a maneuver sequence, and other users can call the function from their mission sequence.

Our team has continued to try new business models and this year we began a partnership with AFRL to share the cost of implementing orbit determination features in GMAT. The collaborative effort involves both organizations in all aspects of the software engineering life-cycle and identifies a lead for each area. AFRL is the lead for algorithm design and testing while GSFC is the lead for software design and implementation. We expect a prototype with basic orbit determination functionality early in FY09 and look forward to a long partnership developing a world-class orbit determination system

[Technical contact: Steve Hughes]

5.4 GPS Enhanced Onboard Navigation System (GEONS) Ground Support System (GGSS)

The GEONS Ground Support System (GGSS) is an important component in the Flight Dynamics Support System of any future mission that uses an onboard navigation system such as the Goddard Enhanced Onboard Navigation System (GEONS). Providing an automated system on the ground to support the onboard navigation maintains the mission's level of autonomy while reducing the risk to the mission, especially for multi-spacecraft missions. An automated GGSS that incorporates the GEONS software for ground processing will ensure smooth transitions between orbital phases, a consistent and more rapid assessment of post-maneuver navigation and propulsion system calibration, and timely access to navigation solutions and products from these solutions. After quality assurance, the navigation telemetry from the mission, as well as by-products needed for planning and mission design, can be distributed to the mission's community of subscribers via publication to the Goddard Mission Services Evolution Center (GMSEC) Bus within the Mission Operations Center (MOC).

Improvements made in FY2008 include global verification logic for command uplink file generation, critical usability improvements to the master options and command uplink file generation capabilities, and expanded Monte Carlo, post processing, and plotting capabilities. Also, GGSS was integrated with GMAT for improved Monte-Carlo analysis.

Previously, when truth data was generated for use in GGSS, the user ran whatever high precision orbit propagation software was readily available. If the user was new to orbital mechanics software (i.e. interns and new hires), or if the user needed multiple truth trajectories (i.e. for Monte Carlo analysis), then it was very advantageous to have GGSS create that data automatically. To implement this highly desired capability, we used the General Mission Analysis Tool (GMAT), which is a space trajectory optimization and mission analysis system developed by NASA under GMSEC funding. Because of GMAT's open source structure, it is by far the best software package for our needs. The new integration allows the user to control GMAT from the GGSS user interface in order to automatically create any truth data that is needed.

[Technical contact: Kevin Berry,]

5.5 Orbit Determination Toolbox (ODTBX)

The Orbit Determination (OD) Toolbox is a new OD analysis toolset based on Matlab and Java, the objective of which is to provide a much more flexible way to perform early mission analysis than is currently possible with existing tools. Matlab is the primary user interface, and is used for implementing new measurement and dynamic models from a library of base classes, rather than having to make a major software change every time a new mission proposal comes up, particularly one that implements new flight dynamics technologies. The OD Toolbox uses extensions of the Java Astrodynamics Toolbox (JAT) as an engine for routines that might be slow or inefficient in Matlab, like high-fidelity trajectory propagation, lunar and planetary ephemeris lookups, precession, nutation, and polar motion calculations, ephemeris file parsing, etc. The tool is primarily intended for future mission concept studies, but has been used in support of Phase A work for MMS, ST9, OSIRIS, and the Exploration Program. In particular, the OD Toolbox provides Goddard a strategic advantage in winning proposals and will also be invaluable in the Mission Design Laboratory (MDL). It will be of particular utility to formation flying and exploration missions that make extensive use of novel combinations of onboard sensors. The OD Toolbox is designed to “publish and subscribe” to a GMSEC-compliant “software bus,” to enable the exchange of data with our flight dynamics tools, such as the General Mission Analysis Tool (GMAT).

Our primary goal for FY08 was to implement a consider parameter analysis capability, which allows for determining sensitivity to unsolved-for error sources. This was a key need since existing capability existed only in ODEAS which is not being updated to meet new mission needs. We also added measurement models to the OD Toolbox to provide the capabilities of the DSN and TDRSS. Other accomplishments include added support for SPICE formats and attitude-dependent solar radiation pressure and drag models.

