NASA/TM—2005–212777

Flight Dynamics Analysis Branch End of Fiscal Year 2004 Report

Prepared by members of the Flight Dynamics Analysis Branch
Applied Engineering and Technology Directorate
NASA Goddard Space Flight Center, Greenbelt, MD 20771

February 2005

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Acknowledgments

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's Goddard Space Flight Center (GSFC).

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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) 2004. 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; attitude analysis; attitude determination and sensor calibration; and attitude control subsystem (ACS) analysis and design. 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 is the sixth annual report 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 for trajectory and attitude systems. This includes dynamics and control analyses and simulations of space vehicles. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis, navigation, attitude determination, and controls analysis. The Branch also provides the expertise to support a wide range of flight dynamics services, such as spacecraft mission design, on-orbit sensor calibration, and launch/early orbit operations. An active technology development program is maintained, with special emphasis on developing new techniques and algorithms for autonomous orbit/attitude systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are:

- Attitude and trajectory analysis and control design
- Control/structure interaction analysis
- Mission (attitude & trajectory) planning
- Estimation techniques
- Vehicle autonomy
- Constellation analysis
- Flight dynamics model development

The FDAB also provides flight dynamics operations services through its Flight Dynamics Facility (FDF). This facility supported flight dynamics computations for more than twenty spacecraft in Fiscal Year (FY) 2004. Operational services include orbit determination, acquisition data generation for the space and ground networks, tracking data evaluation, attitude determination 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 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 FY 2004. 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 FY 2004 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 FY 2004 are:

- ***Successful branch support for the launch and early operations of the Aura spacecraft.*** As part of this support, the branch designed and implemented orbit-raising maneuvers.

- ***Successful transition of FDF management to the FDAB***. Prior to January 2004, the FDF operations were the responsibility of the Consolidated Space Operations Contract (CSOC) under management by the Goddard Mission Services Program Office. In FY 2004, FDF operations were transitioned to the Mission Operations & Mission Services (MOMS) contract and overall management responsibility for the facility transitioned to the FDAB.

- ***Completion of the Solar Dynamic Observatory (SDO) preliminary design.*** The in-house attitude control system analysis team and the flight dynamics team successfully presented their preliminary design and supporting analysis at the SDO Preliminary Design Review (PDR) in December, 2004.

- ***ST5 Team completes redesign activities.*** A new launch vehicle (Pegasus XL) was selected to deliver ST5 to orbit. As a result, the ST5 team re-designed an orbit and constellation scheme to satisfy the capabilities of the new launch vehicle

- ***Successful ST7 Dynamic Control System (DCS) critical design completed.*** Flight software builds were also delivered and mode transition strategies were completed.

- ***GEONS wins the Federal Laboratory Consortium Mid-Atlantic Regional Award.*** The GEONS software package used for autonomous navigation also had two new releases in FY 2004.

- ***Hubble Robotic Vehicle concepts studied.*** Branch engineers played a key role in defining robotic servicing concepts for the Hubble Space Telescope. Simulations and early control concepts were developed to show the feasibility of robotic servicing.

2.0 Flight Project Support

2.1 Development Missions

2.1.1 Aquarius

Aquarius is an Earth System Science Program (ESSP) mission that plans to answer questions about the global cycle of water and the response of ocean circulation to climate change. The required mission lifetime is three years, with a goal of five years.

FDAB personnel continued to provide analysis support for the Aquarius mission team. Coverage analysis was performed for the two 9-day repeating orbits at 596 and 630 km that fell within the allowable altitude span. Results showed that the 596 km orbit provided the desired coverage of 4 observations of each grid point every 36 days while the 630 km orbit had several grid points that were only observed 3 times during the same period.

[Technical contact: Frank Vaughn]

2.1.2 Earth Observing System (EOS) Constellation Management

FY 2004 has been a busy year for the Earth Sciences Mission Operations (ESMO) Project constellation management. Aura joined Aqua this year in ESMO's Afternoon Constellation (AC); these two satellites anchor the two ends of the AC (see Figure 2-1).

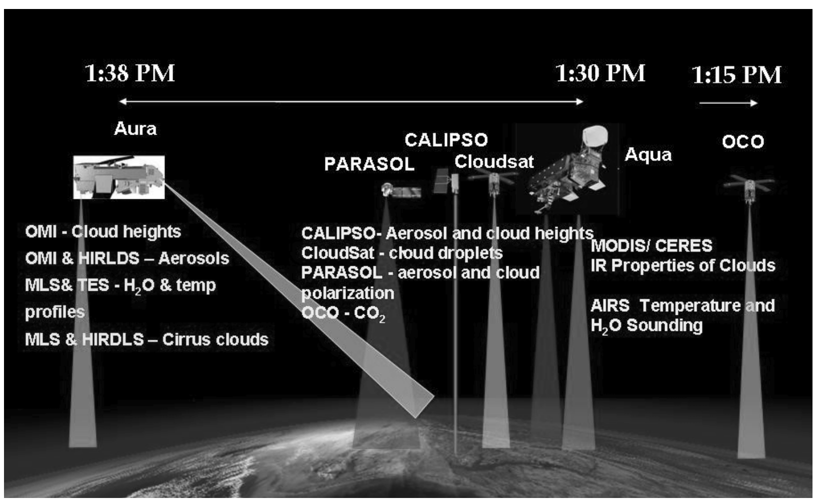

Figure 2-1. The ESMO Afternoon Constellation Configuration

Three new satellites will join the AC within the next calendar year. PARASOL, a CNES satellite, is scheduled to launch in December, 2004. CALIPSO, another CNES satellite, and JPL's CloudSat will launch as dual payloads in April 2005. OCO will join the AC in 2008 and is expected to assume the lead position in front of Aqua. The six satellites will perform coincident Earth observations while flying in a loose constellation that crosses the equator at approximately 13:30 (descending node).

Coordinating activities and sharing resources between missions becomes increasingly complex as the number of missions within the AC grows. The Constellation Coordination System (CCS), a web-based application for collaboration and data sharing, is a first step in reducing the complexity of this type of constellation operations. The goal of the CCS is to make constellation coordination as routine and automated as possible. CCS provides the member missions of ESMO's Morning (MC) and Afternoon Constellations with a tool to ensure constellation health and safety, to facilitate data exchange and coincident observations, and to allocate shared resources.

The FDAB is responsible for defining the CCS requirements, software acceptance testing, and performing analysis with the system. The first release was in May 2004; this release incorporated the capabilities of the ES Collaborator for continued use by members of the MC as well as added capabilities for the AC. The CCS checks constraints and monitors the satellites' positions within their control boxes. It detects when constraints are violated, when control box limits are exceeded, and when a satellite might have a close approach with another AC satellite. CCS performs automated analyses and sends the results to any affected satellite's flight operators, who can resolve any potential problems. Figure 2-2 shows a CCS display containing the MC visualization of control boxes and groundtracks.

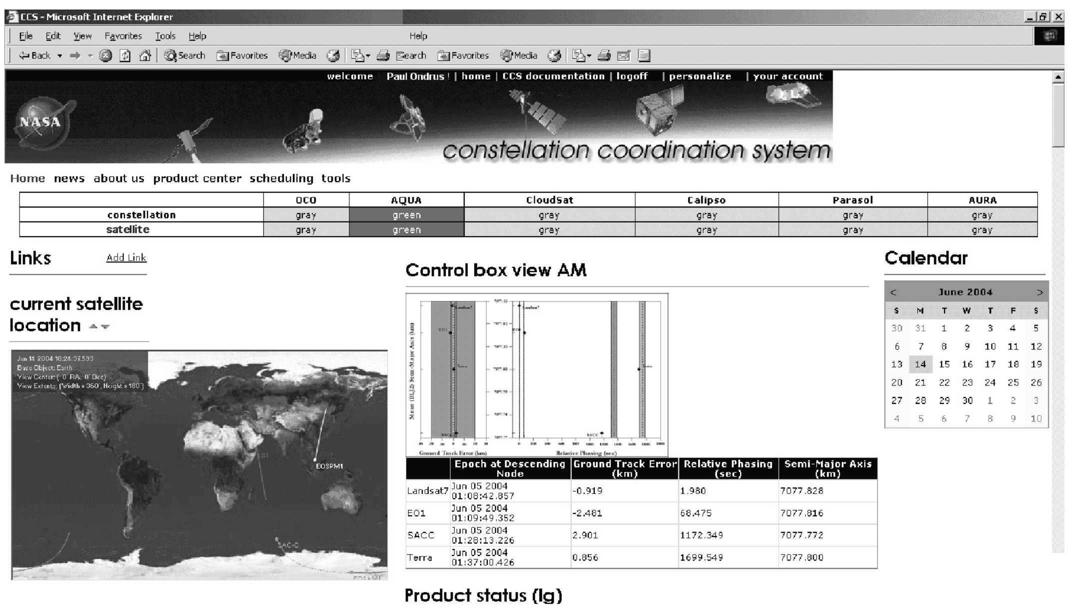

Figure 2-2. CCS display

CCS Release 1 was used for Aura's launch and ascent and for monitoring the inclination maneuvers that Aqua and Aura performed in Fall 2004. It has also supported CALIPSO/CloudSat long-term simulations and will be a critical tool during the three AC launches next year. Release 2 is scheduled for delivery to operations in October 2004. This release will include the capabilities to read, convert, and output new product formats needed by PARASOL, CALIPSO and CloudSat, and to provide visualizations of the AC in addition to the MC.

[Technical contact: Karen Richon]

2.1.3 InFocus

The FDAB has supported pointing system development and flight operations of the InFocus Telescope Experiment since 1999. This experiment is a nine-meter focal-length imaging X-ray telescope designed to observe celestial targets from a balloon gondola at altitudes greater than 40 km. The telescope had its first flight in July, 2001, onboard a stratospheric balloon and used an azimuth/elevation pointing system that had been modified from a smaller and lower resolution telescope. To achieve InFocus's desired pointing accuracy of one arcminute, a star camera sent images to the ground that were used in identifying the pointing error and commanding corrections to the closed loop pointing control, which was controlled by sensors of the local magnetic and g fields. Unfortunately, higher-than-normal winds at the observing altitude continuously excited the swinging of the gondola from the load train. These oscillations could not be dampened sufficiently to read the star camera, so very little data was obtained, other than demonstrating that the telescope was working.

A more robust system was clearly needed for a telescope of this size under these disturbance conditions. A design effort led to upgraded performance of the pointing system, including the pointing algorithms, software, computer hardware, and actuators, in preparation for the next flight. Members of the FDAB were part of an engineering team in this effort. The basic azimuth/elevation approach was kept, and a new control loop to make small angular adjustments about the remaining axis, cross elevation, was added to eliminate the source of the largest pointing error seen on the first flight, namely that caused by the inadequacy of the azimuth control loop (at high elevation) to cancel the rotation of the gondola due to swinging from the balloon load train. The cross elevation approach used actuators that continuously adjusted the lengths of two of the three straps from which the gondola was suspended. Also, plans were made to close the loop around the star camera and the gyros mounted to the gondola base. Because pointing during the daytime was desired during the 24-hour mission, GPS attitude sensing was incorporated and was based on the Pivot GPS receiver (see section 4.5 for more discussion on the Pivot receiver).

The InFocus Balloon payload was flown twice from Fort Sumner, New Mexico, in FY 2004. Branch members supported field operations for the first flight. During the field operations several significant revisions were made on the pointing system design, including in-field implementation of a star camera/gyro control mode to complement the GPS pointing. The star camera was a piggyback experiment camera from the University of Pennsylvania designed to accommodate daytime star tracking. After extensive field testing and weather delays, the first InFocus flight was launched on May 31, 2004. Unfortunately, shortly after launch the telescope elevation drive was damaged from high loads after a hold-down cable was pyrotechnically released. The flight was terminated after a few hours of attempting to command a fix. The cause of the anomaly was further disguised by the damage caused by the parachuting of the gondola onto rocky terrain. Nevertheless, the principal investigator and his science team decided to return for a second campaign in August and September. FDAB members did not travel to the field but provided consultation support particularly for gyro alignment. The final configuration, having been greatly modified throughout the previous year, flew successfully on September 17, 2004, with long observations of significant X-ray targets, the results of which are now being studied. Despite the success, once again, the gondola and telescope suffered severe damage on landing. Nevertheless the science team tentatively plans to fly InFocus within two years on a long duration balloon.

Figure 2-3. InFocus readying for launch

[Technical contact: Dave Olney]

2.1.4 Gamma Ray Large Area Telescope (GLAST)
http://glast.gsfc.nasa.gov/

GLAST is planned for launch in February, 2007. During its mission lifetime, GLAST will perform a full-sky survey of the gamma ray field and will repoint to observe gamma ray bursts. Spacecraft orbit determination will be performed using a redundant pair of General Dynamics Viceroy GPS receivers.

The FDAB is involved in orbit and attitude analysis, design, operations, and on-orbit validation of the spacecraft. FDAB provided TDRSS and ground station view period analyses. Analysis was performed to show that Differenced One-Way Doppler (DOWD) can be used to validate the GPS receivers. GLAST orbital decay profiles were provided for altitudes in the range of 565 km to 600 km to aid in analysis of Kapton erosion rates. FDAB also worked with the Flight Operations Team (FOT) to design flight dynamics software for the MOC.

[Technical contact: Mark Woodard]

2.1.5 Global Precipitation Mission (GPM)

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

GPM is an international cooperative constellation of precipitation-measuring satellites. GPM will 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 fulfill its mission 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. The FDAB's contributions to the mission are in the areas of trajectory design, mission analysis, and attitude determination and control for the GPM primary spacecraft.

A major FDAB effort in the past year has been determining an optimal control box with respect to the following objectives: (1) minimizing orbit altitude variation; (2) minimizing delta-V; and (3) maximizing radiometer and radar coverage. The final goal of this study is to help the science team choose a control box size that will provide the maximum science return while satisfying the mission constraints, such as power and thermal constraints.

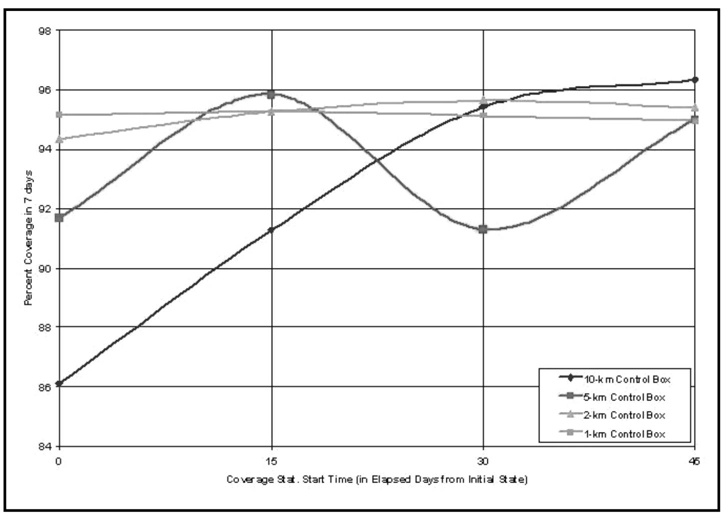

Figure 2-4. Cumulated Earth coverage for 7 days as a function of the starting time for the different control boxes

Other orbit-related analyses that the FDAB has performed over the past year for the GPM Project include optimization of the GPM constellation for science; TDRSS coverage during insertion, descent, and mission orbit phases; ground operations concept; mission lifetime drag studies; radar footprint coverage analysis; and autonomous orbit maintenance strategies.

Another major FDAB effort is the design and development of GPM's ACS, which will be flown onboard as part of the flight software. The ACS consists of the logic and algorithms required to keep the spacecraft within its pointing requirements for each control mode throughout the mission's lifetime. In FY 2004, the analysis team worked with the Project and other subsystems to develop a design that will meet all mission requirements, designed the control modes and gains, and began the stability analysis for each mode. The team also provided feedback to the Project on requested information and studies, such as actuator sizing, sensor configuration and location, slew requirements, error budgets and other attitude related analyses. The culmination of the attitude team's work is an algorithms document that software personnel will use to integrate the ACS into the flight software, and an ACS requirements and specifications document, which references all the ACS-derived requirements and design practices that went into the ACS design.

[Technical contacts: Chad Mendelsohn, Joseph Garrick]

2.1.6 Geostationary Operational Environmental Satellite (GOES) – N

The GOES-N launch is planned for the first quarter of 2005. Unlike previous GOES missions, the FDF will not have primary support for launch and early orbit (L&EO) flight dynamics (FD) activities and will instead serve as consultants to the GOES Project while Boeing Satellite Systems (BSS) performs the FD work for L&EO.

The GSFC FD Team has been preparing for this role by reviewing the nominal BSS profile and performing any mission analysis, such as ground station coverage and ascent profile validation, that is requested by the GOES Project. Task personnel have worked with the Network Support Manger to help secure the Universal Space Network (USN) as a backup to GOES-N's primary ground network, JPL's DSN (26-meter Subnet). Telemetry and command services will be supplied to the BSS Flight Dynamics System (FDS) at Suitland Spacecraft Operations Control Center (SOCC) and tracking data will be supplied to the FDF. The FDF will incorporate both the DSN and USN data into "shadow" orbit determination solutions that will be available to BSS on request. While the FDF will perform orbit determination at GSFC, other members of the FDF team will be resident at SOCC to monitor BSS FDS operations and serve as consultants to the Project.

Following L&EO support, which will cover about 24 days, the FDF will become prime for orbit determination and acquisition data generation and delivery during the GOES-N Post Launch Testing (PLT) period, which covers about 45 days. FDF will aid in several of the PLT scenarios as the NOAA Orbit and Attitude Tracking System (OATS) undergoes its final checkout. At the completion of testing, OATS will be able to assume full responsibility for GOES-N FD operations.

FDF has one additional responsibility on this mission. A new DSN frequency ranging system is being installed at the NOAA Command and Data Acquisition station at Wallops Island, Virginia. The FDF has been tasked to help certify the operational integrity of this system.

[Technical contact: Robert DeFazio]

2.1.7 Hubble Robotic Vehicle (HRV)

HRV was conceived when NASA decided, after the *Columbia* accident, not to use the Space Shuttle for a fourth Hubble Space Telescope (HST) servicing mission. The HRV's mission is to autonomously rendezvous with, grapple via a robotic appendage, and berth with the Hubble Space Telescope. Upon completion of a successful berthing to the aft of HST, the HRV will attempt a complex set of servicing tasks intended to extend the usable lifetime of the telescope. These services include battery augmentations, gyro replacement, Cosmic Origins Spectrograph (COS) instrument replacement, and Wide Field Camera 2 installation. When servicing is complete, the Ejection Module (EM) component of the HRV will separate from HST and de-orbit. The compact Deorbit Module (DM), which remains attached to HST, will ultimately be used to dispose of the telescope some time in the next decade.