[Technical contacts: Russ Carpenter, Kevin Berry,]

5.6 Schatten Solar Predicts

The FDAB provides a number of services that require long-term prediction of solar activity in order to obtain accurate, long-term prediction of satellite orbits, and orbit decay rates in low altitude orbits. In particular, FDAB analysts and GSFC solar physicists, continue to use the solar flux predictions provided by Dr. Kenneth Schatten’s models. Dr. Schatten employs a physically based method, know as a solar precursor method, to predict the mean solar flux for the upcoming solar cycle. This method uses direct and indirect measurements of the sun’s polar magnetic fields near the minimum of the 11-year solar flux cycle, and solar dynamo theory to estimate the solar activity during the remainder of the cycle. Analysis over the past year has also identified a need for improved understanding of the effects of short-term solar flux variations on satellite orbit decay rates. To this end, FDAB has supported scientific analysis to incorporate physical phenomena of the sun and known characteristics of solar activity to develop a model of the short-term variations in solar flux. These models enable FDAB analysts to perform extensive (Monte-Carlo) satellite orbit decay analyses with a statistical set of solar flux profiles, and to determine the sensitivity of spacecraft orbit decay to short term solar flux variations.

[Technical contact: Edwin Dove]

6.0 EMPLOYEE DEVELOPMENT

6.1 COOP Program

The FDAB is a strong supporter of the Goddard Cooperative Education (COOP) Program. We look forward to working with three new COOP students that will begin their work experience in FY09. These new students are:

- Wayne Yu (University of Maryland)
- Cassandra Alberding (University of Maryland)
- Kenneth Getzandanner (Penn State University)

During FY08, two of our COOP students worked in the branch. Given below is a summary of their work.

<u>Rizwan Qureshi (University of Minnesota)</u>

My first co-op session began on June 09, 2008. I was assigned to work for a team working on designing interplanetary mission trajectories. During the first three weeks of my work, I took several tutorials on Satellite Tool Kit (STK) software. Specifically my technical mentor Greg Marr instructed me in understanding the Astrogator application of STK and learning how to set up Mission Control Sequence (MCS) in designing interplanetary mission segments. Once I gained sufficient understanding of STK and key lessons in orbital mechanics behind the specifics of interplanetary mission design, I got involved in working on trajectory design and mission orbit analysis of the Planetary Probe IRAD effort. Currently I am learning about various mission design segments related to the Planetary IRAD effort, but specifically I am involved in performing engineering analysis of the nominal mission orbit.

<u>Patrick Conrad (MIT)</u>

During my tour this summer I studied two main areas: automation for close-proximity operations and dynamics around the Lagrange points and low-thrust transfers. For the first task I worked with Bo Naasz to prepare for a proposed IRAD on autonomous proximity operations and docking. My role was to write a document making suggestions for safely dividing an autonomous mission into phases, defining some terminology, and applying those ideas to two sample missions. My second task was to investigate the uses of a recent paper into low-thrust transfers between Jovian moons and was undertaken at the suggestion of Conrad Schiff. Further investigation led to some previous work in the branch done by Mark Beckman into manifolds and efficient transfers. I completed a survey of related literature and developed software to begin preliminary investigations, which should be helpful when this line of research is continued in the future. As a side project I completed a short investigation into the suitability of accelerating computations with the parallel processing capabilities of modern graphics cards, determining that while large performance gains are possible the development cost is significant and the particular uses that I considered would easily benefit from that technology.

6.2 New Employee Profiles

The FDAB was happy to welcome two new employees to the branch in FY08. Their profiles are given below:

Dennis Woodfork

Dennis Woodfork, II joined the FDAB on July 7, 2008. After receiving his B.S. degree in Aerospace Engineering from the US Naval Academy in 2000, Dennis joined the US Air Force as an astronautical engineer. In his first assignment at US Strategic Command (USSTRATCOM), Offutt AFB, NE, Dennis served as a ballistic missile trajectory engineer supervising the engineering analysis of US and foreign ballistic missile systems for various Department of Defense organizations. He also developed the ballistic missile flight performance databases and computer algorithms for USSTRATCOM's early warning and attack assessment systems. Dennis then attended the Air Force Institute of Technology and in 2005, earned his M.S. degree in Astronautical Engineering with an emphasis in astrodynamics and systems engineering. Dennis was then assigned to the 2nd Space Operations Squadron (2 SOPS) in 2005 at Schriever AFB in Colorado Springs, CO. As the Deputy Flight Commander for GPS Weapons and Tactics, Dennis oversaw the development of GPS tactics for the squadron's space operators who command and control the GPS constellation. Dennis also served as a GPS navigation payload analyst charged with maintaining the integrity and operation of the Kalman Filter used to determine GPS satellite positions and timing. In 2007, Dennis was assigned to Schriever's 50th Operations Group, serving as the executive officer for the 50th Operations Group Commander. As a new employee at GSFC, Dennis is being introduced to the aspects of space operations as co-task monitor for the FDF Orbital Operations Task. Dennis is also drafting a Differenced-One-Way-Doppler users' guide which will explain a FDF early orbit determination measurement type available to Space Network customers.