Figure 2-5. A rendition of the HRV attached to the HST

The autonomous rendezvous and capture (AR&C) relies upon a suite of relative navigation sensors, mostly unproven for this application. The system requires two independent sensors in each of the various operational ranges (relative distances from HST). The baseline compliment includes Optech's *Relavis* Laser Detector and Ranging (LIDAR), Sandia's HST Laser Dynamic Range Imager (HLDRI), Lockheed's camera-based Natural Feature Image Recognition (NFIR) and Enhanced Auto-track Computer Vision System (EAVCS).

The servicing will be accomplished using a dual-appendage dexterous robot, originally designed and built by the Canadian based MacDonald-Dettwiler Robotics (MDR), and a suite of mission specific tools. The Special Purpose Dexterous Manipulator (SPDM) was originally built for NASA and intended to be used in conjunction with the International Space Station's remote manipulator. MDR will also be the manufacturer of the custom Grapple Arm (GA), based on a modification of the Shuttle Remote Manipulator design, that will autonomously capture HST.

Due to the predicted rate of decay in HST's battery capacity, a launch date of Decmeber 2007 has been selected for the HRV– less than four years from project inception. In order to meet the mission's significant technical challenges and aggressive schedule, the HRV project has recruited a large number of team members from the public and private sections. They include but are not limited to: GSFC, JSC, MSFC, Lockheed-Martin Services, Draper Labs, MDR, Sandia National Laboratories, Orbital Sciences Corp., Swales Aerospace, Jackson & Tull Engineering, and University of Maryland.

The FDAB has been involved with this mission since its inception. At the very early stages, Code 595 has provided orbit decay analysis, tumble rate predictions (assuming an uncontrolled Hubble), and AR&C feasibility studies. Code 590 personnel also provided the GNC designs for the straw-man concept and participated on the source evaluation board for the primary contractor selection.

The current responsibilities for the FDAB include the trajectory planning, complete GNC design of the EM, verification of the robotic tasks servicing dynamics, and mission GNC performance analysis and verification. To address these tasks Code 595 personnel have developed high performance simulations of the vehicle dynamics and control. The *Freespace* simulation environment is a GSFC-developed tool that provides advanced simulation features such as 128-bit precision, multi-processing, advanced integrators, a MATLAB™ compatable script parser, and scene graph visualization using OpenGL Performer™ and hard real-time capability. Current plans are to evolve this system, with its high-fidelity HRV models, into a component of the hardware-in-the-loop test lab, man-in-the-loop trainer, and HRV ground system.

[Technical Contact: Steve Queen]

2.1.8 James Webb Space Telescope (JWST)

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

JWST is planned to be launched in 2011 to the Sun-Earth L2 libration point. JWST just recently completed its Mission, Spacecraft and Ground System Requirements Review (SRR). In addition, a Flight Dynamics Peer Review was held in August, 2004.

A number of design, requirement, and operations-concept changes have been incorporated since the original Northrop Grumman proposal:

- Increased number of stationkeeping maneuvers to eight per revolution (every 22 days)
- New sun shield design – smaller, less solar torque
- Requirement for only one momentum unload within each tracking arc
    - Approximately 11-day frequency
    - Enables accurate OD without the use of accelerometer
    - Requirement placed on STScI (observation scheduling)
- Requirement for telemetry on spacecraft attitude and propulsion system to FDF
    - Used for momentum unload and SRP modeling and calibration
- Requirement for reorientation of spacecraft prior to momentum unloads
    - Minimized stationkeeping delta-V

The changes have led to a robust design and ops concept that meet all mission requirements. The fuel mass budget also is consistent with the current operations concept.

A number of important issues still remain to be resolved. The first is the issue of spacecraft venting. Instrument venting will affect early orbit determination and will induce torques that will increase the frequency of momentum unloads. The effects and design impacts of this venting are still being analyzed. The second issue is the desire not to have a burn towards the Sun. This has been accomplished for all but the first correction maneuver. The JWST FD team will perform trade studies for the first maneuver because the burn constraint affects launch opportunities and fuel mass. The last issue is the mission orbit size. No current requirement limits the size of the orbit about the Sun-Earth L2 point. A current trade team is being formed to analyze the impacts of restricting the mission orbit size. This trade will also affect launch opportunities and/or fuel mass.

[Technical Contact: Mark Beckman]

2.1.9 Lunar Reconnaissance Orbiter (LRO)

http://centauri.larc.nasa.gov/lro/

LRO will be the first US mission to the moon since the 1997 Lunar Prospector mission. The current LRO baseline is a mean 50-km circular polar orbit. LRO has just released an Announcement of Opportunity (AO) for instruments. It is expected that three to five instruments will be selected.

A key design criterion for LRO is the altitude control box. Mean altitude varies due to lunar non-spherical gravity effects. The FDAB has designed a control algorithm that optimizes fuel usage while achieving a desired altitude control constraint. The required fuel mass to meet constraints of +/-5, 10, 15 and 20 km has been developed. Figure 2-6 shows the altitude of LRO for a +/- 10 km control.

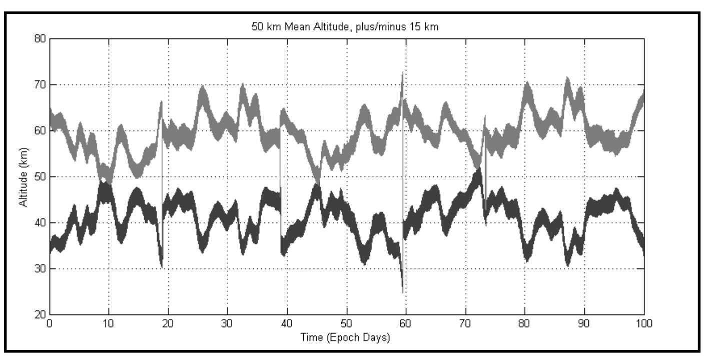

Figure 2-6. Apoapsis/Periapsis Altitudes with +/- 10 km Control

Orbit determination for LRO will be challenging. At 50 km altitude, lunar gravity is the leading source of orbital uncertainty. Based upon current tracking systems and models, LRO is expected to achieve a total position uncertainty of 500 meters with 18 meters of that being a radial uncertainty to the lunar surface.

[Technical Contact: Mark Beckman, David Folta]

2.1.10 Magnetospheric Multiscale (MMS) Mission

http://stp.gsfc.nasa.gov/missions/mms/mms.htm.

MMS is part of the Earth Sun System program, one of the science themes of NASA's Science Mission Directorate. The major focus of the Sun-Earth Connection program is investigating the physical processes that link the Sun and the Earth. MMS is a four-spacecraft solar-terrestrial probe designed to study magnetic reconnection, charged particle acceleration, and turbulence in the key boundary regions of the Earth's magnetosphere. An Announcement of Opportunity for the instrument complement and principle investigator teams was released in January 2003. Two proposal teams responded and in September 2003, both teams were selected for further refinement of their mission concept. Final selection of one team is expected in early 2005. More details about the mission can be found at the Web site provided above.

During 2004, both proposal teams requested technical assistance in matters related to the trajectories. Branch personnel were precluded, due to the proposal-process rules, from proposing a trajectory design but were permitted to provide answers to specific technical questions from the proposal teams. After the final proposals were submitted, branch personnel participated in a technical review of the proposals, and provided comments that the advisory panel used in developing its report.

The MMS navigation team delivered *Magnetospheric Multiscale Mission Phase 2; Navigation Performance Analysis*, which provides a thorough analysis of the absolute and relative navigation accuracy achievable for the MMS Phase 2 formation using ground station range and two-way Doppler measurements, GPS pseudorange measurements, cross-link range measurements, and various combinations of these different measurement types. The team also delivered *Magnetospheric Multiscale Mission Phase 4; Navigation Performance Analysis*, which provides a thorough analysis of similar candidate navigation scenarios that are consistent with the use of the proposed Inter-spacecraft Ranging and Alarm System (IRAS). This work identifies and compares several ground-based and onboard navigation support scenarios that can satisfy the absolute and relative position accuracy requirements to meet the MMS Phase 2 and Phase 4 science objectives. This work provides a foundation for the selection of the navigation system by the MMS flight project in the future. The team wrote and presented the technical paper "Relative Navigation Strategies for the Magnetospheric Multiscale Mission" at the 18th International Symposium of Flight Dynamics held in Munich Germany October 11-15, 2004. This paper summarized the results of several navigation approaches for Phases 1 and 2 of the MMS mission that the team has performed.

[Technical Contacts: Charles Petruzzo, Russell Carpenter]

2.1.11 Solar Dynamics Observatory (SDO)

The SDO mission, part of the Living With a Star Program, is slated for launch in 2008. It will observe the Sun with three instruments from geosynchronous orbit over a period of five years.

2.1.11.1 SDO Trajectory Design

The trajectory team has planned a preliminary L&EO profile to help answer many questions from spacecraft subsystem designers. Although the launch vehicle has not been selected, the decision will be between a Delta IV and an Atlas V and is expected well before the spacecraft CDR in April, 2005. Other mission analysis studies such as high gain antenna visibility, omni antenna coverage, star tracker interference, and lunar shadow occurrences and durations have been performed to answer project questions and points of interest.

In addition to mission analysis, the SDO trajectory team is heavily involved in refining the critical design of the Flight Dynamics System (FDS). This system, which is mainly resident in the MOC, will be used to perform most trajectory-related computations in all phases of the mission. Orbit determination will be performed by the FDF at Goddard. The FDF is the center of orbit determination expertise at GSFC and will provide orbit solutions to the SDO FDS/MOC.

Three documents describe the FDS design and interface agreements. The SDO FDS System Description and Design Document maps the SDO FDS Level 4 requirements into the FDS software. Any requirements, which will necessitate software modifications or new development, are noted. Also, the inputs and outputs related to each required task are documented. The SDO FDS to Ground System Interface Control Document (ICD) details the formats and delivery information for all FDS products. The SDO FDS/MOC to FDF Interface Agreement Document (IAD) details functions and deliverables between the FDS/MOC and the FDF. Drafts of all three documents were completed by the end of FY 2004 and will be boarded with the project's Configuration Control Board (CCB) before the Project CDR.

2.1.11.2 SDO Attitude Analysis

SDO provides a wealth of engineering challenges from an ACS perspective: the need for highly stable pointing accuracies of 1-2 arcseconds with respect to the Sun and the need to guarantee smooth transitions between inertial sensors and Sun pointing guide telescopes are two examples of the problems being solved by FDAB engineers.

The fall of 2003 saw typical linear analysis and nonlinear simulation combined with flight software interface efforts and deployables reviews in preparation for the December, 2003, PDR. A trade study for safe-hold mode resulted in a gyroless controller design for safe-hold. Flight software requirements definitions and algorithms, including sensor data processing, controllers and estimators, and high-accuracy ephemeris, have been in constant development and refinement over the course of the year. Most recently, flight software engineers have worked with analysts to define telemetry packets and some preliminary fault detection and correction schemes.

A high-fidelity (HiFi) simulator has been developed using the Simulink development tool. This HiFi serves a dual purpose: to provide time-domain simulations as verification of all algorithms and analyses and to establish Real-Time Workshop models from which the core ACS control algorithms may be automatically converted to flight code.

The analysis team supported discussions concerning GNC-related hardware, including the propellant tank and propellant management device, the instrument guide telescopes, star trackers, reaction wheels, and other GNC items. Component specifications and statements-of-work were written and sent out, and analysts participated in the instrument interface working group meetings in May, 2004, and August, 2004, to assist with the extremely complex pointing budget required for such stringent goals.

ACS analysts provided substantive assistance on the topic of high-frequency dynamics (i.e., jitter). FDAB analysts aided the development of requirements at the Observatory system level, provided estimates that prove jitter requirements will be met, and supported other subsystems (e.g., mechanical, high-gain antennas) both in definition of their requirements and in forming performance estimates. SDO instruments will be highly sensitive to jitter—pointing stability/jitter has been one of the top five driving requirements throughout SDO development—so detailed mechanical models and end-to-end dynamical analyses are required to guarantee successful performance.

[Technical contacts: Robert L. DeFazio, Scott R. Starin]

2.1.12 Space Technology (ST5)

http://st5.gsfc.nasa.gov/

ST5 is a mission in the New Millennium Program and NASA's first experiment in the design of miniaturized-satellite constellations. The mission will last 90 days. During this time the constellation of three spin-stabilized spacecraft will validate new technology for spaceflight while demonstrating formation flying capabilities. Technologies to be validated include a miniature cold gas thruster, an x-band transponder, flexible interconnects, variable-emissivity coatings, ultra lower-power logic, autonomous constellation management ground software, and various technological improvements embedded in the spacecraft itself.

In January, 2004, Orbital Sciences Corp.'s Pegasus XL launch vehicle was selected to deliver ST5 to orbit. The performance of the Pegasus XL is dramatically less than what the mission had originally planned to receive from its launch vehicle. Therefore the GNC team identified an entirely new orbit regime to accommodate the ST5 mission. Numerous iterative consultations with the project's science team and systems engineering team resulted in redefined science and mission requirements, eventually driving the design of the mission to its current orbit.

The ST5 GNC team evaluated the new mission requirements and re-designed an orbit and constellation scheme to satisfy those new requirements. ST5 has a 300 x 4500 km orbit with a sun-synchronous inclination of 105.6°. A 06:00 GMT descending-node crossing time was selected to keep the orbit in full sun for the duration of the mission.

In 2004, the following reviews were supported by the ST5 GNC team:

- Orbital / KSC Technical Interface Meeting, January 15, 2004
- Delta-CDR, July 21-22, 2004
- Mission Operations Review, September 14-15, 2004
- Orbital / KSC Mission Interface Working Group conference, September 30, 2004

The ST5 GNC team has developed a maneuver plan to validate onboard thrusters and deploy the constellation to two predefined formations over the 90-day mission. This plan will obviate the need to precess the attitude of each spacecraft before and after each orbit maneuver, which will simplify operational support and ultimately save propulsion.

[Technical Contact: Marco Concha, Mark Woodard]

2.1.13 Space Technology 7 (ST7) Disturbance Reduction System (DRS)

http://nmp.jpl.nasa.gov/st7/

The ST7 DRS is a project within the New Millennium Program with a mission objective to test two advanced technologies: Gravitational Reference Sensor (GRS) and colloidal micronewton thrusters (CMNT). ST7 is scheduled to fly in 2008 as an instrument package aboard ESA's SMART-2: LISA Pathfinder spacecraft, which will orbit around the Sun-Earth L1 Lagrange point. Technical objectives of this mission include validating that a test mass follows a trajectory determined by gravitational forces within 3×10^{-14} x $(1+(f/3\ \mathrm{mHz})^2)\ \mathrm{m}/(\mathrm{s}^2\sqrt{\mathrm{Hz}})$, and obtaining spacecraft position control to an accuracy of less than 10 nm/$\sqrt{\mathrm{Hz}}$ within the measurement band of 1-30 mHz. ST7 is a joint venture consisting of JPL, Stanford University, Busek Co., Inc., and GSFC. The responsibilities of the FDAB to the project include the development of the Dynamics Control System (DCS) that controls the spacecraft position and attitude to establish drag-free motion of the test masses within the GRS units, development of a full nonlinear dynamic model of the spacecraft and test masses (Hi-fidelity simulation model), and generation of flight code for the DCS.

ST7 consists of two GRSs with internal free-floating cubic test masses, designed to follow gravitational trajectories, and two clusters of four thrusters for spacecraft translational and rotational control. The DCS is responsible for using star-tracker data and GRS data to generate commands, which are DCS-mode dependent, for the thrusters. Five operational modes exist within the DCS: attitude-only mode, accelerometer mode, initial drag-free mode, interim drag-free mode, and full-drag free or science mode. In the science mode, the DCS centers the spacecraft in translation about the reference test mass and centers the spacecraft in the transverse axis about the non-reference test mass using spacecraft rotation in the measurement band. Control for test masses' relative attitude and non-reference test mass's position in the sensitive axis is provided by the GRS suspension loop. A representation of the ST7 mission is shown in figure 2-7.

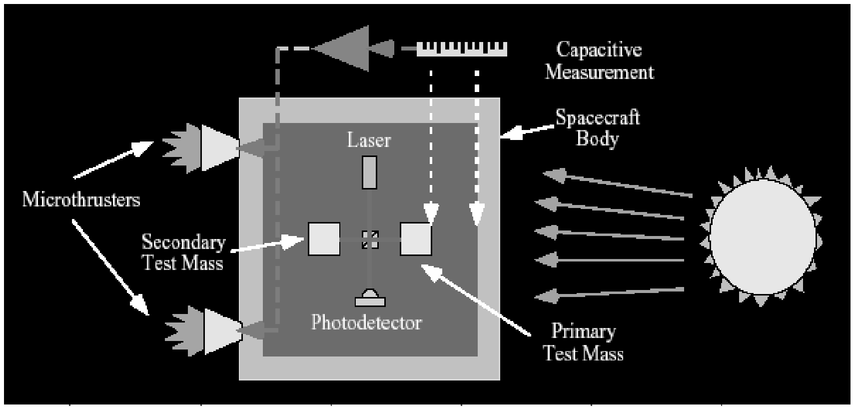

Figure 2-7. ST7 Mission Representation

During FY 2004, the FDAB accomplishments include:

- Delivery of DCS Flight Software Builds 0.1, 1.0, and 2.0.
- Developed and tested mode transition strategies.
- Completed controller designs.
- Presented papers on ST7 at GSFC Flight Mechanics Symposium, AIAA Guidance Navigation & Control Conference in Providence, RI, and the 49th Annual SPIE Conference.
- Successfully held DCS CDR at GSFC.
- Supported other ST7 subsystem CDRs.

[Technical Contact: Oscar Hsu]

2.1.14 Swift

http://swift.gsfc.nasa.gov/

Swift was launched in November of 2004. The FDF will provide support to the Swift mission during the first week of operations. FDF support will include delivery of Swift ephemerides, local oscillator frequency reports, and acquisition data for the Space Network (SN). These products are made available to the Swift MOC via the FDF Product Center Web site. Detailed requirements between the FDF and the Swift project are documented in the Memorandum of Understanding (MOU) between the FDF and the Swift MOC.

FDF performed C-band radar site selection and coverage analysis to augment SN tracking support during the early orbit period. C-band radar sites ASCQ, KMRQ and KPTQ have the best Swift coverage after separation and will provide angle and range tracking data on launch day for critical initial orbit determination and ephemeris generation.

FDF has supported pre-launch testing with the SN as well as two interface tests with the MOC. Past and future simulations include the support of nominal and contingency L&EO periods. FDF has also consulted on flight dynamics issues of relevance to FOT operations.

[Technical Contact: Mark Woodard]

2.1.15 Time History of Events and Macroscale Interactions during Substorms (THEMIS)

http://sprg.ssl.berkeley.edu/themis/Flash/THEMIS_flash.htm

The THEMIS mission is a NASA Explorer Program mission set to launch in mid-2006. The THEMIS spacecraft is being built by Swales Aerospace under contract to the University of California Berkeley. THEMIS is a formation of five spacecraft in various highly elliptical Earth orbits. The five probes will have apogee radii of 10 to 30 R_e (Earth radius). The periods of the probes will be one, two and four days, allowing the probes to align at apogee during conjunction.