Dr. Trevor Williams

Trevor Williams obtained his B.A. (with Honours) in Engineering Science from Oxford University, his M.Sc. (with Distinction) in Systems Engineering from The City University, London, and his Ph.D. in Electrical Engineering from Imperial College, London. He then carried out post-doctoral research into numerical methods for controls analysis and into the dynamics and control of large space structures, first at Kingston Polytechnic in the United Kingdom, and then at NASA Langley Research Center. He subsequently joined the faculty of the Department of Aerospace Engineering at the University of Cincinnati, initially as Assistant Professor, then Associate Professor, and finally Professor. While there, he taught subjects such as orbital mechanics, spacecraft attitude dynamics, spacecraft design and control theory, and carried out research, funded by sources including NASA, the Air Force and the State of Ohio, on topics involving the control of large space structures, satellite formation flight, and the dynamics and control of hypersonic vehicles. He also performed dynamics analysis in support of two NASA Johnson Space Center flight projects, the Simplified Aid For EVA Rescue (SAFER) astronaut maneuvering unit (tested on STS-64 in 1994), and the Autonomous EVA Robotic Camera (AERCam) Sprint orbital inspection unit (test-flown on STS-87 in 1997). Finally, he has been a visiting researcher at Surrey Satellite Technology, Ltd. in Guildford, England, working on problems related to orbital maneuvering plans for the UoSAT-12 minisatellite and SNAP nanosatellite flight projects. He is currently working on orbital dynamics for the Magnetospheric MultiScale (MMS) project.

6.3 New Employee Welcoming Board

The GSFC New Employee Welcoming Board (Newb) is an organization that works to improve the transition of new employees to the work force at Goddard. Since it's inception in 2004, members of the Flight Dynamics Analysis Branch have been active in the organization. In the past year Newb has continued it's work with the Office of Human Capital Management by providing and updating a Goddard 101 Handbook and assisting with the new employee orientations. FDAB employees representing Newb participated on the planning committee that designed the new 2-Day New Employee Orientation –*Welcome to the NASA/GSFC family: Captivating, Cultivating and Challenging YOU*! FDAB employees continue to help with the day to day running of Newb as well as its involvement with other organizations at Goddard.

[Technical contact: Leigh Janes]

6.4 OpenGoddard

http://www.opengoddard.com

Several branch members have been involved in creating a new organization called OpenGoddard. The group is a grassroots initiative made up of folks who are interested in influencing the future of Goddard Space Flight Center. The people of OpenGoddard are passionate and energetic about enabling innovation, collaboration, and inspiration! This group has a weekly discussion where folks talk about interesting items or the challenges that Goddard currently faces. The folks in this group are heavily involved in agency-wide discussions on communication and leadership. In addition, there are social opportunities for building new communities across branches, directorates, and centers.

[Technical contact: Rivers Lamb]

7.0 OUTREACH ACTIVITIES

7.1 Flight Dynamics Analysis Branch (FDAB) Summer Interns

The FDAB sponsored a sizable set of summer interns in the summer of 2008. The interns worked on a variety of flight projects and technology programs. Our summer interns of 2008 were:

Intern Name	Intern Program	Mentor	Project
Marty Ozimek	Graduate Student Research Program	Dave Folta	Solar sails
Dan Grebow	Purdue grant	Dave Folta	Dynamical systems theory
Cassie Alberding	Student Intern Program (SIP)	Mark Beckman	LRO
Eduardo Villalba	Summer Institute in Engineering & Computer Applications	Steve Cooley	LCROSS
Brandon Farzad	SIP	Kevin Berry	OD Toolbox
Michelle Pelletier	Univ. of New Hampshire (UNH)	Dave Folta	Lunar glint mission
Chris Hill	UNH	Lauri Newman	Conjunction Assessment
Jim Gealy	UNH	Edwin Dove	GMAT
Tyler McCluskey	SIP	Dave Folta	Maven
Benjamin Beers	SIP	Edwin Dove	GMAT
Brad Cheetham	NASA Academy	Dave Folta	Artemis
Andrew Schaeperkoetter	NASA Academy	Edwin Dove	GMAT
Kenji Nagoaka	NASA Academy	Edwin Dove	GMAT
Sean Lawlor	High School Intern Program	Mark Beckman	LRO

[Technical contact: Mark Beckman]

7.2 LaunchFest 2008

On September 13, 2008 Goddard Space Flight Center opened its gates to the community to share with the world what we do, the people who work here and why the work we do is relevant to society. This day celebrated this unprecedented year for NASA and GSFC which includes 15 science launches, 8 of those managed out of GSFC. LaunchFest featured tours of the center, demonstrations and exhibits, entertainment, and food. The event had fun and educational activities including model rocket launches and robots.

The Flight Dynamics Analysis Branch played many roles in making LaunchFest possible. Members of the branch worked on the planning committee and volunteered their time on the day of the event. Most notably the FDAB ran tours all day of the Flight Dynamics Facility which included demonstrations featuring LRO and tracking processes. Visitors were also allowed to enter the Flight Dynamics CAVE for a 3D interactive experience.

[Technical contact: Leigh Janes]

7.3 Yuri's Night

http://www.yurisnight.net/2008
http://dc.yurisnight.net

Created in 2001, Yuri's Night is an annual celebration on April 12th organized by young people around the world with an interest in space exploration. The date is the anniversary of the first manned flight in space by Yuri Gagarin as well as the first launch of the space shuttle. Yuri's Night is a worldwide celebration that in 2008 had events in 198 cities in 51 countries. The goals of Yuri's Night are to inspire the public, connect the space community, and provide a training opportunity for those who organize it!

The Space Generation Advisory Council teamed up with Goddard Space Flight Center to host the first Yuri's Night party at Goddard on April 12th, 2008. Several branch members participated in the efforts to organize the event at the Goddard Visitor Center. Expecting an attendance of a couple hundred, more than 750 people came to the party and enjoyed live music, dancing, and a moon bounce! During the night, the partiers had a chance to mingle amongst the visitor center exhibits and to hear presenters talk about some of the awesome science that is being done at Goddard.

[Technical contact: Rivers Lamb]

Appendix A – Conference and Papers

Given below are abstracts from professional papers and technical presentations that were prepared and delivered in FY08 by branch members.

2008 AAS/AIAA Space Flight Mechanics Meeting / Galveston, TX / Jan 27 – 31, 08

“A Stable Clock Error Model Using Coupled First- And Second-Order Gauss-Markov Processes,” J. Russell Carpenter And Taesul Lee

ABSTRACT: Long data outages may occur in applications of global navigation satellite system technology to orbit determination for missions that spend significant fractions of their orbits above the navigation satellite constellation(s). Current clock error models based on the random walk idealization may not be suitable in these circumstances, since the covariance of the clock errors may become large enough to overflow flight computer arithmetic. A model that is stable, but which approximates the existing models over short time horizons is desirable. A coupled first- and second-order Gauss-Markov process is such a model.

“Operational Impact of the Chinese ASAT Event Debris on the Earth Science Constellation Missions,” Matthew Duncan, Lauri K. Newman, and David K. Rand

ABSTRACT: Routine flight operations for the NASA Earth Science Constellation (ESC) includes assessing the risk of collision between members of the constellation as well as between the constellation members and other space objects. The ESC collision risk assessment process is performed by the Flight Dynamics Analysis Branch and consists of:

1. Generating close approach predictions between members of the ESC and other objects in the United States Strategic Command’s Space Object Catalog
2. Probabilistically assessing the collision risk posed by predicted close approach events
3. Working with the member mission to plan any necessary risk-mitigating action

On January 11, 2007, destruction of a Chinese weather satellite (Fengyun 1C) created a significant amount of debris near the ESC operational altitude. The Fengyun 1C satellite was in a sun-synchronous orbit with a mean equatorial altitude of 850 km and an inclination of 98.6 deg. Some models estimate that the number of fragments larger than 1 cm generated by this event is approximately 35,000. Although the ‘anti-satellite’ (ASAT) event took place approximately 150 km above the ESC altitude, the results of the event were to distribute debris through an altitude range from 200 to 4000 kilometers. Two weeks following the event, the first close approach with an ESC mission was observed. Since then, a near constant presence of ASAT debris within the ESC ‘Monitor Volume’ has been observed. The severity of the event was demonstrated when the Terra spacecraft was forced to perform a collision avoidance maneuver in June to reduce the risk of impact with one of the debris pieces.