The FDAB is providing consultation and software support to the THEMIS project. This support includes orbit determination, maneuver planning and attitude determination software and training UCB personnel in its use. FDAB personnel also serve on the NASA Review Panel evaluating THEMIS progress.

THEMIS completed their CDR and subsystem peer reviews in 2004.

[Technical Contact: Mark Beckman, Robert DeFazio, Richard Harman]

2.2 Operational Missions

2.2.1 EOS Aura

http://eos-aura.gsfc.nasa.gov/

The Aura spacecraft successfully launched from the Western Test Range aboard a Delta 7920 rocket on 15 July 2004 at 10:01:59.364 GMT. Aura is 3-axis stabilized and operates in a near-circular, 705-km altitude, sun-synchronous polar orbit with ascending nodal crossings at 1:45pm +/- 15 min solar mean local time (MLT). Aura is flying in the ESMO Afternoon Constellation behind EOS Aqua and is positioned such that Aqua's nadir FOV intersects the Aura's atmospheric limb FOV. This viewing intersection imposed two additional requirements on Aura's orbit: a separation of 8-15 minutes later than Aqua in MLT, with a goal of 8 minutes, and a separation of 15-22 minutes later in along-track, with a goal of 15 min. The FDAB has responsibility for all Aura flight dynamics work until mid-November 2004, when the FOT will take over routine operations; FDAB personnel will continue to be responsible for maneuver planning and calibration and will be available for contingency support throughout the six-year mission lifetime. The FDF will also continue to provide orbit determination services for the duration of the mission.

In FY 2004, FDAB provided both pre- and post-launch support for Aura. Pre-launch activities included performing attitude and orbit analyses, presenting at mission-level reviews, testing the Aura Flight Dynamics System (FDS), participating in mission simulations and readiness tests, and the drafting and updating of various requirements and documents. L&EO operations support is being provided in four key areas: maneuver planning and calibration, attitude determination and calibration, product generation, and orbit determination.

Maneuver support has consisted of ascent and inclination maneuver planning. The maneuver team planned the 6 orbit-raising maneuvers, which moved Aura from its injection orbit to its mission orbit rendezvous with Aqua. To better predict maneuver performance, the maneuver planning employed lessons-learned from Aqua's ascent; in particular, using the effects of orbital position and solar-array angle on thruster duty cycles. The maneuvers were very repeatable and were each calibrated to within the stated accuracy of the control system. Once Aura achieved mission orbit the two spacecraft had an ascending node MLT separation of 8.25 min and an along-track separation of 15.74 min, well within the stated requirement. Figure 2-8 shows the ground-track error relative to the control box limits throughout the ascent maneuver phase.

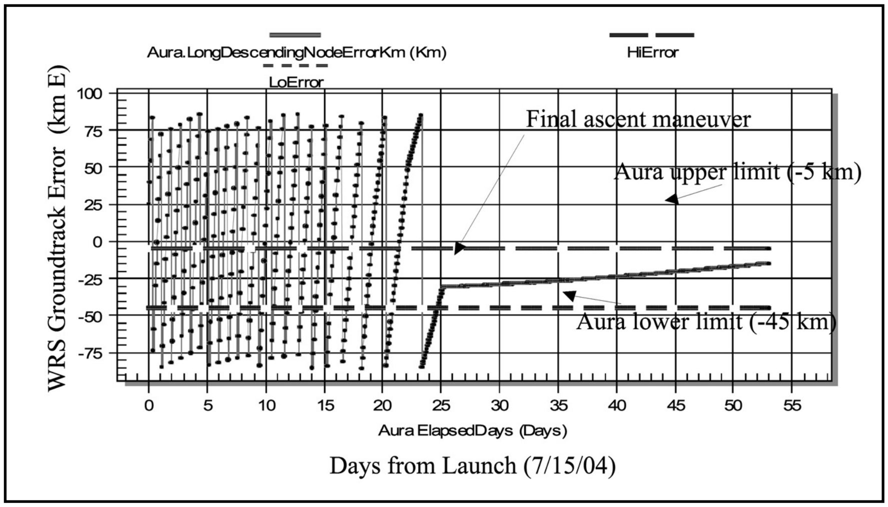

Figure 2-8. WRS Error During Ascent Relative to Control Box Limits

Aqua completed a series of inclination maneuvers in the Fall 2004. To maintain proper constellation configuration, the Aura maneuver team planned 4 maneuvers designed to match Aqua's inclination adjustment and to minimize semi-major axis changes. Figure 2-9 shows the Aqua and Aura inclination change plans.

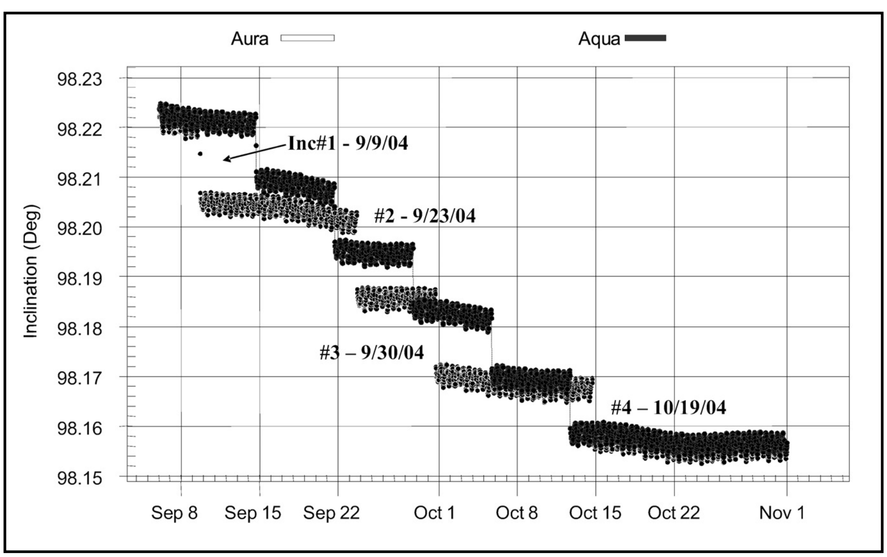

Figure 2-9. Inclination Adjust Maneuver Plan

The attitude team has performed various calibrations, improvements, and analyses to date. Determining coarse magnetometer biases improved the yaw-pointing performance in Earth Point Mode by 7-10°. Fine magnetometer calibration assessed and showed the effects of induced magnetic fields caused by internal power loads. Gyro alignment and scale factor calibration was completed with data from dedicated attitude maneuvers. Star tracker calibration revealed the relative alignment between the two trackers to be ~60 arcseconds different from pre-launch alignment due to launch shock and ground alignment measurement limitations. The team will provide updates for onboard gyro and star tracker parameters if necessary. Emergency support for roll-rate phasing requirement in Sun Point Mode was quickly provided to address new science instrument thermal requirements. Attitude histories were provided to the thermal engineers to help improve their instrument models. The calibration of a science instrument's gyros was not completely successful due to the observed instrument gyro performance characteristics. An investigation of stars with large position residuals in onboard attitude determination exposed problems with the onboard and ground star catalogs for Aura (and Aqua). In a particular case examined, a variable star, faint in the visual magnitude (Mv) passband but relatively bright in the star tracker passband, was close enough to the onboard catalog star to offset the observed position of the catalog star by 41 arcseconds. Analysis showed that up to 10% of the onboard catalog stars (~330 stars) could suffer to varying degrees from similar effects. The effect on Aura onboard attitude determination is still under investigation.

The products team used the FDS in the EOS MOC to generate the planning and scheduling data for the FOT and instrument teams as dictated by the FDS requirements. Collision avoidance computations were obtained from US Stratcom and evaluated by the FD team throughout the ascent and inclination-adjust phases. The products team also provided training on routine FDS operations for the FOT.

[Technical contacts: Lauri Newman, David Tracewell]

2.2.2 Gravity Probe-B (GP-B)

GP-B is a relativity gyroscope experiment that was developed by NASA and Stanford University to test two unverified predictions of Albert Einstein's general theory of relativity. GP-B launched successfully from Vandenberg Air Force Base on April 20, 2004. FDAB support was provided through the FDF.

FDF and FDAB personnel worked with the GP-B team to define the FDF's role and responsibilities for GP-B. FDF participated in pre-launch simulations, provided launch support, and provided OD and acquisition data to the GP-B MOC. During early orbit operations, the FDF confirmed an orbit perturbation that was later determined to be caused by excess spacecraft venting. SN center frequency updates were provided after GP-B began having acquisition problems after launch. The FDF provided extended orbital support during GP-B's initialization and orbit check-out phase due to the anomalistic venting on-board the spacecraft and problems with gyro spin-up. Additional support included orbit determination, updating the GN and SN with daily acquisition data updates, and providing one-line summaries for GP-B MOC planning.

The FDF recently provided orbital updates due to stale two-line elements (TLE) caused by GP-B orbit perturbation. The FDF provided updated GN acquisition data after reports of excessive data loss due to the TLE inaccuracies. In addition, the FDF sent GP-B MOC FDF orbital solution for comparison to GPS solutions.

The FDF continues to monitor GP-B as a part of its routine operation.

[Technical Contact: Anne DeLion]

2.2.3 Hubble Space Telescopre (HST) Two-Gyro System (TGS)

https://edocs1.hst.nasa.gov/

The HST Project and Lockheed Martin have nearly completed a pointing control system for HST which requires only two gyros. In development for one year, the TGS may become necessary; only three of the original six gyroscopes of the Rate Sensing Units are still working (a fourth is demonstrating an unstable bias). The TGS comprises a sequence of sub-mode controllers - progressing from magnetometers (M2G) to star trackers (T2G) to, finally, the fine guidance sensors (F2G). Rate estimates for the missing third axis are derived from these attitude sensors.

The TGS is expected to provide a pointing stability of 10-20 milliarcseconds, compared to the current 7. The controllers show adequate single axis stability margins of 9 dB and 30 deg. A set of enhancements, such as operating with a single fine guidance sensor and modifying F2G acquisition logic for increased robustness against guide star loss-of-lock, will be studied in the upcoming “phase 2”.

Final algorithms will be delivered to the Lockheed Flight Software Group by Oct 15, 2004. An on-orbit test of the TGS is planned for February 2005. Investigation into the feasibility of a one-gyro system is beginning. FDAB personnel are working closely with Lockheed Martin and HST Project personnel to develop these algorithms.

[Technical Contact: Michael Femiano]

2.2.4 LandSat-7

http://landsat7.usgs.gov/index.php

LandSat-7, launched in 1999, is a three-axis-stabilized, Earth-observing spacecraft in a circular, Sun-synchronous, near-polar orbit at a nominal altitude of 705 km. The design mission lifetime is five years. LandSat-7’s orbit is a prime Earth-observing orbit; other missions in that orbit include EOS Terra and EO-1. One of LandSat-7’s three gyros on indicated a possible failure in the near future. On May 5, 2004, the USGS decided that the safest course of action was to turn off the failing gyros and switch to the redundant gyros to continue taking science data. A major concern was that if another gyro failed, then it might not be possible to lower the spacecraft out of the 705-km constellation. The spacecraft would then be taking up valuable “real-estate” in the orbit and it may become a collision hazard for other spacecraft.

At the request of USGS, the FDAB performed a brief analysis to determine how much to lower Landsat-7's altitude to safely move it out of its orbit. The original desire had been to drop Landsat-7 about 5 km in altitude to effect possible repairs to the spacecraft and then restore it to its nominal orbit. The analysis, however, showed that it would require a decrease of almost 20 km to remove LandSat-7 completely from its science orbit. At the time results were presented, a 20km decrease in altitude was thought to be unfeasible.

A later analysis request from ESMO studied the no-burn orbital decay rate of LandSat-7. An orbit propagated for one year with no drag modeled approximated the spacecraft staying in its nominal orbit with ground track control. A second propagation was made with drag modeled and no ground track control. Comparison of the two propagated orbits showed that Landsat-7 would be safely out of the 705-km orbit range in about 5 months. If Landsat-7's orbit were allowed to decay in this way, then the orbit should be monitored for close approaches with other sun-synchronous spacecraft during those 5 months. Any spacecraft in danger of colliding with Landsat-7 would have to take evasive action.

The FDAB also assembled a brainstorming team to explore new ways of continuing the mission and to decommission the spacecraft when necessary. The team came up with about a dozen concepts. Cost and schedule reduced the concepts down to deriving rates using the Earth sensor, magnetometer or the coarse Sun sensors. A software module will be developed that will continually derive the rates from the selectable sensors and be monitored from the ground. This derived rate can be switched into any control mode on the spacecraft.

[Technical contacts: Dave Mangus, Robert DeFazio, Karen Richon]

2.2.5 Rossi X-Ray Timing Explorer (RXTE) Tracker Anomaly

RXTE observes various high-energy sources, with a large angle slewing and 1-arcsecond attitude control system. The primary attitude references for this ACS are two CT-601 star trackers from Ball Aerospace. Since RXTE's launch in 1995, the trackers have performed well even with some initial loss-of-track anomalies that occurred immediately after launch and were subsequently repaired in flight software.

Recently one tracker has, on at least six occasions, exhibited spurious detections, which are indistinguishable from real star measurements, that appear in a single CCD column and are one arcminute wide. These readings are from tracker slots operating in 'search' mode rather than 'directed track' mode, the mode used for Kalman filter updates in Fine Pointing.

While the anomalous detections can affect the centroid calculation of a legitimately tracked star, they only minimally interfere with the essential attitude determination process and may, with further investigation, prove to be supressable with flight software filters. Spacecraft pointing capabilities are unaffected at present. Star-mapping activities in ground software have been disrupted by the anomalous data, as they are reliant on 'search mode' telemetry. The cause is unknown; one possibility is radiation damage to the CCD resulting in an increased charge transfer inefficiency. The investigations continue, with the participation of personnel from FDAB and other organizations.

[Technical Contact: Michael Femiano]

2.2.6 Tropical Rainfall Measuring Mission (TRMM)

http://trmm.gsfc.nasa.gov/

TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) and is designed to monitor and study tropical rainfall. TRMM was launched in November, 1997.

2.2.6.1 TRMM Reengineering

The purpose of the TRMM re-engineering effort was to move most of the flight dynamics (FD) functions into the TRMM MOC using both COTS and GOTS software packages. TRMM's reengineering effort led to automated FD functions and streamlined operations, both of which reduced the overall satellite operations costs and increased the system's reliability. The Autonomous Flight Dynamics System (AutoFDS) was used to automate FD functions for TRMM. The products are scheduled in AutoFDS and automatically generated using tools such as FreeFlyer, Matlab, and Excel. Products include station contacts, TDRS contacts, node crossing, shadow times, maneuver planning, etc.

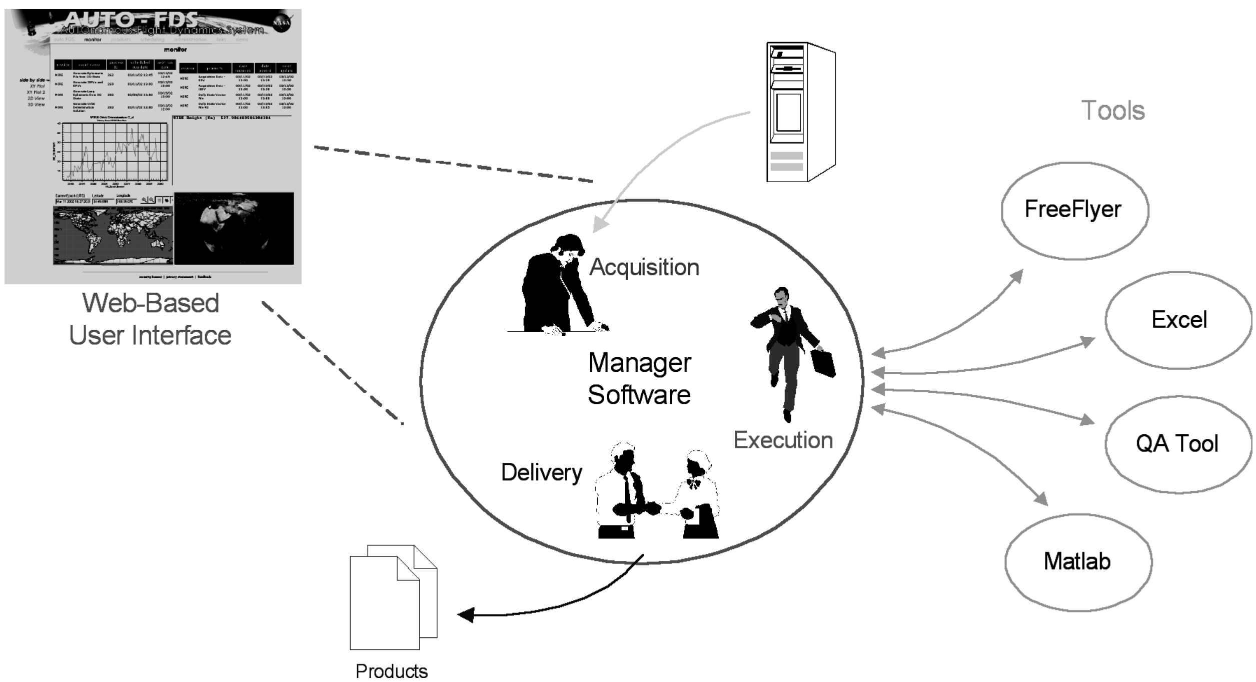

Figure 2-10. AutoFDS

COTS applications were used for the new TRMM FDS, as this is standard for most Earth Observing System (EOS) missions. The TRMM reengineering effort used FreeFlyer for planning and maneuver products generation and Matlab for attitude products generation. The Quality Assurance (QA) tool was used for the QA of all flight dynamics products generated by TRMM AutoFDS. The transition to the new TRMM AutoFDS in the MOC was accomplished in three phases to minimize risk to mission operations support. Phase 1 consisted of moving the scheduling/planning functions into the MOC while Phase 2 and 3 consisted of moving the maneuver and attitude functions respectively.

The TRMM AutoFDS went through the acceptance, integration, and parallel operations testing that allowed the system to be certified for operations support. A Real-time Attitude Determination System (RTADS) front-end socket connection (TPOCC server) was also developed and installed in the MOC computers. This connection allows the TPOCC telemetry data to be properly placed in the appropriate arrays and later ingested by RTADS. A version of the Multimission Three-Axis-Stabilized Spacecraft (MTASS) attitude determination system was also developed and installed in the TRMM MOC. An Operational Readiness Review was held on December 8, 2003 before the new TRRM AutoFDS system was accepted and approved for operations. Since January 6, 2004, the TRMM AutoFDS system has successfully provided Flight Dynamics support in a lights-out environment.

[Technical Contact: Osvaldo O. Cuevas]

2.2.6.2 TRMM Reentry Planning

FDAB personnel continued the development of a controlled reentry plan for the TRMM spacecraft. In January 2004, a MESA-led independent evaluation of TRMM's controlled reentry reliability showed that TRMM could continue science operations for two more years without reducing its reentry reliability. The solar array drive was identified as a credible single point failure. In response to this and to concerns about the approximately three-year-long descent phase, the GNC team investigated different solar array configurations and discovered that an "X-wing" configuration (arrays at ± 45 degrees) would reduce the descent time to about two years and also eliminate the solar array drive single point failure. The GNC team started to prepare for controlled reentry in March, 2004, but this was complicated by the failure of the –Y array in the spring of 2004.