This paper describes the operational impact of the ASAT event on missions in the Earth Science Constellation. Close approach statistics on the number of conjunction events are presented. Reported statistics will include: the number of unique of events; the number of unique objects; and the miss distance distribution. A summary of the Terra avoidance maneuver will also be presented, including a summary of the evolution of the miss distance and the collision probability.

Finally, the evolution of the debris population is estimated by performing long-term predictions using the publicly available mean element catalo. An expectation of increased future ESC mission risk is postulated based on this analysis.

ION NTM 2008 Conference/San Diego, CA/ Jan 28-30, 2008

“A GPS Receiver for Lunar Missions,” William A. Bamford, Gregory W. Heckler, Greg N. Holt and Michael C. Moreau

ABSTRACT: Beginning with the launch of the Lunar Reconnaissance Orbiter (LRO) in October of 2008, NASA will once again begin its quest to land humans on the Moon. This effort will require the development of new spacecraft which will safely transport people from the Earth to the moon and back again, as well as robotic probes tagged with science, re-supply, and communication duties. In addition to the next-generation spacecraft currently under construction, including the Orion capsule, NASA is also investigating and developing cutting edge navigation sensors which will allow for autonomous state estimation in low Earth orbit (LEO) and cislunar space. Such instruments could provide an extra layer of redundancy in avionics systems and reduce the reliance on support and on the Deep Space Network (DSN).

One such sensor is the weak-signal Global Positioning System (GPS) receiver “Navigator” being developed at NASA’s Goddard Space Flight Center (GSFC). At the heart of the Navigator is a Field Programmable Gate Array (FPGA) based acquisition engine. This engine allows for the rapid acquisition/reacquisition of strong GPS singles, enabling the receiver to quickly recover from outages due to blocked satellites or atmospheric entry. Additionally, the acquisition algorithm provides significantly lower sensitivities than a conventional space-based GPS receiver, permitting it to acquire satellites well above the GPS constellation.

This paper assesses the performance of the Navigator receiver based upon three of the major flight regimes of a manned lunar mission: Earth ascent, cislunar navigation, and entry. Representative trajectories for each of these segments were provided by NASA. The Navigator receiver was connected to a Spirent GPS signal generator, to allow for the collection of real-time, hardware-in-the-loop results for each phase of the flight. For each of the flight segments, the Navigator was tested on its ability to acquire and track GPS satellites under the dynamical environment unique to that trajectory.

Space Operations 2008 Conference, Heidelberg, Germany/ May 12-16, 2008

"Evolution and Reengineering of NASA's Flight Dynamics Facility (FDF)," Thomas Stengle and Sue Hoge

ABSTRACT: The NASA Goddard Space Flight Center's Flight Dynamics Facility (FDF) is a multi-mission support facility that performs ground navigation and spacecraft trajectory design services for a wide range of scientific satellites. The FDF also supports the NASA Space Network by providing orbit determination and tracking data evaluation services for the Tracking Data Relay Satellite System (TDRSS). The FDF traces its history to early NASA missions in the 1960's, including navigation support to the Apollo lunar missions. Over its 40 year history, the FDF has undergone mjany changes in its architecture, services offered, missions supported, management approach, and business operation. As a fully reimbursable facility (users now pay 100% of all costs for FDF operations and sustaining engineering activities), the FDF has faced significant challenges in recent years in providing mission critical products and services at minimal cost while defining and implementing upgrades necessary to meet future mission demands. This paper traces the history of the FDF and discusses significant events in the past that impacted the FDF infrastructure and/or business model, and the events today that are shaping the plans for the FDF in the next decade. Today's drivers for change include new mission requirements, the availability of new technology for spacecraft navigation, and continued pressures for cost reduction from FDF users. Recently, the FDF completed an architecture study based on these drivers that defines significant changes planned for the facility. This paper discusses the results of this study and a proposed implementation plan. As a case study in how flight dynamics operations have evolved and will continue to evolve, this paper focuses on two periods of time (1992 and the present) in order to contrast the dramatic changes that have taken place in the in the FDF. This paper offers observations and plans for the evolution of the FDF over the next ten years. Finally, this paper defines the mission model of the future for the FDF based on NASA's current mission list and planning for the Constellation Program. As part of this discussion the following are addressed: the relevance and benefits of a multi-mission facility for NASA's navigation operations in the future; anticipated technologies affecting ground orbit determination; continued incorporation of Commercial Off-the-Shelf (COTS) software into the FDF; challenges of a business model that relies entirely on user fees to fund facility upgrades; anticipated changes in flight dynamics services required; and considerations for defining architecture upgrades given a set of cost drivers.

The F. Landis Markley Astrodynamics Symposium/ Cambridge, Md, June 29-July 2, 2008.

"Generalized Linear Covariance Analysis," J. Russell Carpenter and F. Landis Markley

ABSTRACT: We review and extend in two directions the results of prior work on generalized covariance analysis methods. This prior work allowed for partitioning of the state space into "solve-for" and "consider" parameters, allowed for differences between the formal values and the true values of the measurement noise, process noise, and a priori solve-for and consider covariances, and explicitly partitioned the errors into subspaces containing only the influence of the measurement noise, process noise, and a priori solve-for and consider covariances. In this work, we explicitly add sensitivity analysis to this prior work, and relax an implicit assumption that the batch estimator's anchor time occurs prior to the definitive span. We also apply the method to an integrated orbit and attitude problem, in which gyro and accelerometer errors, though not estimated, influence the orbit determination performance. We illustrate our results using two graphical presentations, which we call the "variance sandpile" and the "sensitivity mosaic," and we compare the linear covariance results to confidence intervals associated with ensemble statistics from a Monte Carlo analysis.

"The HST SM4 Relative Navigation Sensor System," Richard D. Burns, Bo J. Naasz, Steven Z. Queen, John Van Eepoel, Joel Hannah, and Eugene Skelton

ABSTRACT: The upcoming Hubble Space Telescope (HST) Servicing Mission 4 (SM4) includes a Relative Navigation Sensor (RNS) experiment which uses three cameras and an avionics package to record images, and estimate in real-time the relative position and attitude (aka "pose") during the Shuttle capture and deployment of the telescope. RNS recently completed its third and final phase of testing at the Marshall Space Flight Center Flight Robotics Laboratory. This testing utilized flight spare cameras, engineering development unit avionics and flight pose algorithms to estimate the pose of a Hubble mockup mounted to the Flight Robotics Laboratory (FRL) Dynamic Overhead Target Simulator (DOTS). The mockup was moved through a variety of flight-like lighting conditions and trajectories. In this paper we present pose estimation results from the third phase of RNS FRL testing.

AIAA Guidance, Navigation, & Control Conference & Exhibit, Honolulu, HI, August 2008.

"Formation Design and Sensitivity Analysis for the Magnetospheric Multiscale Mission (MMS)," Steven P. Hughes/GSFC/595

ABSTRACT: MMS is a NASA mission to study the Earth's magnetosphere scheduled to launch in 2014. The mission will employ 4 spacecraft that must maintain a near-regular tetrahedron in a region centered about apoapsis of a highly elliptic orbit. This paper contains a sensitivity analysis that illustrated which error sources and perturbations are drivers of formation degradation. The sensitivity to navigation and control errors is performed by comparing the semimajor axis errors due to position and velocity knowledge errors and errors in maneuver direction, magnitude, and location. Sensitivity to perturbations is investigated by comparing the magnitudes of the monodromy matrix at apoapsis for different dynamics models. We also present several design techniques to mitigate or remove the effects of perturbations. The design techniques combine numerical methods with analytic conditions designed to eliminate or reduce effects of the J2 perturbation. Finally, we present Monte Carlo analysis that addresses the practicality of using the design techniques given the navigation and control errors expected for MMS.

“SDO Onboard Ephemeris Generation,” Kevin Berry And Kuo-Chia Liu

ABSTRACT: The Solar Dynamics Observatory (SDO) spacecraft is a sun-pointing, semi-autonomous satellite that will allow nearly continuous observations of the Sun with a continuous science data downlink. The science requirements for this mission necessitate very strict sun-pointing requirements, as well as continuous ground station connectivity through high gain antennas (HGAs). For SDO’s onboard attitude control system to successfully point the satellite at the Sun and the HGAs at the ground stations with the desired accuracy, in addition to the need for accurate sensors it must have good onboard knowledge of the ephemerides of the Sun, the spacecraft, and the ground station. This paper describes the minimum force models necessary for onboard ephemeris generation in support of an attitude control system. The forces that were considered include the Sun’s point mass, Moon’s point mass, solar radiation pressure (SRP), and the Earth’s gravity with varying degree and order of terms of the geopotential.