The FDAB team supported a GNC peer review of the reentry plan in June, 2004. The team presented a mature reentry plan, contingency flowcharts and procedures, nominal and contingency burn plans and orbital analysis, and a well-validated simulator to perform simulations with the new solar array configuration. The team solved algorithm and modeling problems in various simulators, updated the Solar Pressure and Aerodynamic Drag (SPAD) model of TRMM, solved the hangoff and attitude drift errors appearing in the thruster modes, and created test procedures, new telemetry plots, and commit and abort criteria. Orbit maintenance maneuvers were discontinued in July 2004 to start the drag-down phase of the reentry plan, but after negotiation with NASA, NOAA provided funding to continue operations through January 1, 2005, in order to provide data during the 2004 hurricane season; orbit maintenance maneuvers resumed in August, 2004. Reentry simulation support has begun and FDAB personnel have developed and provided products in support of those simulations. Preparations are also in work for support of a Code 300 review in late 2004 or early 2005.

In early 2005, the National Academy of Sciences will provide an evaluation of the value of the TRMM data versus the hazards of an uncontrolled reentry and make a recommendation either to continue the science mission or proceed with preparations for a controlled reentry. If the decision is made to end the science mission in January, the earliest that the final reentry operation would begin is July 2006 according to current estimates.

[Technical contacts: Frank Vaughn, Steve Andrews]

2.3 Flight Dynamics Facility (FDF)

2.3.1 FDF Overview

Goddard's FDF is a multi-mission operations facility that provides routine orbit, attitude and network support. Located in Goddard's building 28, the FDF has supported Goddard flight projects for more than 30 years. The FDF often provides operational services to non-Goddard projects as well, including launch support for both expendable boosters and the Space Shuttle, navigation support to National Oceanographic and Atmospheric Administration (NOAA) missions, and network acquisition data for non-Goddard NASA flight projects.

Prior to 2004, the FDF was operated under the Consolidated Space Operations Contract (CSOC) and was managed at Goddard by the Mission Services Program Office. In 2004, management responsibility for the FDF transitioned to the FDAB and contractor support for the facility is now obtained from the new Mission Operations Mission Services (MOMS) contract. This represents a significant change and was accomplished successfully with no interruption in service to operational missions.

Many challenges exist with the FDF. Cost reduction in operations is a major driver in reengineering operational processes as well as hardware and software systems. In 2004, attention was given to hardware upgrades and assuring security needs were met. In 2005, more attention will be given to retiring old software systems and initiating reengineering activities, especially with regard to the attitude support operations in the FDF.

Work within the facility is organized by functional area: attitude operations, orbit operations, expendable launch vehicle support, human spaceflight support, maneuver support, tracking data evaluation, software maintenance, and sustaining engineering activities. Accomplishments in each of these areas are discussed in the sections that follow.

[Technical Contacts: Tom Stengle, Sue Hoge]

2.3.2 Attitude Operations

The FDAB wrote the Statement of Work (SOW) and discussed the Task Implementation Plan (TIP) to ensure the FDF would provide the required attitude operations services. A task manager in FDAB worked closely with the Attitude Operations task leader throughout the year; the task support was excellent. Monthly task status meetings addressed monthly accomplishments, performance metrics, mission anomaly resolution, and other items. The SOW for 2005 was written. This task provided attitude determination, calibration, and product generation support for the ERBS, UARS, ACE, RXTE, SOHO, Wind, and Polar missions.

[Technical Contact: Mark Woodard]

2.3.3 Expendible Launch Vehicle (ELV) Support

The FDF ELV Support Task has successfully supported 15 missions since the beginning of the MOMS contract. 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 to date are listed below:

ELV LAUNCH LOG (2004)		
	DATE/EPOCH (Z)	LAUNCH
1	January 11, 2004 011/04:13:00.000	Sea Launch/Estrela doSul (SL-19)
2	February 5, 2004 036/23:46:02.651	Atlas IIAS/AMC-10 (AC-165)
3	February 14, 2004 045/18:50:00.948	Titan/IUS B-39 (DMSP-22)
4	March 13, 2004 072/05:40:00.844	Atlas IIIA/MBSAT (AC-202)
5	April 16, 2004 107/00:45:00.306	Atlas/Superbird-6 (AC-163)36B
6	April 20, 2004 111/16:57:23.754	Delta/Gravity Probe -B
7	May 4, 2004 125/12:41:59.000	Sea Launch/DirecTV (SL-21)
8	May 19, 2004 140/22:22:00.513	Atlas IIAS/AMC-11 (AC-166)36A
9	May 20, 2004 141/17:47:03.310	Taurus/ROCSAT
10	June 29, 2004 181/03:58:59.000	Sea Launch/SL-20 Telstar-18
11	July 15, 2004 197/10:01:59.344	Delta II/AURA (WR)
12	July 29, 2004 211/17:18:00.000	P-3/ARROW FT-1 (drop)
13	August 3, 2004 216/06:15:56.537	Delta II/Messenger
14	August 26, 2004 239/17:09:00.000	P-3/ARROW FT-2 (drop)
15	August 31, 2004 244/23:17:00.717	Atlas/NROL-1 (AC-167)

[Technical Contacts: Frank Vaughan, Michael Mesarch]

2.3.4 Human Spaceflight Support

The FDF supports both the Space Transportation System (STS) and the International Space Station (ISS). For both the STS and ISS programs, FDF personnel continued to evaluate potential risks to mission support and, as risks were identified, developed plans to mitigate those risks. Support items under continuous risk review include mission support personnel development and training, and FDF hardware and software diversity, redundancy, and reliability.

2.3.4.1 STS Support

During FY 2004, the FDF supported the STS Program's Return-to-Flight (RTF) efforts, which included full-up simulations with external mission support elements and both the Ground Network (GN) and Space Network (SN). These simulations exercised FDF pre-mission and launch support procedures. FDF personnel developed and conducted internal and FDF/SN-only proficiency simulations, as well as joint ascent-abort simulations with JSC. The simulations were designed to train new FDF Space Shuttle support personnel, as well as to rigorously exercise FDF and SN contingency procedures not typically exercised during the full-up network simulations. The JSC Flight Design and Dynamics Division levied a new requirement on the FDF by requesting that TDRS beam angle displays be provided via the Internet during Emergency Mission Control Center activation periods. This effort involved the development of new Space Shuttle display capabilities and is still on-going. FDF personnel also participated in integrated networks RTF meetings and reviewed STS program documentation, and provided input as needed. Personnel also supported the Network Support Group (NSG) meetings at JSC in March, 2004, and September, 2004.

2.3.4.2 ISS Support

The FDF supported two Soyuz crew rotation missions to the ISS; Soyuz 7S launched in October, 2003, and Soyuz 8S launched in April, 2004. The FDF also began preparations for supporting the Soyuz 9S mission, which is scheduled for launch in early FY 2005. FDF personnel supported several ISS orbit reboosts throughout the year, as well as testing of the United States's very high frequency (VHF)-1 and VHF-2 emergency communication systems. The first and only planned test of the VHF-2 system, performed in September, 2004, was successful and received pre-test approval from the FAA due to potential interference with commercial aviation. The JSC ISS personnel requested that the FDF analyze results from a test of the 150-megabit-per-second (mbps) K-band communication system; FDF presented the analysis results at the September 2004 NSG meeting. FDF personnel participated in teleconferences about ISS Backup Control Center operations and developed new FDF support procedures based on those discussions. The FDF continued to evaluate ISS tracking data and provided the networks with weekly local-oscillator-frequency reports. FDF personnel also reviewed documentation and participated in meetings to discuss support of the ESA's Autonomous Transfer Vehicle (first launch to ISS is planned for late 2005) and Japan's H-II Transfer Vehicle.

[Technical Contacts: John Lynch, Chad Mendelsohn]

2.3.5 Maneuver Operations

The FDF Maneuver Support Task, planned and monitored orbit maneuver operations on a complement of NASA spacecraft including WIND, POLAR, SOHO, Aqua, and ACE. The task also helped to troubleshoot anomalies occurring during orbit maneuvers. Since January, 2004, the task has performed the two maneuvers for WIND, three for SOHO, three for ACE, and one for Aqua. These maneuvers can generally be classed as station keeping or orbit maintenance maneuvers. Task personnel also supported recovery from a SOHO anomaly that occurred during a SOHO attitude maneuver. In that case, recovering from the anomaly involved an orbit adjustment.

[Technical Contacts: Robert DeFazio, Dave Quinn, Rivers Lamb]

2.3.6 Metric Tracking Data Evaluation

This task provides tracking network validation and calibration, STS support, ELV support, space mission support, and new tracking antenna certification support for missions supported by and tracking systems utilized by the GSFC FDF.

[Technical Contacts: Greg Marr, Sue Hoge]

2.3.7 Orbit Operations

FDF Orbit Operations supported over forty missions, which ranged from suborbital balloon missions to Earth-orbiting missions to libration point missions, in FY 2004. The Orbit group has continued providing excellent support to all flight projects while undergoing a significant contract change. They provide thousands of products each year, such as orbit determination (OD) products, station coverages, and various reference files, that require a high degree of automation and expertise when that automation fails. In addition to all its standard products and services, FDF Orbit group provided its expertise to Hubble end-of-life planning, launch support for EOS Aura and Gravity Probe-B (GP-B), TDRS relocation efforts, and UARS SN coverage.

Task personnel received special requests from both the Hubble Space Telescope (HST) and the FDAB for HST end-of-life planning. The requests included a listing of HST's definitive accuracy achievements, orbital solution coefficient-of-drag values for the past four years, current year solve-for-drag correction terms, and the Extreme Ultraviolet Explorer early- and late-mission orbit vectors. These data are being used to characterize the predicted HST orbital decay for use in the future HST rendezvous effort.

Task personnel successfully supported the pre-launch, L&EO, and on-orbit activities for two major satellites this year: EOS Aura and NASA/Ames Research Center's GP-B. The Aura support has been flawless; products that are provided to the Aura MOC include orbit determination during all mission phases, acquisition-data generation on launch day, weekly local-oscillator-frequency reports, and a number of reference files, i.e. drag coefficient updates and atmospheric models. FDF support of GP-B was due to end 30 days after launch, but Ames chose to extend that support to retain the FDF's orbit expertise in orbit determination and prediction and network acquisition.

The FDF also played a key role in the relocation of TDRSs 5, 7, 8, 9, and 10. This support involved planning and real-time support for 80 maneuvers, which were a combination of stationkeeping burns, north thruster flushings, and the actual relocation burns. Orbit personnel provided OD and acquisition data support for every maneuver; most maneuvers were supported in real time. For some maneuvers, task personnel performed collision avoidance analysis and assisted the White Sands Complex in choosing maneuver dates to assure spacecraft safety and performance.

The Upper Atmospheric Research Satellite (UARS) is an on-orbit mission that receives FDF support. UARS has been supported by two TDRS satellites since its launch in July 1991, but system failures have led to TDRS-coverage problems. Due to continued failures, a transition to a third TDRS was required for additional coverage. FDF personnel performed extensive interface and acceptance testing with external elements prior to the transition to the new TDRS.

[Technical Contact: Karen Richon]

2.3.8 Software Maintenance

This task is responsible for the development and maintenance of the Flight Dynamics software used by the FDF in support of institutional space mission operations activities as well as maintenance of the FDAB R&D software tools to ensure consistency with the broader aerospace community practices. The flight dynamics software supports the following activities: attitude error analysis, prediction and determination; navigation, orbit prediction and determination, and error analysis; mission analysis; trajectory design and analysis; maneuver planning; acquisition data generation; and other mission planning tools.

The team's main challenge for 2004 was to take over responsibility of FDF's software maintenance from the previous contractor. The new team performed an inventory of all applications that needed maintenance and created the processes and procedures for performing the maintenance and configuration management of those applications. An added difficulty was the general lack of up-to-date documentation for the majority of the software. The maintenance plan created by the team lays the groundwork for continual maintenance task activities because software that is not properly maintained is a risk with very real consequences to the FDF's operational environment.

Following the maintenance plan has created good results. The team has begun the analysis for reducing the number of applications on the inventory list. A configuration plan has been created, as well as specifications for a configuration management system implementation. Plans have also been created for risk management, software maintenance and testing. The team responded to early challenges presented by the Tracking Data Formatting system and effectively researched and solved the problem, then created a plan to upgrade the system to eliminate future issues.

Another challenge for the team is the requirement that the facility upgrade to a Hewlett-Packard operating system version that is supported by the vendor. The facility currently makes wide use of HP UX 10.2 and must upgrade to 11.i. As a result, all of the applications maintained in the FDF must be analyzed, tested, and rebuilt to be maintainable under the new OS. The upgrade of the operating system presents a further challenge to maintenance of the tracking data databases, as the version of Oracle in use is no longer supported and will not run on the newer OS, while the newer version of Oracle will not execute on the older OS. The team has been involved heavily in analyzing and creating the plans to perform these upgrades with minimal impact to the user community.

[Technical contact: Felipe Flores-Amaya]

2.3.9 Sustaining Engineering

The FDAB took over management of the FDF beginning January 2004. An assessment was done of the condition of the computing systems within the facility at the time of the contract change. Based on that assessment, several upgrades and system changes were implemented. The Fiber Distributed Data Interface (FDDI) ring was removed, the network was rebalanced to provide better communications, and an open IONet connection was established. The entire facility hardware and software was place under a rigorous configuration management process. A re-engineering plan was developed and will be implemented in 2005.

[Technical contact: Sue Hoge]

3.0 Study Mission Support

3.1 Integrated Mission Design Center (IMDC)

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

The IMDC 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 IMDC provides specific engineering analysis and services for mission design and provides end-to-end mission design products.

The FDAB provides its engineering expertise in the areas of trajectory design and attitude control. The trajectory engineers provide critical mission-specific analysis and design for mission trajectories. Attitude control engineers provide expertise in the refinement of ACS requirements, sensor selection, actuator sizing, component placement and specification, control modes design, and risk assessment. Engineers also identify "tall-poles" that require science requirement revisions. Many of these tall-poles are ACS-related such as formation sensing, tight attitude requirements, and fuel constraints. ACS engineers also provide critical cost analyses and trade studies to determine the lowest cost configuration that will meet the science requirements. The innovative nature of the missions proposed by IMDC customers challenges the FDAB engineers to find creative solutions to meet those missions' science requirements.

Eleven mission studies, covering a wide range of mission types, were supported in FY 2004; these included low and high Earth orbits, Sun-synchronous, Molniya, Sun-Earth L2, Solar drift-away orbits, and formation flights. Some missions required point solutions while others required new technology concepts to achieve the science goals. Many of the formation-flight studies required innovative ways of solving the problems posed by the customers.

FDAB personnel also participated in human spaceflight and Mars mission design workshops sponsored by the IMDC.

[Technical Contacts: Frank Vaughn, Michael Mesarch, Joseph Garrick]

3.2 Autonomous NanoTechnology Swarm (ANTS)

http://ants.gsfc.nasa.gov/

The ANTS advanced concept, proposed by GSFC's Laboratory for Extraterrestrial Physics, envisions the use of a large number of small, autonomous spacecraft to explore the asteroid belt. The FDAB, in partnership with the University of Cincinnati and NASA/Langley Research Center, has performed analysis for the transfer trajectory and asteroid proximity operations phases.

[Technical contacts: Greg Marr, David Folta]

3.3 Constellation X Formation Flying Mission

https://conxproj.gsfc.nasa.gov

Constellation X is an x-ray telescope mission that will investigate black holes, Einstein's Theory of General Relativity, galaxy formation, the evolution of the Universe, recycling of matter and energy, and the nature of "dark matter". One design alternative being considered calls for two spacecraft flying in precise formation at the Earth/Moon-Sun L2 libration point. The spacecraft maintain a separation of 50 meters. Figure 3-1 shows the two spacecraft, the coordinate frames, the mirror focal point, and the actual image location.

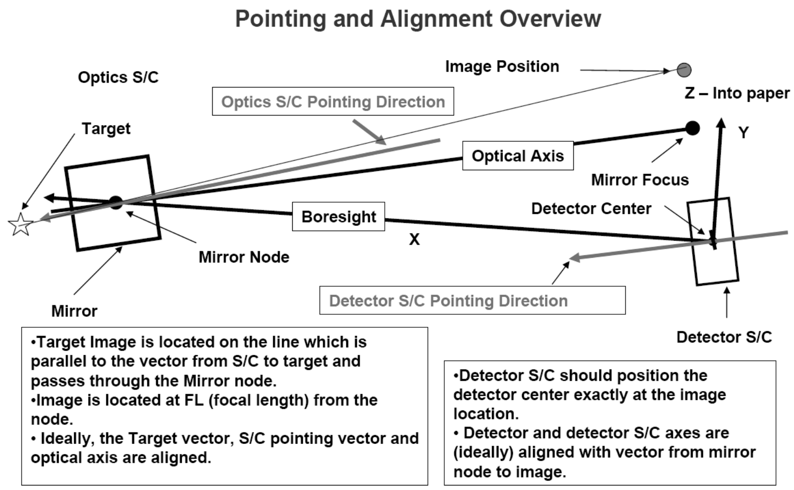

Figure 3-1. Pointing and Alignment Overview for the Constellation X Formation Flying Mission

Ideally, the center of the detector spacecraft, the mirror focal point, and the image location will coincide. The current control requirements are to maintain translation errors (in Y and Z) within ± 4mm and the relative position within ± 5 mm. The estimated relative positions must be accurate to within 0.25 mm. The individual spacecraft pointing control requirements are ±10 arc-sec in pitch and yaw and ± 20 arc-sec in roll, the estimation requirements are 1.5 arc-sec in pitch and yaw and 10 arc-sec in roll.

Preliminary studies of the Constellation X formation flying concept have focused on characterizing the fuel and thruster requirements for the formation alignment and station-keeping. The nominal science plan includes two formation re-orientation maneuvers per day, with an average maneuver size of 63 degrees. Additional studies characterizing the estimation problem have been initiated. The estimation system, in addition to estimating the individual spacecraft navigation states, must also estimate the location of the detector spacecraft with respect to the optics spacecraft. The estimation will involve the use of both RF and laser ranging systems simultaneously with a visual navigation system. The visual navigation system will include a star tracker, mounted on the detector spacecraft, that is capable of detecting both stars and 'star-like beacons' that will be placed on the optics spacecraft. An IMDC run in June 2004 provided a high level, complete system description of the formation flying mission.

[Technical contacts: Julie Thienel, Rich Luquette]

3.4 Dark Universe Observatory (DUO) Science Observation Analysis

http://duo.gsfc.nasa.gov/

FDAB personnel provided analysis support for the DUO mission proposal team by analyzing the effect of various orbit and attitude parameters on DUO observations of the Sloan (Northern) and Deep (Southern) fields. Each field was modeled by a series of points in right ascension and declination on the celestial sphere. A dynamic model of the viewing geometry was developed using STK, which was driven by a Matlab script to generate and display visibility data for each point in each field during a one-year time span. Analysis of this data helped determine when to schedule each point's observation period in to order to avoid solar, lunar, South Atlantic Anomaly, Earth-limb grazing, and spacecraft latitude and attitude constraints. It also unexpectedly revealed that clocking the spacecraft roll angle in discrete increments of 60° in order to track the solar panels with the Sun while maintaining proper scan tracking geometry resulted in a portion of the Sloan field being unobservable.

[Technical contacts: David Folta, Chad Mendelsohn, Frank Vaughn]

3.5 Extrasolar Planet Imager Coronagraph (EPIC)

EPIC is a heliocentric mission designed to detect giant planets in other solar systems using its unique nulling coronagraph. The FDAB supported the GSFC Principal Investigator in the development of EPIC's Discovery-Program proposal. The FDAB performed trade studies to determine the optimum mission orbit. Because of science viewing requirements, a Sun-Earth L2 libration point Halo orbit and an Earth-trailing heliocentric, or "drift-away", orbit were the primary mission orbits considered. With regard to the choice of a mission orbit, it is important to note that EPIC must fire its thrusters approximately every four days in order to unload momentum stored in on-board reaction wheels. The FDAB noted that if a Sun-Earth L2 orbit was chosen, then these frequent momentum dumps may adversely affect the orbit determination process, which is a great concern in this inherently unstable orbit. Based partly upon this information, a heliocentric drift-away orbit was chosen for EPIC. In addition to the trade studies and orbit determination analysis, the FDAB also analyzed launch vehicle requirements, generated nominal trajectory data, generated nominal ground coverage statistics, and determined spacecraft energy (delta-V) requirements.

[Technical contact: Steven Cooley, Greg Marr]

3.6 Geospace Electrodynamic Connections (GEC)

http://stp.gsfc.nasa.gov/missions/gec/gec.htm

The GEC mission is a multi-spacecraft mission managed by NASA's Solar Terrestrial Probe Office (STP) at GSFC. Currently in the formulation phase, GEC plans to use three or four spacecraft to study the Earth's Ionosphere-Thermosphere (IT) system. While this region has been studied before, the coordinated use of multiple spacecraft will allow scientists to discover the spatial and temporal scales on which magnetospheric energy input to the IT region occurs, determine the spatial and temporal scales for the response of the IT system to this input of energy, and quantify the altitude dependence of the response.

The second GEC Rapid Spacecraft Development Office (RSDO) study was finished at the end of FY 2004 with presentations from the three respondents – Astrium GmBH, Orbital Sciences Corp., and Spectrum Astro. All three gave excellent presentations covering the two different options for GEC – flying three spacecraft with multiple dipping campaigns or flying four spacecraft without performing dipping campaigns.

Following the RSDO study, an effort was made to perform an independent optimization study of the GEC orbit. Using the same data that was given to the industry teams, FDAB personnel developed MATLAB scripts to optimize the GEC parking orbit with the requirement to complete ten, one-week dipping campaigns with perigee near 130 km (the original requirement). The complete range of launch vehicle performance data was analyzed, and it was determined that a 222 x 1525 km orbit was optimal as it maximized the dry mass available for the spacecraft subsystems and instrument payload. Further analysis was performed to assess the sensitivity of this optimal solution as a function of the number of dipping campaigns (varied from 8 to 12), the coefficient of drag (2.5 ± 10%), and propellant specific impulse (285 sec to 310 sec). The results of the optimization and sensitivity analyses were compiled in the paper "Orbit Optimization for the Geospace Electrodynamics Connections (GEC) Mission" and were presented at the AIAA/AAS Astrodynamics Specialists Conference in Providence, RI in August of 2004.

Funding for GEC was halted late in FY 2004 following the refocusing of NASA priorities stemming from the Vision for Space Exploration (VSE). While the STP Office and the science community remain committed to the realization of the GEC mission, it is unclear when study efforts will resume.

[Technical Contact: Michael Mesarch]

3.7 Glory

FDAB personnel continued to provide analysis support for the Glory mission team. Analysis included validation of orbit requirements to meet mission goals, Sun angle calculations to determine the frequency of yaw maneuvers to track the Sun, and development of tools to generate and analyze Sun glint observation data for various attitude geometries.

[Technical contact: Frank Vaughn]

3.8 Laser Interferometer Space Antenna (LISA)

http://lisa.gsfc.nasa.gov/

LISA is one of the first gravitational science missions that will detect ripples in space-time itself. Gravity waves are detected by measuring the strain in space, i.e. the change in distance between a set of masses separated by a great distance. LISA uses laser interferometric measurement to detect change in distance between test masses which are located on three different spacecraft; these spacecraft are in heliocentric orbit. The orbits are chosen so that the three spacecraft form a roughly equilateral triangle, with its center located at a radius of 1 AU and 20 degrees behind the Earth. The 5-million-km arms and very quiet acceleration environment (3.5×10^{-15} m/s$^2/\sqrt{\text{Hz}}$) of LISA allow for the detection of gravity wave strains to a best sensitivity of 3×10^{-24} strain$/\sqrt{\text{Hz}}$ over the measurement band of 0.1 mHz to 0.1 Hertz for a one-year observation. Stringent requirements are placed on the rotational ($8x10^{-9}$ rad/$\sqrt{Hz}$) and translational dynamics ($10x10^{-9}$ m/$\sqrt{Hz}$) of each spacecraft to ensure that the proper sensitivity for science measurements can be achieved.

The FDAB personnel supported LISA's acquisition control and the design and analysis of Disturbance Reduction System (DRS) control. There are six optical links that need to be established before the constellation's science operations can commence. Two acquisition strategies for establishing the laser links were developed. The first strategy is based on a scanning approach. The width of the outgoing beam does not typically cover the position uncertainty of the receiving spacecraft, so a scan has to be performed to allow the receiving spacecraft to identify the orientation it has to assume to be able to illuminate the transmitting spacecraft. Overall, three scans have to be performed. Once a scan is complete, it uses an array of available sensors, with varying degrees of resolution, to lock in one laser link at a time. The order of the links, as they are established, is shown in Figure 3.2. An acquisition time history plot for a typical link is shown in Figure 3.3.

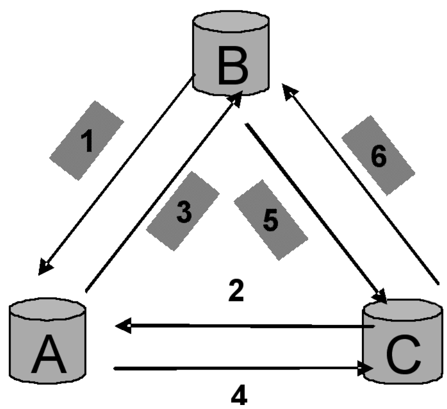

Figure 3-2. Link Acquisition Order for Scan Acquisition Strategy

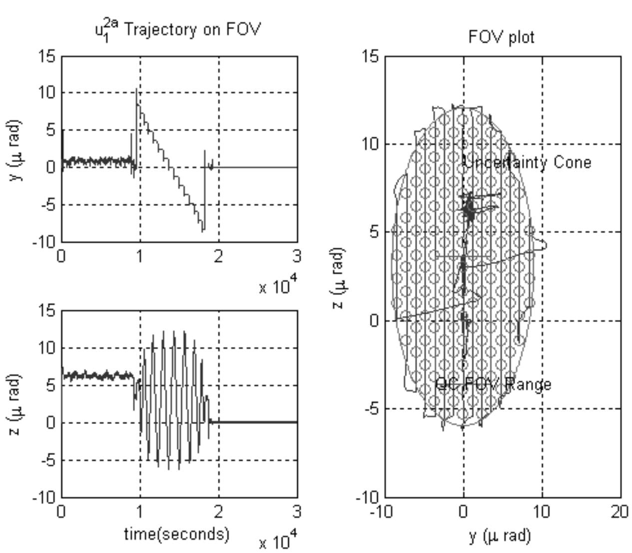

Figure 3-3. A Typical Scan Time History

The second strategy defocuses the outgoing laser beam by a factor of q to encompass the accuracy and alignment of the star tracker as well as orbital knowledge, and hence avoids the need for time-consuming scans. Because of potential stray light issues and the dim incoming beam, the local laser is turned off until the start of the heterodyne wavefront sensing. The order of the link establishment is different than the scan strategy, and it is shown in Figure 3.4. An acquisition time history plot for a typical link is shown in Figure 3.5.

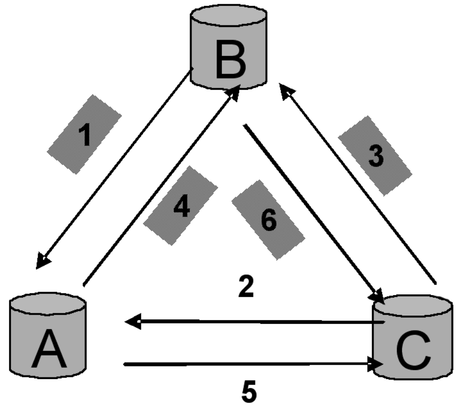

Figure 3-4. Link Acquisition Order for Defocus Acquisition Strategy

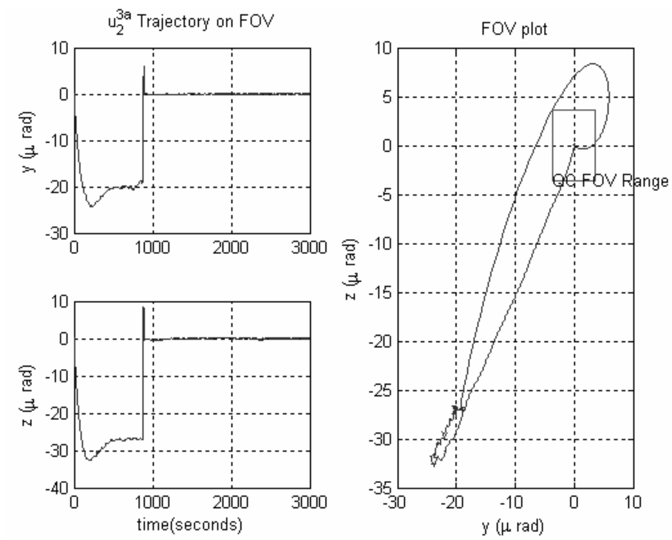

Figure 3-5. A Typical Defocus Time History

A Kalman filter, which uses star tracker information as well as gravitational sensor acceleration data, is used to estimate attitude errors during the time it takes to scan, achieve phase locking, and to obtain heterodyne wavefront tilt measurements. Both strategies are sequential, in which one one-way link is established at a time. The process for the single-link acquisition is initiated from ground command and then accomplished autonomously. Constellation-level models and simulations with refined DRS controls have been developed and used to assess the efficiency of both proposed strategies.

[Technical contacts: Peiman G. Maghami]

3.9 Organics Origins Observatory (OOO)

The OOO, a Discovery Program proposal, is a Sun-Earth L2 libration-point mission concept that is being led by GSFC's Laboratory for Extraterrestrial Physics. The FDAB has analyzed launch vehicle requirements, generated nominal trajectory data, analyzed spacecraft fuel requirements, and performed OD error analysis.

[Technical contacts: Steven Cooley, Greg Marr]

3.10 Solar Sentinels

http://lws.gsfc.nasa.gov/sentinels.htm

The Solar Sentinel mission concept, proposed by GSFC's Laboratory for Extraterrestrial Physics as part of the Living With A Star Program, plans to study the connection between solar phenomena and geospace disturbances. The current orbit design calls for multiple spacecraft launched on the same launch vehicle to make use of Venus fly-bys to place the spacecraft in different heliocentric orbits. The FDAB has performed trajectory design analysis in support of this concept.

[Technical contacts: David Folta, Greg Marr, John Downing]

3.11 Sub-millimeter Probe for Evolution of Cosmic Structure (SPECS)

http://space.gsfc.nasa.gov/astro/specs/

In the spring of 2003, NASA issued a request for proposals for a series of Vision Mission studies, which are intended to examine the justification for mounting challenging long-term missions of potential interest to the agency and to determine the key technical capabilities that would have to be in place to assure success. One of these studies called for an investigation of a kilometer-baseline far-infrared and submillimeter interferometer in space. The SPECS Vision Mission proposal was funded in May, 2004. The SPECS project consists of a science team, an engineering team, and a smaller core group that belongs to both teams and assures rapid exchange of information between them.

The science team examined what capabilities an interferometer would need to assure that currently unattainable astrophysical or cosmological observations will be made possible. The engineering team translated these capabilities into hardware and software requirements and has sought to identify the key technical hurdles to be overcome. The science team reconsidered the capabilities when the technological hurdles seemed excessive and supplied the engineering team with an alternative set of requirements that will still yield appreciable advances. This back-and-forth exchange has led to agreement on a set of key scientific objectives and a corresponding preliminary interferometer architecture. The team is currently studying this architecture in greater depth to identify the major technological problems it may entail.

The current concept envisions SPECS as a basic configuration of two light collectors – telescopes – relaying far-infrared and sub-millimeter radiation to a central beam combiner with an angular resolution of 50 mas, comparable to that obtained with the HST (Hubble Space Telescope). The wavelength range for SPECS will be 40 - 640 microns and is expected to span a gap that other missions, such as HST, JWST, and ALMA, will not study. Since SPECS will be located at the Sun-Earth L2 Lagrangian point, this angular resolution requirement calls for the baseline (separation between collector spacecraft) to vary between 20 and 500 meters.

Several significant problems are currently being examined including the use of tethers for relative position control, active cooling systems capable of maintaining all elements of the optical at 4° Kelvin, and advanced metrology systems capable of delivering the degree of precision and accuracy required for mission success.

[Technical Contact: Dave Quinn]

3.12 Space Infrared Interferometric Telescope (SPIRIT)

The FDAB recently began a comprehensive effort to design trajectories for the SPIRIT mission, which was selected in July 2004 for further study under an Origins Program NASA Research Announcement (NRA). SPIRIT, led by GSFC, is an interferometric mission with a large Sun-Earth L2 libration point mission orbit. The FDAB will produce several years of launch window data using mission design techniques first developed for the TRIANA and FKSI missions. The goal is to build upon this past work, which uses invariant manifold theory techniques, to further automate the process of generating nominal trajectories over a multi-year time frame. It is anticipated that the trajectory design refinements developed here will be useful for all future libration point missions. In addition, the FDAB also plans to analyze launch vehicle requirements, generate nominal ground coverage statistics, determine spacecraft energy (delta-V) requirements, and develop contingency strategies for the SPIRIT mission.

[Technical contacts: Steven Cooley, Greg Marr, Dave Quinn]

3.13 Terrestrial Planet Finder (TPF)

http://planetquest.jpl.nasa.gov/TPF/tpf_index.html

TPF, one of the proposed missions under NASA's Origins Program, will search for habitable extra-solar planets and life beyond Earth. Currently there are two promising architectures viable for extra-solar planet detection: visible-light coronagraph, and infrared interferometer. In April, 2004, NASA decided to proceed with both architectures; JPL will lead the missions and GSFC will provide the telescopes.

During FY 2004, a variety of dynamic analyses were done for the TPF Coronagraph (TPF-C) team. Figure 3-6 shows a plot of the deployed TPF-C observatory and the proposed actuator and sensor locations.

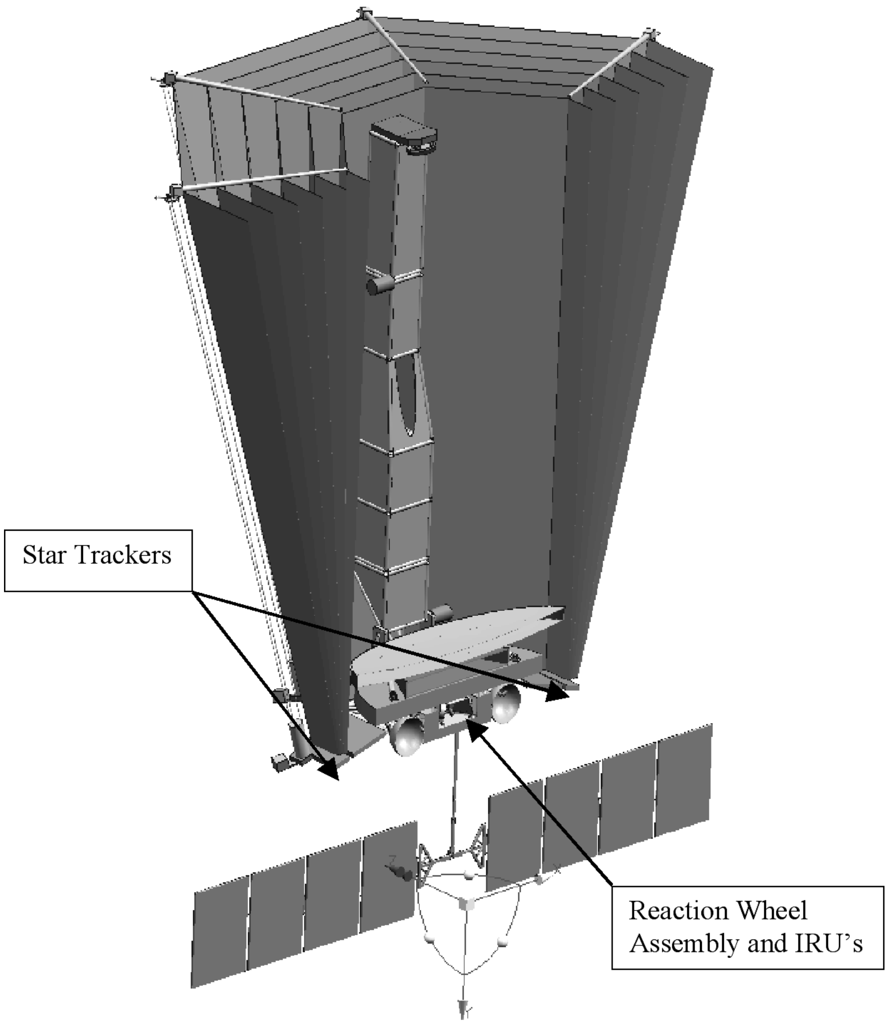

Figure 3-6. Location of ACS Actuators and Sensors *(courtesy of Timothy Ho)*

To enable planet detection, the observatory must achieve one-billion-to-one image contrast, which translates to maintaining dynamic pointing stability in the sub-milliarcsecond level. Meeting these stringent stability requirements poses great engineering challenges and stretches current state-of-the-art technologies. A preliminary design of the pointing control system (PCS) for TPF-C has been developed to meet the stability requirements. The PCS topology combines a three-axis, inertially-stabilized attitude control system, an image motion control system that provides tighter control around pitch and yaw axes, and a vibration isolation system that reduces high frequency structural jitter.