International Astronautical Congress Conference, Glasgow, Scotland, September 27-October 3, 2008

“Formation Flying of a Telescope/Occulter System with Large Separations in an L2 Libration Orbit,” Mr. David Folta and Mr. Jonathan Lowe

ABSTRACT: Flying an occulter in formation with a telescope in a sun-Earth L2 co-linear libration orbit requires an understanding of the interactions between the dynamics and limitations of the three-body restricted system and formation control methods. When the formation separation distances become a large fraction of the telescope’s libration orbit amplitude, linear approximations break down and formation control becomes problematic, requiring high-fidelity modeling and specific targeting methods. This paper considers control approaches and determines ^V requirements to re-align the New Worlds Observer telescope-occulter formation and to maintain the viewing geometry during an observation sequence. Analyzed for both impulsive and finite (low-thrust) maneuvers using two different Lissajous classes, a feasible mission design is found with control cost (^V) in the km/sec range

“The NASA Robotic Conjunction Assessment process: Overview and Operational Experiences,” Lauri Kraft Newman

ABSTRACT: Orbital debris poses a significant threat to spacecraft health and safety. Recent events such as China’s anti-satellite test and the Breeze-M rocket explosion have led to an even greater awareness and concern in the satellite community. Therefore, the National Aeronautics and Space Administration (NASA) has established requirements that routine conjunction assessment screening shall be performed for all maneuverable spacecraft having perigees less than 2000 km or within 200 km of geosynchronous altitude. NASA’s Goddard Space Flight Center (GSFC) has developed an operational collision risk assessment process to protect NASA’s high-value unmanned (robotic) assets that has been in use since January 2005. This paper provides an overview of the NASA robotic conjunction assessment process, including descriptions of the new tools developed to analyze close approach data and of the risk mitigation strategies employed. In addition, statistical data describing the number of conjunctions experienced are presented. A debris avoidance maneuver performed by Aura in June of 2008 is described in detail to illustrate the process

APPENDIX B: ACRONYMS AND ABBREVIATIONS

AAS	American Astronautical Society
AC	Afternoon Constellation
ACE	Active Coronal Explorer
ADS	Applied Defense Solutions
AETD	Applied Engineering and Technology Directorate
AGI	Analytical Graphics, Inc.
AIAA	American Institute of Aeronautics and Astronautics
AOP	Argument of Perigee
AR&D	Autonomous Rendezvous & Docking
ASAT	Advanced Situation Awareness Technologies
ATV	Autonomous Transer Vehicle
BCC	Backup Control Center
BEOC	Backup EOS Operations Center
BRTS	Bilateration Ranging Transponders
CA	Conjunction Assessment
CAA	Collision Avoidance Assessment
CCR	Configuration Change Request
CCS	Constellation Coordination System
CFE	Commericial & Foreign Entities
Con-X	Constellation-X
COTS	Commercial-Off-the-Shelf
CNSR	Comet Nucleus Sample Return
CRTBP	Circular restricted three body problem
CS	Cloud Sat
CSTS	Compatibility Test Set
CxP	Constellation Program
DAS	Debris Assessment Software
DESTINY	Dark Energy Space Telescope
DMU	Drag Make-Up Maneuver
DOWD	Differenced One Way Doppler
DSN	Deep Space Network
EAGLE	Enceladus Astrobiology and Geophysical Landing Expendition
ECANS	Exploration Communication and Navigation System
EDUS	Earth Departure Upper Stage
ELV	Expendable Launch Vehicle
EMCC	Emergency Mission Control Center
EOS	Earth Observing System
ESA	European Space Agency
ESC	Earth Science Constellation
ESMD	Earth Science Mission Directorate
ESMO	Earth Science Mission Operations
FDAB	Flight Dynamics Analysis Branch
FDF	Flight Dynamics Facility
FDPC	Flight Dynamics Product Center
FDS	Flight Dynamics System
FMU	Fault Management Unit
FOT	Flight Operations Team
FOV	Field of View