Once the PCS was defined, an integrated model was developed by incorporating dynamic models from various disciplines, including structures, optics, and controls. Such a model allows end-to-end performance prediction from various disturbance sources. Estimates of rigid-body pointing error, image jitter motion, and wavefront error were computed using reaction wheel disturbances as inputs. In addition to the linear, frequency domain jitter analysis, a time-domain nonlinear simulation was also developed to evaluate the slew/settle performance of the observatory.

Results obtained from integrated modeling analysis and time simulations were presented at JPL's Minimum Mission Review. The analysis results show that the point design (0.75 Hz bus-payload isolation, 2 Hz RWA isolation) meets both the image centration and contrast requirements. From the slew/settle simulation, the observatory was shown to meet the slew time requirement, although acquisition phase has not been properly modeled in the simulation. These benchmark results demonstrate that a properly designed system can meet the stringent performance requirements for TPF-C. The analysis can now proceed to explore various design options and simultaneously examine the effects of modeling uncertainty and actuator/sensor non-idealities.

[Technical contact: Kuo-Chia (Alice) Liu]

3.14 Venus Sounder for Planetary Exploration (VESPER)

The FDAB supported VESPER, which is a proposal mission in NASA's Discovery Program and is led by GSFC's Laboratory for Extraterrestrial Physics. VESPER will integrate key mission measurements with atmospheric models to investigate the coupled processes of chemistry and dynamics in the Venus middle atmosphere; the VESPER goal is to conduct a tightly focused study of the Venus atmosphere as part of a larger NASA program of comparative planetology. VESPER consists of a spacecraft and an atmospheric entry probe. The FDAB has analyzed launch vehicle requirements, generated nominal trajectory data, and analyzed potential probe impact locations for 2009 and 2010 launch opportunities.

[Technical contact: Greg Marr]

4.0 Technology Development

4.1 Advanced Attitude Determination and Sensor Calibration

The purpose of the advanced attitude determination and sensor calibration task is to improve the accuracy and efficiency of both processes while taking into account any current and future mission requirements. In FY 2004, this task studied spinning spacecraft attitude issues and attitude determination efficiency.

Algorithms were developed to better estimate attitude for spinning spacecraft. In the past, the requirements on spinning spacecraft ground attitude systems did not require the sophisticated algorithm development that is necessary for three-axis stabilized missions. Within the next two years, two missions consisting of spinning spacecraft, THEMIS and ST5, will launch with modest attitude sensors but with challenging attitude requirements. In many respects, spinning spacecraft attitude estimation and sensor calibration now require more sophisticated algorithms than those developed for three-axis stabilized missions. The ground attitude estimation studies led to two attitude estimation algorithms being developed for spinning spacecraft: pseudo-linear Kalman filter estimating the attitude and rate and an extended Kalman filter (EKF) using Markley variables. Two pseudo-linear algorithms were developed: q-filter and D-filter. The q-filter estimates the attitude quaternion and rate while the D-filter estimates the direction cosine matrix and rate. Both filters were successfully operated on simulated spinning spacecraft sensor data. The 7-state q-filter had the advantage of smaller state vector than the 12-state D-filter. However, the D-filter demonstrated improved attitude accuracy due to an inherently linear dynamics model as opposed to the pseudo-linear measurement model for the q-filter. The Markley variable EKF algorithm has been developed and will undergo testing in the next fiscal year. Upon completion of algorithm testing using simulated and flight data, the next step is to develop the spinning spacecraft sensor calibration algorithm. This step is expected to be completed in the first quarter of FY 2006.

The task also worked to improve the efficiency of advanced attitude determination and sensor calibration. First, the Mission Three-Axis Stabilized Spacecraft (MTASS) software system was successfully integrated into the GMSEC system architecture. In the short term, this provides MTASS with a standard real-time interface that could either be used to just collect data for later processing or as the front-end for a Real-Time Attitude Determination System (RTADS). Second, an autonomous module has been added to the gyro calibration portion of MTASS. This module has been successfully tested using flight data. The immediate advantage for missions performing a significant number of attitude maneuvers is that the need for special gyro calibration maneuvers decreases potentially to zero. The implemented sequential Davenport algorithm has the ability to update the latest gyro calibration parameters with the information from discrete maneuvers instead of needing to use all the maneuvers at once. The MTASS system is currently being moved to the Rossi X-Ray Timing Explorer (RXTE) control center with the eventual goal of being operated autonomously for ground attitude validation of the onboard attitude estimate as well as autonomously performing gyro calibration. A prototype system is expected to be completed in the early FY 2005 timeframe. FY 2005 work on this task will concentrate on automating the Mission Spin Stabilized Spacecraft (MSASS) multi-mission attitude system as well as automating the MTASS sensor alignment calibration process.

[Technical contact: Richard R. Harman]

4.2 Advanced Navigation Concepts

"Libration Point Navigation Concepts Supporting the Vision for Space Exploration"

This paper was presented at the American Astronautical Society's Astrodynamics Specialists Meeting, in Providence, RI, and it examines the autonomous navigation accuracy achievable for a lunar exploration trajectory from a translunar libration point (L2) lunar navigation relay satellite, augmented by signals from GPS. The paper also provides a brief analysis comparing the libration point relay to lunar orbit relay architectures and discusses some issues of GPS usage for cis-lunar trajectories. This study indicates that accuracies of better than 1 km and 5 cm/sec may be feasible, which are quite promising in comparison with the trans-lunar post-maneuver results on the order of kilometers and dozens of centimeters-per-second achieved during Lunar Prospector using two-way Doppler from DSN 34- and 26-meter tracking sites. Since these are single-case results, the value of the actual errors in predicting real-world performance is somewhat reduced. Instead, one may view these results as a guideline for the range of accuracy that might be achievable. Although a case can be made for lunar orbiting constellations in support of long-term human and robotic lunar exploration, the authors believe that the Earth-Moon L2 Orbiter provides a great deal of capability with minimal investment as a starting point for a comprehensive lunar and planetary navigation and communications infrastructure beyond near Earth orbit.

[Technical contact: Russell Carpenter]

4.3 Space Science Mission Operations (SSMO) Ground Attitude System Reengineering

The Goddard SSMO Project operates five missions at Goddard that observe various space science phenomena. The Active Coronal Explorer (ACE) orbits the libration point between the Earth and the Sun and observes the Sun's corona. The SOHO spacecraft also orbits the libration point between the Earth and the Sun and is most known for observing solar flare activity. The Rossi X-ray Timing Explorer (RXTE) orbits the Earth at an altitude of 500 km and observes x-rays, one of the highest energy waves, to investigate space phenomena. The POLAR spacecraft also orbits the Earth, but at an altitude of 1.6 Re at its apogee and 1.2 Re at perigee. This orbit allows the POLAR spacecraft to observe the poles for extended periods to explore the Aurora phenomena. Finally, the WIND spacecraft has modified its orbit many times to explore the solar wind phenomena between the Sun and the Earth.

Each of these missions suffers from the same problem: age. The youngest mission, ACE, was launched in 1997. Each mission is nevertheless still called upon to operate without fail, and in the face of reduced budgets. This has led SSMO to look for ways to reduce its operating costs to remain within these lower budgets.

Ground-based attitude determination accounts for a significant portion of spacecraft operating costs. Reengineering of these systems to a more efficient system is necessary to reduce operations and enable safe operation of the spacecraft into the future. A study was conducted of the missions mentioned above that documented the current architecture of the attitude system, detailed the operating procedures, and how difficult the system was to operate. A second study analyzed the current systems and determined which systems were candidates for reengineering, along with different paths to a new system. These two studies led to a categorization of reengineering needs.

The reengineering of the ground attitude systems of SSMO will be a continual effort into the next year, with the focus being on ACE, RXTE and SOHO. In the case of the ACE mission, it was deemed that the level of complexity for routine operations was too high. The path of its reengineering effort is currently being examined. For the RXTE mission it was clear that the attitude system was very mature with moderately complex attitude operations. As a result, the system and its operation could be moved from the FDF to the RXTE MOC with minimal effort but with a significant reduction in operations costs. The SOHO mission has an attitude system that, over the years, has had several independent pieces developed, but that do not all operate together. The reengineering approach for SOHO is to bring the different pieces together into a cohesive system and then potentially place the new system in the Payload Operations Control Center. The WIND and POLAR missions are slated to be decommissioned and would consequently not recover the cost of the reengineering.

[Technical contacts: John M. Van Eepoel, Richard R. Harman]

4.4 Global-Positioning-System-Enhanced Onboard Navigation System (GEONS)

http://geons.gsfc.nasa.gov

The GEONS team completed two new releases of GEONS during FY 2004. GEONS 2.1 includes upgrades to celestial navigation for horizon sensor and sun sensor measurements from spinning spacecraft; a cold-start initialization procedure that uses GPS measurements in a batch form; and the capability to integrate user-provided formation control algorithms. GEONS 2.2 includes a capability to model antenna offsets for spin-stabilized satellites; improvements to the cross-link measurement models, including explicit modeling of clock bias and drift for both one-way and two-way measurements; and modeling of antenna-offsets for multiple antennas on both transmitting and receiving satellites. In addition, the team completed the mathematical specification for GEONS 2.3. This release was targeted for completion during FY 2004, but, due to contract transition issues, and a greater degree of difficulty than anticipated for the software improvements in GEONS 2.2, has been delayed to approximately the end of calendar year 2004. GEONS 2.3 will include capabilities for processing one-way Doppler data from TDRS (i.e. TDRSS Onboard Navigation System, or TONS, capability); modeling ionospheric delay for low-Earth orbit users; and improvements in bias and state reset commands.

The GEONS software has been licensed to Orbital Sciences Corporation and to Ball Aerospace and Technologies Corporation. Ball is currently incorporating GEONS into the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) to fly in formation with French-built Coalition for Environmentally Responsible Economies (CERES) instruments on the EOS Aqua satellite. The CALIPSO mission is managed by NASA's Goddard Space Flight Center and implemented by NASA's Langley Research Center for the NASA Earth System Science Pathfinder (ESSP) program and collaborates with the French space agency Centre National d'Etudes Spatiales (CNES), Ball Aerospace and Technologies Corporation, Hampton University, and the Institut Pierre Simon Laplace in France. CALIPSO is scheduled for launch in 2005. Orbital Sciences incorporated an orbit determination package based on GEONS into OrbView-3, and is currently putting GEONS in the Solar Radiation and Climate Experiment (SORCE), which is a NASA-sponsored satellite mission that will provide state-of-the-art measurements of incoming x-ray, ultraviolet, visible, near-infrared, and total solar radiation. GEONS has also been released to numerous contractor and grantee teams under NASA project releases. New agreements of this type in 2004 were with Broad Reach Engineering and Star Technologies.

GEONS also was nominated for two awards during 2004: the Space Technology Hall of Fame, and the Federal Laboratory Consortium Mid-Atlantic Regional Award. As of September, 2004, the GEONS team received word that they had won the latter.

[Technical contact: Russell Carpenter]

4.5 GPS-Based Navigation for High Earth Orbits

The FDAB has been a leader in technology development to enable autonomous navigation and formation flying for spacecraft in high Earth orbits. Recent advances in GPS receiver designs and signal processing capabilities now make it feasible to consider using GPS to provide autonomous onboard navigation for high altitude space missions.

In the past, GPS applications for absolute and relative navigation have been limited to altitudes below ~3000 kilometers, where a conventional instantaneous GPS solution is always possible. GPS-based navigation can reasonably be expanded to geostationary and highly eccentric orbits extending to ~50 Re using a specially-designed GPS receiver coupled with an orbit determination filter to sequentially process the sparse pseudorange measurements. Figure 4-1 illustrates the geometry for receiving GPS main and side-lobe signals in a high Earth orbit, when the spacecraft is sometimes above the altitude of the GPS constellation.

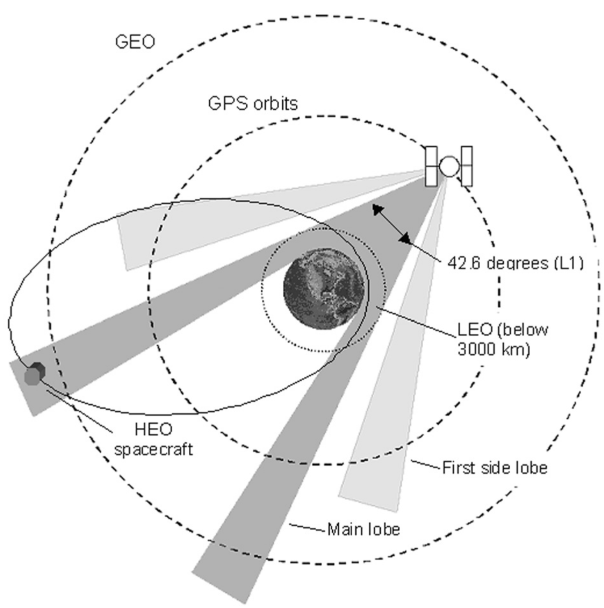

Figure 4-1. Geometry for reception of GPS signals by a HEO spacecraft. Side-lobe signals are weaker, but can still contribute to GPS observability for HEO users.

The FDAB is involved with several technology initiatives to advance capabilities for applying GPS to high altitude orbits through analytical studies, GPS receiver development, and hardware in-the-loop testing. The DATSIM and GEONS software tools provide a high fidelity measurement simulation capability that may be used to assess navigation performance in a wide range of orbital regimes using GPS and other measurement types. GPS receiver development support in the FDAB has focused on the PiVoT and the Navigator receivers. The PiVoT receiver was originally developed for LEO applications, but the FDAB has developed modifications that enable its operation above the GPS constellation, which provides the branch with a unique hardware-in-the-loop testing capability. Navigator is a new, fully spaceflight qualified HEO receiver optimized for fast signal acquisition and weak signal tracking. It acquires and tracks GPS signals with a carrier-to-noise ratio (C/N_0) as low as 25 dB-Hz, a significant improvement over PiVoT and other receivers suitable for spaceflight. A breadboard version of the receiver will be available for hardware-in-the-loop testing in early 2005.

FDAB personnel participated in a study in MESA's Formation Flying Test Bed (FFTB) to assess real-time GPS-based orbit determination accuracies obtainable in a range of high Earth orbits. The FFTB uses real-time, distributed software to integrate RF signal simulators, actual GPS receivers and/or cross-link transceivers, and flight processors to provide a real-time simulation environment for system- and component-level studies. In this study, actual measurements were recorded from GPS receivers and processed in real-time using the GEONS flight software. This study indicates that autonomous, onboard navigation using GPS is possible in a comprehensive set of high earth orbits. Initial results indicate position accuracies on the order of tens of meters are routinely possible in some of the higher orbits. Work is ongoing to conduct real-time tests of longer period orbits for the GOES and MMS Projects.

[Technical contact: Mike Moreau]

4.6 Formation Flying Technology

Spacecraft formations are a subset of the global collection of multiple spacecraft missions, classified as Distributed Space System (DSS). In general a DSS is a collection of two or more space vehicles designed to accomplish similar or shared objectives; an end-to-end (information) system consisting of two or more space vehicles, coordinated flight management, and an integrated infrastructure for data acquisition, storage, analysis, and distribution. In contrast a formation is comprised of multiple spacecraft with the ability to cooperatively detect, maintain, and agree on the appropriate maneuver to maintain a desired position and orientation. Formation flying is enabling technology required to maintain the relative separation, orientation, or position between or among the formation spacecraft.

Overall responsibility for DSS technology development resides with the Guidance, Navigation & Control Systems Engineering Branch of the MESA Division at GSFC. DSS/formation flying technology development is supported by personnel within the FDAB. The specific focus areas are Earth-orbiting Formation Control; Earth-Orbiting Formation Design; Fault-Tolerance, Collision Avoidance, and Formation Safety; High-Altitude Relative Navigation; Libration Point Formation Control; and Libration Point Formation Design. The progress for each topic during FY 2004 is summarized below.

4.6.1 Earth-Orbiting Formation Control

[Technical Contact: Dave Quinn]

This subtopic covers all missions in which the gravitational influence of the earth is the primary external force. Applicability to other bodies is of minor interest. Disturbances include but are not limited to drag, solar radiation pressure, and non-primary gravitational bodies.

Below is the supervised research within this topic that is being completed under Cooperative Agreements.

4.6.1.1 Formation Navigation, Control, and Mission Design Algorithms

Principal Investigator: Jonathan P. How, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA

Recent hardware-in-the-loop experiments performed on the NASA GSFC Formation Flying Testbed confirmed that decentralized Carrier-phase Differential GPS (CDGPS) yields excellent position accuracies (~ 2cm) for close formations in LEO. These results suggest that CDGPS would be an attractive sensor for the relative navigation of the formation flying missions described in the NRA. However, there is a problem because the corresponding velocity estimate errors are small (<= 0.5mm/s) but have a significant impact on the fuel cost of the LEO/HEO formations. Thus the objectives of this effort are: (1) Complete the analysis of the impact of the velocity errors (i.e., consider more general orbit configurations); (2) Investigate the fundamental limits of the CDGPS estimator and explore possible changes that might improve upon the accuracy of the current velocity estimates; (3) Identify sensing augmentation approaches that could be efficiently added to the spacecraft to improve the velocity estimates; (4) Extend current control techniques to mitigate the effect of these velocity errors on the fuel cost. It is anticipated that these investigations would be performed on the various testbed at MIT and on the FFTB at GSFC.

FY 2004 Publications:

A. G. Richards and J. P. How, "Analytical Performance Prediction for Robust Constrained Model Predictive Control," AIAA Guidance, Navigation and Control Conference, Providence RI, August 2004. AIAA-2004-5110.

J. P. How, T. Alfriend, L. Breger, and M. Mitchell, "Semimajor Axis Estimation Strategies," presented at the 2nd International Formation Flying Symposium, Sept. 2004.

M. Mitchell, L. Breger, J. P. How, and T. Alfriend, "Effects of Navigation Filter Properties on Formation Flying Control," presented at the AIAA Guidance, Navigation and Control Conference, Aug.~2004. AIAA-2004-5024

M. Mitchell, "CDGPS-Based Relative Navigation for Multiple Spacecraft," S.M. Thesis, Massachusetts Institute of Technology, Dept. Aeronautics and Astronautics, June 2004.

L. S. Breger, "Model Predictive Control for Formation Flying Spacecraft," S.M. Thesis, Massachusetts Institute of Technology, Dept. Aeronautics and Astronautics, June 2004.

4.6.1.2 "Virtual Rigid Body" (VRB) Satellite Formation Control Technology Using Relative Vehicle Dynamics

Principal Investigator: Robert M. Sanner, Department of Aerospace Engineering
University of Maryland, College Park, MD

This research will extend the VRB control paradigm for formations of satellites, developed under a previous NASA grant. In particular, we will reformulate the methodology so as to be applicable for relative referenced formations, as opposed to the inertial referenced formations, assumed in our current model. This new capability will be added to our formation flying simulation facility, and its performance will be evaluated on baseline Earth-orbiting mission concepts identified in the NRA. The accuracy of the new algorithm will be evaluated, and compared with our previous designs. The control synthesis technique will also be extended to incorporate additional robustness and fault tolerance features, both for parametric uncertainty in the spacecraft dynamics, sensors and actuators, as well as for stochastic perturbations arising in the vehicle's environment and sensing system. Additional, and more realistic, actuator and sensor models will be incorporated, and the control formulation extended to include these new models.

FY 2004 Publications:

R. M. Sanner, and D. K. Proffen, "Virtual Rigid Body (VRB) Satellite Control with Formation Preserving Cross-Coupling," 2nd Intl Symp on Formation Flying Missions & Technologies, Arlington VA, Sept 2004 (in preparation for submission to AIAA Journal of Guidance, Control & Dynamics).

4.6.2 Earth-Orbiting Formation Design

[Technical Contact: Steven Hughes]

This topic covers all aspects of mission design and guidance for Earth orbiting formations including LEO and HEO. This research effort investigates formation design approaches and optimal guidance and maneuver planning. We have used Magnetosphere Multiscale Mission (MMS) as a benchmark problem and are applying new trajectory design methods to provide orbit solutions for MMS.

Below is the supervised research within this topic that is being completed under Cooperative Agreements.

4.6.2.1 Pseudospectral Methods for Guidance Law Development for Optimal Design of Formations

Principal Investigator: Anil V. Rao, The Charles Stark Draper Laboratory,
555 Technology Square. Cambridge MA 02139.

The objectives of this research effort are as follows: (1) to develop a unified numerical approach for minimum-fuel trajectory design and guidance for satellites flying in Earth-orbiting formation and (2) to gain insight into the underlying structure of the minimum-fuel mission designs using the obtained numerical results. The numerical methodology used in this research is the Gauss pseudo-spectral method for discretizing continuous-time optimal control problems. The expected significance of the results are (1) the development of an advanced approach in that the same methodology will be used for guidance as is used for optimal mission design and (2) an increase in the fundamental understanding of the key issues required for both trajectory planning and guidance of satellite formation flying.

4.6.3 Fault-Tolerance, Collision Avoidance, and Formation Safety

[Technical Contact: Russell Carpenter]

This is an interdisciplinary topic that includes all aspects of relative trajectory estimation and control in off-nominal circumstances, such as detected and undetected failures and significant degradations of performance in sensors, actuators, communications systems, onboard processors or busses, etc. It also covers all aspects of predicting unplanned close approaches and any other anomalies that would require that the formation enter a stable "safe mode" of operations. Design of such "safe mode" formation configurations that would allow time for recovery operations without loss of the formation due to collision, dispersal, or other circumstances is of special interest. Algorithms for fault detection, identification, and recovery are of interest, as are control and estimation architectures that enhance overall mission reliability via distribution or decentralization of the estimation, guidance, and/or control computations. Examples of planned NASA missions that could benefit from the research include the NASA ST-5 Nanosat Constellation Trailblazer mission, Magnetospheric Multiscale (MMS) and Magnetospheric Constellation (MagCon) missions (the latter involving 50-100 nanosats) and the Laser Interferometric Space Antenna (LISA); and the European Space Agency DARWIN space infrared interferometer. In addition, techniques required for autonomous satellite formation flight have recently been demonstrated on-orbit by the Landsat-7/Terra (EO-1) Enhanced Formation Flying (EFF) experiment and the Gravity Recovery and Climate Recovery (GRACE) mission.

Below is the supervised research within this topic that is being completed under Cooperative Agreements

4.6.3.1 Fault Detection, Identification, Reconstruction, and Fault-Tolerant Estimation for a Satellite Cluster

Principal Investigator: Jason L. Speyer, Mechanical and Aerospace Engineering Department, University of California, Los Angeles

Over the last few years, powerful fault detection filters that generate geometrically constrained residuals have been developed. These fault detection filters are generalizations of previous filters to robust, time-varying, and decentralized fault detection filters. Due to the presence of system uncertainty, the residuals generated by the geometric properties of the fault detection filters are compromised. To enhance fault detection and identification, sequential probability tests have been developed to process the residual. The output of these residual processors is a probability of the identification of a fault. Furthermore, fault reconstruction processes have been developed to obtain the magnitudes of the faults. Fault detection filters, residual processors, and fault reconstruction processes should be designed together. This work applies these analytical redundancy schemes to single satellites and satellite clusters. Based on extensions of our fault detection, identification, and reconstruction schemes, new methodologies are being developed for constructing fault-tolerant estimators for single satellites and decentralized fault-tolerant estimators for satellite clusters.

FY 2004 Publications:

Robert H. Chen, Hok K. Ngy, Jason L. Speyer and Lokeshkumar S. Guntur, Russell Carpenter, "Health Monitoring of a Satellite System" AIAA GNC 2004, Providence, RI.

Gene M. Belanger, Slava AnanyevÝ , and Jason L. Speyer, David F. Chichka, J. Russell Carpenter, "Decentralized Control of Satellite Clusters Under Limited Communication" AIAA GNC 2004, Providence, RI.

4.6.3.2 Collision Avoidance and Safe Mode for Satellite Formations

Principal Investigator: Trevor W. Williams, Professor of Aerospace Engineering
Co-Investigator: Gary L. Slater, Professor of Aerospace Engineering

The objective of this research is to develop techniques for collision prediction and avoidance for satellite formations in low-Earth orbit, and to derive useful "safe hold" configurations for them to enter under certain failure modes. The collision prediction problem is closely related to that of relative orbital navigation of the formation satellites, which in turn depends on the type(s) of sensor and data that are available. The research will therefore first investigate the classes of sensors that exist for the formation flight relative orbital navigation problem, and the orbit determination performance that is obtainable with each. In addition, the low thrust electric propulsion that is typical of formation missions will severely limit the class of safe hold formations that are reachable.

FY 2004 Publications:

G.L. Slater, S.M. Byram, T.W. Williams, "Collision Probabilities for Satellites in Formation Flight" AIAA GNC 2004, Providence, RI.

Trevor Williams, Justin Register, and Gary Slater "Formation-Keeping Maneuver Dispersions and Safe Mode Insertion For Satellite Formation Flight" AIAA GNC 2004, Providence, RI.

4.6.4 High-Altitude Relative Navigation

[Technical Contact: Mike Moreau]

Onboard formation flying and navigation techniques and systems are being investigated to provide new and improved capabilities to support relative navigation for Distributed Space Systems (DSS). This topic includes all aspects of relative orbit determination specifically targeted towards high Earth orbit (HEO) and libration point orbit (LPO) missions. Navigation algorithms of interest include, but are not limited to, those that perform relative and simultaneous navigation of multiple spacecraft using GPS beyond LEO, celestial navigation, very-high-precision relative ranging techniques using optical and radio frequency cross-links, and passive techniques such as reflected GPS and angles-only relative state measurements.

Below is the supervised research within this topic that is being completed under Cooperative Agreements.

4.6.4.1 Mitigation of the Impact of Sensing Noise on the Precise Formation Flying Control Problem

Principal Investigator: K. T. Alfriend, Texas A&M University

The major error source for the control of precise formations in Earth orbit is the relative navigation error. Currently differential carrier phase GPS (DCGPS) is the preferred method for the relative navigation. The primary error is the in-track drift that results from an incorrect estimate of the semi-major axis (SMA) difference. The equations of motion indicate, and other research has shown, that the SMA estimate error is minimized if the radial/in-track velocity correlation coefficient, ρ, is (-1). However the real world results have shown that $\rho \approx -0.1$. An analytic investigation that developed an approximate solution to the 4x4 Riccati equation for the planar relative motion was performed. The results showed that $\rho \approx -0.1$ is the correct answer. The analytic approach showed that the high data rate was dominating the radial/in-track coupling that occurs at orbit rate. It also demonstrated a) the only effective way to reduce the SMA error is to reduce the process noise, and that physically attainable relative velocity measurements will only provide minimal improvement in the SMA estimate.

FY 2004 Publications:

Mitchell, M., Breger, L., How, J. P. and Alfriend, K.T., "Effects of Navigation Filter Properties On Formation Flying Control," Paper No AIAA 2004-5024, 2004 AIAA/AAS Astrodynamics Conference, Providence, RI, Aug. 2004.

4.6.4.2 Assessment of Intersatellite Measurements for Precise Relative Navigation of HEO Satellite Formations

Principal Investigator: Penina Axelrad, University of Colorado

The primary project objective is to evaluate relative navigation accuracy of satellite formations in high earth orbits, especially elliptical orbits. This includes modeling of measurement errors for direct and reflected GPS and cross-link ranging measurements. Over the past year we have also pursued an investigation of linearized dynamic models applicable to this environment and the benefits of using these models for formation design and navigation filter state propagation. Geometrical methods for formation flying design based on the analytical solution to Hill's equations have been previously developed and used to specify desired relative motions in near circular orbits. By generating relationships between the vehicles that are intuitive, these approaches offer valuable insight into the relative motion and allow for the rapid design of satellite configurations to achieve mission specific requirements. Prior work presents a similar set of geometrical relationships for formations in eccentric orbits. Several configurations are shown to illustrate how these relationships can be used to model the formation dynamics. Analysis of propagation errors due to the linearization and the formulation of a navigation filter based on this model are currently underway.

FY 2004 Publications:

C. Lane, P. Axelrad, *Analysis of Formation Flying in Eccentric Orbits Using Linearized Equations of Relative Motion*, 2nd International Symposium on Formation Flying, September 2004.

4.6.4.3 Precise Relative Navigation for High Earth and Libration Point Missions

Principal Investigator: Robert Bishop, University of Texas

The problem of autonomous navigation of multiple spacecraft in the vicinity of a libration point is under consideration. The strategy for the algorithm development is to employ extended Kalman filters (EKFs) as the basic computation unit supplemented by a hierarchical mixture-of-experts (HME) utilizing gating networks for regulation. The first year emphasized the development of a single EKF capable of processing inertial measurement unit information aided by celestial navigation sensors and radiometric cross-links. Realistic sensor errors and environmental uncertainties were considered. The EKF performance was verified through the use of monte carlo analysis and the estimation errors were quantified. The sensor suite elements were compared in their respective abilities to contribute to the observability of the inertial state, relative state, and various bias and other error estimates. The first year effort also includes a re-formulation of the EKF to process lunar altimetry in addition to DSN and libration point sensors. This was in response to the recently announced Vision for Space Exploration which created a desire to consider formations in the Earth-Moon system in a fashion that supported a possible moon exploration mission to locate resources for future manned landings.

FY04 Publications:

P. Huxel and R. H. Bishop, "Navigation Algorithms for Formation Flying Missions," 2nd International Symposium on Formation Flying Missions and Technologies, September 2004.

4.6.4.4 Sensing and Estimation Methods for Relative Navigation and Attitude Determination of Large Satellite Formations

Principal Investigator: Glenn Lightsey, University of Texas

Over the past 12-month period, three primary accomplishments have been attained. In the area of long baseline relative navigation, a navigation filter was implemented and tested using a hardware-in-the-loop GPS simulator at separation distances up to 500 km. It was determined that at distances up to 100 km, improvements in the relative navigation position solution could be achieved by processing the measurements centrally and providing detailed environmental models. Beyond 100 km, the measurements become sufficiently independent that the improvements by differencing and modeling are marginalized. Separately, progress was made on a distributed real-time simulation test environment that can support an arbitrarily large number of vehicles. Although there were some security problems with networking simulators in different locations, most of these have been overcome and a real-time hardware demonstration using a constellation of more than 4 satellites with GPS receivers is expected soon. Also, attitude determination was combined with navigation in a 6N degree of freedom simulation (N is the number of vehicles in the simulation, which are modeled as rigid bodies). This capability was demonstrated using a 2 vehicle gravity gradient formation, and relative attitude estimation accuracy was quantified using GPS receivers as sensors.

FY 2004 Publications:

E. G. Lightsey, "Relative Attitude Determination of Earth Orbiting Formations Using Global Positioning System Receivers," 2nd International Symposium on Formation Flying and Mission Technologies, Sept. 15, 2004, Crystal City, VA.

W. Bamford, "Navigation and Control of Large Satellite Formations," Ph.D. Thesis Defense, The Univ. of Texas at Austin, May 28 2004, Austin, TX.

4.6.4.5 Relative Navigation of Formations of High-Earth-Orbiting Satellites Using Dual Frequency Civilian GPS Technology

Principal Investigator: Mark Psiaki, Cornell University

Techniques are being developed to use civilian dual-frequency GPS signals for relative navigation of high-altitude Earth orbiting satellite formations. These navigation techniques will allow satellite formations to acquire and track GPS signals and perform relative navigation using differential carrier phase techniques. Progress has been made on receiver algorithm design for acquiring weak civilian L2 signals and on methods for processing/filtering GPS carrier phase observables for high precision relative orbit determination. FFT-based block processing acquisition methods have been developed and tested for L2 civilian signals with carrier-to-noise ratios as low as 9 dB-Hz, which enables side-lobe signal acquisition at altitudes ranging from geosynchronous out to 17 Re. The performance of double-differenced carrier phase differential GPS has been investigated for relative orbit determination. We have found that double-difference integer ambiguity resolution techniques should be feasible for these applications if the formation's spacecraft carry properly designed receivers.

FY 2004 Publications:

Psiaki., M.L., Winternitz, L.B., and Moreau, M.C., "FFT-Based Acquisition of GPS L2 Civilian CM and CL Signals", Proceedings of the ION GNSS 2004, Sept. 21-24, 2004, Long Beach, CA.

4.6.5 Libration Point Control

[Technical Contact: Rich Luquette]

This subtopic covers all missions in which the gravitational influence of at least two major bodies plays a significant role, so that approximations of the three-body problem of Lagrange are applicable. Of major interest are missions in large repeating trajectories around the co-linear equilibrium points surrounding the secondary body, and in particular, the Sun-Earth/Moon system is of interest. Control of "deep-space" missions, in which the sun may be considered as the central body, is of secondary interest, but approaches that are equally applicable to both "deep space" missions and either or both of the above subtopics are of special interest.

Below is the supervised research within this topic that is being completed under Cooperative Agreements.

4.6.5.1 Libration Point Mission Formation Control

Principal Investigator: S.N. Balakrishnan, University of Missouri-Rolla (UMR)
Co-Investigator: Henry Pernicka, University of Missouri-Rolla

Since receipt of funding under the NASA GSFC Formation Flying NRA, efforts at the University of Missouri-Rolla (UMR) have focused on various aspects of formation control. Both continuous and discrete control strategies have been developed, initially applied to a pair of spacecraft in a Leader-Follower configuration. The efforts in discrete control quantify at what formation size and allowed deviation that the formation design becomes feasible (given a maneuver "threshold," defined as the smallest ΔV that can be reliably executed). The efforts in continuous control have used a new method developed at UMR known as the "Theta-D" technique to control the relative motion of a pair of spacecraft. We have also come up with a virtual architecture for multiple spacecrafts and have tested the concept with a 4 spacecraft formation. In addition to the PI and Co-PI, two graduate students and one post-doctoral student are assisting with this research.

FY 2004 Publications:

Xin, Ming, Dancer, M. W., Balakrishnan, S.N., and Pernicka, H.J. "*Stationkeeping of an L_2 Libration Point Satellite with $\theta - D$ Technique*," American Control Conference, Boston, MA, June 30-July 2, 2004.

Xin, Ming, Balakrishnan, S.N. and Pernicka, H. "*Deep-Space Spacecraft Formation Flying Using $\theta - D$ Control,*" AIAA Guidance, Navigation, and Control Conference, Providence, Rhode Island, August 16-19, 2004, paper AIAA 2004-4784.

4.6.5.2 Modelling and Control of Libration Point Satellite Formations

Principal Investigator: S. R. Vadali, Texas A&M University
Co-Investigator: K. T. Alfriend, Texas A&M University

The investigation develops new dynamic modeling and control techniques for the Sun-Earth/Moon libration point formations. Research develops control laws for relative and absolute motion, during science modes and for reconfiguration. The emphasis of this investigation is the development of impulsive control laws that use thrust intermittently for formation keeping as well as maneuvering. Utilization of solar radiation pressure for orbit control is considered, requiring a combined study of the attitude as well as orbit dynamics (6-DOF). A novel approach to reference trajectory generation, valid for formation slewing as well as reconfiguration, using the concept of eigen-axis rotations are developed. The technique converts the formation control to an attitude control problem and can be utilized for large or small formations. A concept for balancing the fuel consumption among all the subapertures is developed to increase the mission duration as well as the image quality. Nonlinear control techniques that do not require linearization about a reference trajectory is investigated. Besides using impulsive thrust, orbit control using internal mass movement techniques is also considered.

FY 2004 Publications:

Vadali, S. R., Bae, H.-W., and Alfriend, K. T., "*Design and Control of Libration Point Satellite Formations*", 2004 AAS/AIAA Space Flight Mechanics Meeting, Maui, HI, February 2004, Paper No. AAS 04-161.

4.6.6 Libration Point Formation Design

[Technical Contact: David Folta]

This subtopic covers all missions near libration points where the dynamics of the gravitational influence of two major bodies plays an important role. Beginning with approximations of the circular restricted three-body problem of Lagrange to the use of full ephemeris modeling and modeling of all third body perturbation, this topic analyzes the impacts of design for formations in these regions. These orbits include both co-linear (L_1 and L_2) lissajous and halo orbit classes and bifurcations into associated orbits of equilibrium points surrounding the Sun-Earth/Moon system. Control of "deep-space" missions, in which the sun may be considered as the central body, is of secondary interest in this NRA, but approaches that are equally applicable to both "deep space" missions and either or both of the above subtopics are of special interest.

Below is the supervised research within this topic that is being completed under Cooperative Agreements.

4.6.6.1 Libration Point Formation Design

Principal Investigator: K.C. Howell, Purdue University
Co-Investigator: B. Marchand, Purdue University

Upon receipt of funding under the NASA GSFC Formation Flying NRA, efforts at Purdue University and GSFC have focused on various aspects of how to best design formations to minimize the control efforts and to analyze the use of dynamical systems, central manifolds for example, for initialization. The optimization of the design of a formation can be improved by incorporating dynamical relationships representing the evolution of the families of solutions in libration orbits. Combined with full modeling, a high fidelity system is produced which permits the analyst to accurately determine the control cost of maintenance of the orbit as well as the formation. The use of dynamics relationships and input/output feedback linearization has been used to develop control strategies applied to a formation consisting of multiple (6-30) spacecraft in various pointing directions. These efforts quantify the formation orbit and design that allowed minimal deviation that meet the driving optical-plane science requirements. The design efforts used dynamical system methods (Floquet and others) developed at Purdue and at GSFC. We designed an architecture for a multiple formation (MAXIM and Stellar Imager) and have tested the concept with a 7 spacecraft formation. In addition to the PI and Co-PI, two graduate students are assisting with this research.

FY 2004 Publications:

B.G. Marchand and K.C. Howell, "Formation Flight Near L1 and L2 in the Sun Earth/Moon Ephemeris System Including Solar Radiation Pressure," AAS/AIAA Astrodynamics Specialists Conference, Big Sky, Montana, August 3-7, 2003, Paper No. AAS03-596.

D.C. Folta, K.Hartman, K.C. Howell, B.G. Marchand, "Formation Control of the MAXIM L2 Libration Orbit Mission", AIAA/AAS Astrodynamics, Guidance, Navigation, and Control Conference, Providence, Rhode Island, August 16-19, 2004.