FPGA	Field Programmable Gate Array
FPM	Fine Point Mode
FRB	FDF Review Board
FRL	Flight Robotics Laboratory
GEO	Geosynchronous
GEONS	Goddard Enhanced Onboard Navigation System
GEONS	GPS-Enhanced Orbit Navigation System
GGSS	GEONS Ground Support System
GLAST	Gamma Ray Large Area Telescope
GMAT	General Mission Analysis Tool
GMSEC	Goddard Mission Services Evolution Center
GN	Ground Network
GNC	Guidance, Navigation, and Control
GOES	Geostationary Operational Environmental Satelitte
GPM	Global Precipitation Mission
GPS	Global Positioning System
GRC	Glen Research Center
GSFC	Goddard Space Flight Center
GTDS	Goddard Trajectory Determination System
GUI	Graphical User Interface
HEO	High Earth Orbit/Highly Elliptical Orbit
HGAs	High Gain Antennas
HRSDM	Hubble Robotic Servicing and De-orbit Mission
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
IAD	Interface Agreement Document
ICD	Interface Control Document
ICE	Integrated Control Electronics
IDC	Integrated Design Center
IDIQ	Indefinite Delivery/Indefinite Quantity
IDL	Instrument Design Laboratory
IOCs	Instrument Operations Centers
ION	Institute Of Navigation
IRAD	Internal Research and Development
IRAS	Interspacecraft Ranging and Alarm System
IRDWG	Interface Requirements Document Working Group
ISS	International Space Station
ISSFD	International Symposium on Space Flight Dynamics
IXO	International X-Ray Observatory
JAT	Java Astrodynamics Toolbox
JAXA	Japan Aerospace Exploration Agency
JDEM	Joint Dark Energy Mission
JSC	Johnson Space Center
JWST	James Webb Space Telescope
LAN	Longitude of Ascending Node
L&EO	Launch and early Orbit
LCROSS	Lunar Crater Observation & Sensing Satellite
LDCM	Landsat Data Continuity Mission
L&EO	Launch & Early Orbit
LEO	Low Earth Orbit

LHCP	Left Hand Circular Polarization
LRO	Lunar Reconnaissance Orbiter
MABE	Multiple Access Beamforming Equipment
MALTO	Mission Analysis for Low-Thrust Optimization
MAR	Multiple Access Return
MAVEN	Mars Atmosphere and Volatile Evolution
MCS	Mission Control Sequence
MDL	Mission Design Laboratory
MDR	Mission Design Review
METS	Multi- Disciplinary Engineering and Technology Services
MLS	Microwave Limb Sounder
MLT	Mean Local Time
MMS	Magnetospheric Multiscale Mission
MMWG	Momentum Management Working Group
MOA	Memo of Agreement
MOC	Mission Operations Center
MOI	Mars Orbit Insertion
MOR	Mission Operations Review
MOWG	Mission Operations Working Group
MSFC	Marshall Space Flight Center
MTDE	Metric Tracking Data Evaluation
Newb	New Employee Welcoming Board
NOAA	National Oceanic and Atomospherics Administration
NWO	New Worlds Observer
OD	Orbit Determination
ODEAS	Orbit Determination Error Analysis System
ODTK	Orbit Determination Tool Kit
OSC	Orbital Sciences Corporation
OSIRIS	Origins Spectral Interpretation, Resource Identification and Security
OSTM	Ocean Surface Topography Mission
PDR	Preliminary Design Review
PI	Principal Investigator
PNT	Positioning, Navigation and Timing
PSM	Procurement Strategy Meeting
RMM	Risk Mitigation Maneuver
RMS	Root Mean Square
RNS	Relative Navigation Sensors
RFA	Request for Action
RFP	Request for Proposal
SAVIO	Software and Avionics Integration Office
ScaN	Space Communication and Navigation
SCIP	Space Communications and Navigation Constellation Integration Project
SDR	System Design Review
SDO	Solar Dynamics Observatory
SDOGS	Solar Dynamics Observatory Gound Station
SEBs	Source Evaluation Boards
SEWG	Systems Engineering Work Group
SET	Solid-Earth Tide
SLT	Spacecraft Local Time
SM	Service Module

SM4	Servicing Mission 4
SN	Space Network
SOHO	Solar and Heliospheric Observatory
SPICE	Spacecraft Planet Instruments, C-matrix and Events
SRR	System Requirements Review
SRP	Solar Radiation Pressure
SSAR	S-Band Single Access Return
SSR	Solid State Recorder
STK	Satellite Tool Kit
STS	Space Transportation System
SwRI	Southwest Research Institute
TASS	TDRSS Augmentation Service for Satellites
TDRS	Tracking and Data Relay Satellite
TDRSS	TDRS System
TIM	Technical Interface Meeting
TOPO	Trajectory Operations Offices
TOPEX	TOPography Experiment
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
ULA	United Launch Alliance
UPC	UnPressurized Cargo
USStratcom	United States Strategic Command
USN	Universal Space Network
VRO	Venus Reconnaissance Orbiter