K.C. Howell and B.G. Marchand, “Control Strategies for Formation Flight in the Vicinity of the Libration Points,” AIAA/AAS Space Flight Mechanics Conference, Ponce, Puerto Rico, Feb. 9-13, 2003. AAS Paper 03-113.

4.7 Mission Formulation

This effort provided technology enhancements to address three basic areas important to GSFC in support of all missions and future space architectures: support for Project or PI mission design requests, innovative orbit designs, and the application of new algorithms to our ground support software.

Over the last several years, the FDAB has provided projects with support for the study and analysis of current and future missions. The primary areas supported were projects or PIs that request FDAB support and to provide mission formulation in advance to enable the FDAB to respond to future needs of both Earth and Space Science. FDAB personnel applied past development results to the definition of new classes of orbits and computed the trajectory and cost (delta-V, mass, launch vehicle, etc). An example of this is the assessment of the insertion and station keeping costs associated with a mission to any one of the Earth-Moon libration points (see Figure 4-2).

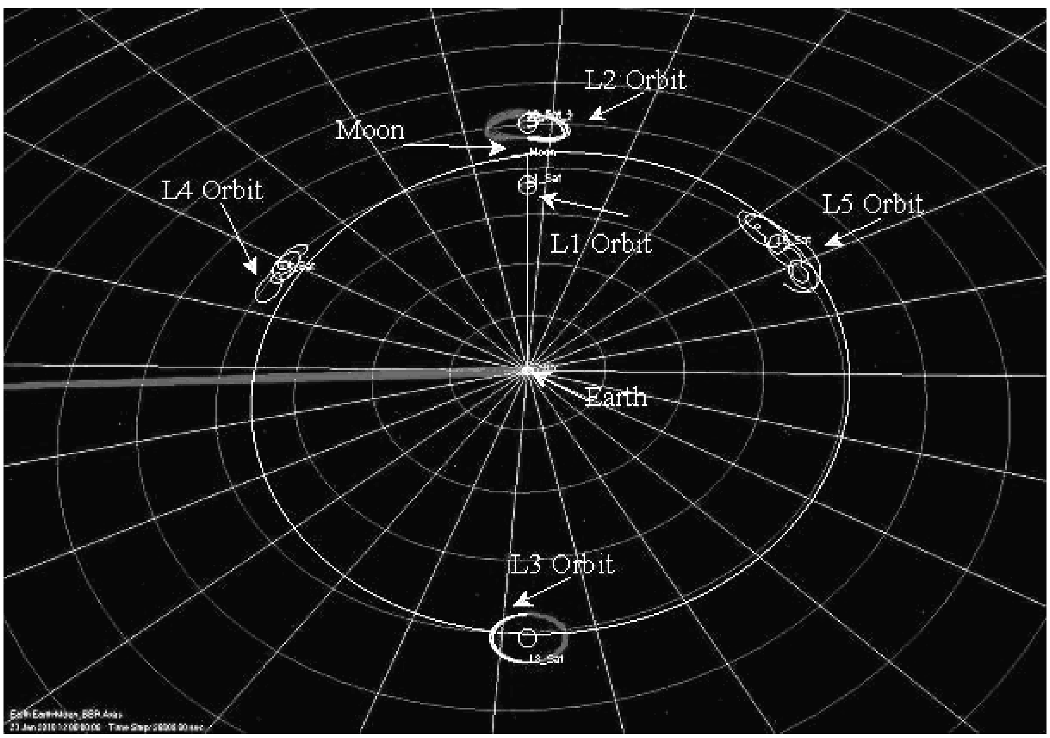

Figure 4-2. Mission Formulation Earth-Moon Libration Orbit Stationkeeping Analysis

FDAB provided support to missions and proposals such as DUO, SIRA, Maxim, Swarm/IT, and the Lunar Initiative. These analysis efforts resulted in analysis that comprised coverage analysis, optimization of orbits for best science collection, formation design, formation control, minimization of Delta V/fuel, sun glint, to name a few.

Innovative orbit designs provide both pure research and applications of previous investigations to support GSFC projects and scientists. The FDAB investigated libration gateways, formation configurations that minimize maintenance requirements, transfers and stationkeeping of Earth-moon libration orbits, and new orbits in the Earth-moon region. The research into these areas of orbit design is new and is performed on a limited basis. GSFC is a leader in these areas and the work proposed here is important for maintaining our expertise.

Ground Algorithms/Software applications ensured that new mission design techniques and software are verified and used effectively. The advantage of previous software utilities is that these can now be easily updated or upgraded to include the research efforts stated above. The development of the Goddard Mission Analysis Tool (GMAT) open source software continued so that the FDAB can meet the demands of mission formulation efforts.

[Technical contacts: David Folta, Frank Vaughn, and Steven Hughes]

4.8 Solar Sails

FDAB continues to participate in the New Millennium Program's Space Technology 9 (ST9) Solar Sail technology validation mission concept studies. The FDAB, in conjunction with GSFC's Mission Applications Branch, developed a medium-fidelity Matlab-based tool that will be used to perform preliminary mission design analysis for low thrust missions. GEODYN is being investigated for navigation-related analysis under low thrust conditions.

The FDAB is working closely with the GSFC Solar Sail team, the MSFC In-Space Propulsion team, JPL and Langley to define an ACS that uses standard and sail actuator systems. The FDAB also developed and validated a low-fidelity coupled ACS and orbit simulator to trade controllability with orbit maneuvering. With heavy FDAB support, the teams are developing solar sail validation and verification concepts and addressing any scalability concerns for various Earth orbit missions.

[Technical contacts: Dave Mangus, Steven Cooley, Greg Marr]

4.9 Magnetometer Navigation (MAGNAV) Experiment Onboard the WIRE Spacecraft

The MAGNAV algorithm ran as a flight experiment as part of the Wide Field Infrared Explorer (WIRE) Post-Science Engineering Testbed. Initialization of MAGNAV occurred on September 4, 2003. The WIRE spacecraft was designed as a four month infrared survey of the universe. WIRE was launched in March, 1999, but was unable to carry out its primary science mission. Since all the non-instrument systems continued to work, WIRE became a test-bed for science opportunities, technology infusion, risk management, educational outreach, and training. MAGNAV ran successfully as an in-flight technology experiment onboard WIRE. The experiment validated MAGNAV as a low cost approach to autonomous navigation that uses existing, reliable sensors.

MAGNAV is designed to autonomously estimate the spacecraft orbit, attitude, and rate using magnetometer and sun sensor data. Since the Earth's magnetic field is a function of time and position, the differences between the computed magnetic field and the measured magnetic field components, as measured by the magnetometer, are a function of the spacecraft trajectory and attitude errors. Therefore, these errors are used to estimate both trajectory and attitude. In addition, the time rate of change of the magnetic field vector is used to estimate the spacecraft rotation rate. The estimation of the attitude and trajectory is augmented with the rate estimation into an Extended Kalman filter blended with a pseudo-linear Kalman filter. Sun sensor data improves the accuracy and observability of the attitude and rate estimates. MAGNAV was loaded in the WIRE onboard computer as a separate task running in step with the attitude control system.

During the experiment WIRE underwent a series of maneuvers and control mode transitions; a period of maximum solar activity and the eclipse season occurred also during the testing. MAGNAV operated during all the events and converged successfully every time it was restarted throughout the experiment. Figure 4.3 shows an example of the results obtained from MAGNAV during the experiment. Figure 4-3(a) shows the MAGNAV attitude estimates and the star tracker based onboard attitude estimates during a maneuver, Figure 4-3(b) shows one axis of the rotation rate during the maneuver, Figures 4-3(c) and 1(d) show the orbit estimation errors.

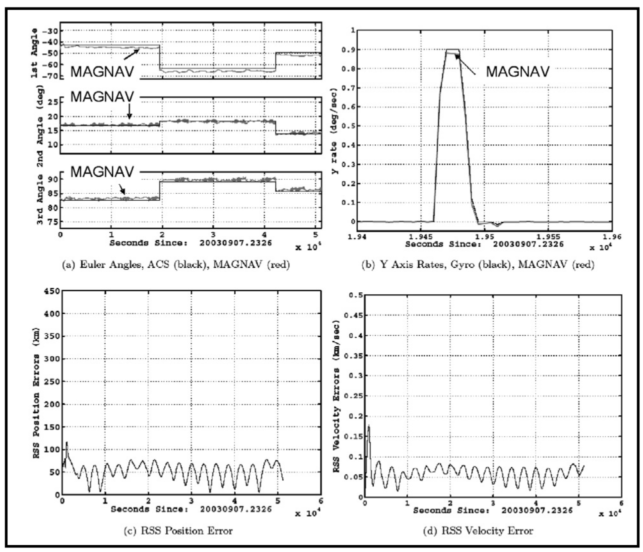

Figure 4-3. MAGNAV Performance during an Attitude Maneuver

Overall, the average attitude accuracies were between 1 and 2 degrees, the average rate accuracies ranged between 0.003 deg/sec to 0.008 deg/sec, and the average position accuracies ranged between 45 and 60 km. The position accuracies, in particular, were somewhat higher than anticipated, possibly from errors in time tags.

Future tests with MAGNAV are planned. Additional testing will help to identify sources of error and improve the overall navigation accuracy. The MAGNAV algorithm will then be coupled with the onboard coarse control algorithm to maintain WIRE in a zenith, sun-pointing attitude. MAGNAV is viable as an autonomous, low cost back-up algorithm, an initialization algorithm, or possibly as a prime navigation algorithm for a future mission with coarse requirements.

[Technical Contacts: Julie Thienel, Richard Harman]

5.0 Branch Infrastructure

5.1 Best Practices for Orbit Analysis, Design, Navigation, and Control

Due to recommendations by the Columbia Accident Investigation Board, the FDAB has begun an effort to identify and record practices essential to mission success by documenting its practices for orbit analysis, design, navigation, and control. In general, these methods are already in use within the branch and will be used as guidelines for future orbit work. Project review boards will verify that these practices are being followed.

All phases of spaceflight missions are covered, from preliminary mission analysis to spacecraft end-of-life. FDAB's set of best practices primarily includes topics that arise during mission development as well as some operations topics. Nevertheless, the FDAB will use AIAA's "Satellite Mission Operations Best Practices", April, 2003, (available at http://www.aiaa.org/tc/sos/bp/Ops_Best_Practices.PDF) as its baseline of best practices for any mission operations phase. The FDAB Best Practices document will be expanded as new experiences provide new insights and as growing familiarity with the document identifies currently accepted practices that are overlooked in the latest version text.

[Technical Contact: Charles Petruzzo]

5.2 Commercial-Off-The-Shelf (COTS) Software Management

The FDAB led the effort to consolidate COTS software licenses for Analytical Graphics, Inc. (AGI) STK at GSFC. STK is used heavily in the FDAB and FDF for feasibility studies, pre-launch analysis, launch and on-orbit operations support. STK is also critical to many operational missions managed by ESMO and SSMO. Future missions, such as SDO, ST5, GPM and LRO, plan to use STK for their pre-launch and operations mission phases, and the demand for STK continues to grow as AGI adds new modules and capabilities to its software. STK's capabilities are outstanding, but the cost is somewhat prohibitive for many missions and organizations so some, as a cost-saving measure, have declined to pay maintenance for their licenses. This approach has its problems, as AGI does not provide technical support for un-maintained licenses (a standard practice in the COTS world) and some missions that dropped their STK maintenance now find that they need to upgrade to necessary capabilities. Approximately 85 licenses were purchased over the last four years, but about 55-60 actually kept up-to-date in maintenance.

A second cost issue is few-license purchases versus multiple-license purchases. Most organizations purchase licenses separately or a few at a time, which precludes them from multiple-license discounts. The FDAB, which maintains 30 licenses for the basic STK modules and varying numbers of specialty-module licenses, benefits heavily from the multiple license discount, saving approximately 30% over the cost of single-license purchase and renewal. The FDAB plans to bring the FDF licenses under the FDAB's STK license maintenance scheme; this plan was also expanded to include the primary users of STK in the ESMO and SSMO MOCs. These licenses constitute the majority of active STK use at GSFC.

The FDAB worked closely with SSMO and ESMO to determine the current and projected use of STK for their respective organizations and to determine the funding available to put a consolidated license scheme in place. After negotiating with AGI, the GSFC group settled on a consolidation and upgrade of 55 basic STK licenses along with an increase in the numbers of licenses for in-demand modules such as the Advanced Visualization and Attitude. The licenses will be available to SSMO & ESMO MOCs, the IMDC, FDAB and FDF through the open and closed networks. Plans for systems administration management and IT security requirements are being formulated now.

Future plans include integrating other GSFC organizations into the consolidation who have expressed interest in using STK, such as AETD's Software Engineering Division, the Mechanical Engineering Division, Networks Engineering Division, the Earth Sciences Directorate and the Space Sciences Directorate, and even the Public Affairs Office. Negotiations will begin next year with AGI in pursuit of a site license for GSFC, as well as a multi-year maintenance agreement for STK products.

[Technical Contact: Karen Richon]

5.3 Generator Tool Enhancements

The FDAB and Purdue University completed major upgrades to the Generator software. Generator, developed at Purdue, is a powerful trajectory design tool that uses invariant manifold theory techniques in conjunction with a sophisticated two-level differential correction scheme to generate libration point trajectories. Generator and its JPL software counterpart, LTOOLS, have a proven track record and have successfully been used to design trajectories for both TRIANA and the recently completed JPL GENESIS mission. Generator is currently being used at GSFC to develop trajectories for the SPIRIT Origins proposal.

Two main enhancements to Generator were completed in FY 2004. First, a new J2 geopotential capability was added to both the force model and the differential corrector. Second, a set of enhancements, intended to allow more efficient use of Generator to design Earth-Moon libration point trajectories, were developed. GSFC had previously used Generator to design mainly Sun-Earth libration point orbits. With this new capability, Generator will be now used to develop mission concepts for the Exploration Vision program.

[Technical contact: Steven Cooley]

5.4 Goddard Mission Analysis Tool (GMAT)

GMAT is an advanced mission analysis system currently under development at GSFC in partnership with private industry. The primary technical objective of the GMAT development effort is to provide a mission analysis system that meets design needs that are not met by current GOTS or COTS products. GMAT has been designed, from the beginning, to perform mission optimization and to interface with external optimization systems. Hence GMAT will enable mission analysts to provide flight projects with the best possible orbit design to maximize the science return of complex missions and to clarify the relationships between specific mission constraints and science performance. GMAT will employ the use of automated optimization and search techniques that will enable one analyst or a small group of analysts to perform rapid trade studies in the mission design process. GMAT can already model the dynamics of distributed spacecraft systems as no other existing system can. The equations of motion for multiple spacecraft missions can be integrated separately or as a coupled dynamic system. This is essential for many missions and also provides a significant speed advantage. GMAT has been designed to allow global epoch synchronization that synchronizes objects in time according to several rules that can be chosen by the user. Current systems either post-process data or require using a common integrator time step for all objects. The secondary objective of the GMAT project is to provide a flexible and modular system that is open source, to facilitate interoperability and reuse and to reduce cost, in the spirit of the One NASA initiative. Due to the open nature of GMAT, models and algorithms can be used by multiple projects and, if necessary, project specific changes can be made efficiently by employing appropriate experts. The GMAT effort is intended to foster active involvement from the private sector and academia, encourage collaborative funding from multiple government agencies and the private sector, and to promote the transfer of technology from government-funded research to the private sector. Below is a screen capture of GMAT in its current form.

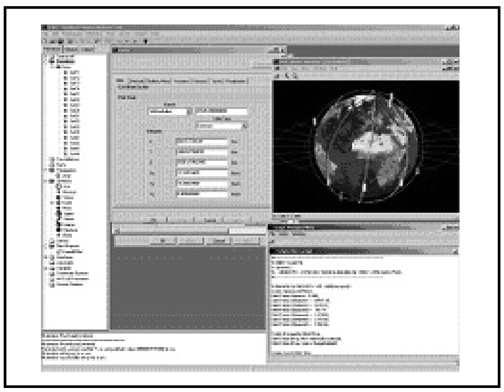

Figure 5-1. GMAT Screen Capture

[Technical contacts: Steven Hughes, David Folta]

5.5 FDAB Web page and Tools

http://fdab.gsfc.nasa.gov

The FDAB Web site Maintenance updated the Web site to make it current and included additional information, such as lunar mission design material. This task is ongoing but the updates to the site included incorporating information from the FY 2003 FDAB End of Year Report and updating the personnel list.

[Technical contact: Oscar Hsu]

5.6 In-House Navigation Systems Development

An in-house navigation systems development effort has been performed by FDAB engineers to maintain and enhance ground-based navigation systems such as the Goddard Trajectory Determination System (GTDS). In this fiscal year, a major effort has been focused on the development of a sophisticated user interface and graphics capabilities (GUI) for GTDS with the support of Code 583 software engineers.

Version 1.1 of this GTDS GUI has been completed and is planned for delivery to GTDS users by December 31, 2004. This version includes basic user interface functions and 2-D graphics capabilities for ephemeris generation (EPHEM), ephemeris comparison (COMPARE), and differential correction (DC). The latest PC version of GTDS available for operations is integrated into this version.

The next version of GTDS GUI will include more complex functions of user interface, the updated version of GTDS and 3-D graphics capabilities.

[Technical Contacts: Son Truong, Joseph Toth]

6.0 Employee Development

6.1 New Employee Profiles

Dean C. Tsai joined the FDAB on February 9, 2004. He received his B.S. degree in Mechanical Engineering from University of California at Berkeley in December 2003. During his undergraduate years, he participated in the development of Joint Strike Fighter (JSF) during his internship at Pratt & Whitney in 2002; he participated in the integration and testing of the Mars Exploration Rover (MER) during his Co-op at Jet Propulsion Laboratory in 2003. Dean is currently developing the satellite simulation for the Magnetosphere Multiscale mission (MMS) as his Professional Intern Program (PIP) project. He is also supporting the ground data processing for the Wire/Magnav experiment and the formation control studies for Constellation-X.

Kevin Berry joined the FDAB on August 23, 2004. He received his B.S. degrees in Applied Mathematics and Mathematical Physics from the California State University at Northridge in June 2004. Since his arrival, Kevin has been busy learning the workings of the Satellite Tool Kit (STK) software by attending a full day training class and executing all of the available tutorials. He has successfully re-run several previous scenarios for the Solar Dynamic Observatory (SDO) in STK and was able to duplicate previous results. STK, plus other software tools, will be used in supporting calculations of the orbit circularization profile of SDO. Kevin will be working on software modeling of the propulsion system of a mono-propellant spacecraft for his PIP I project

Leigh Janes returned to the FDAB on August 23 2004. She first started working in the Branch as a co-op in June 2000 and earned her B.S. in Aerospace Engineering from Purdue University in May 2004. Leigh is currently performing analysis for JWST's transition orbit for her PIP I Project.

6.2 Profession Intern Program (PIP)

The PIP is a developmental program designed to acquaint entry-level professional with NASA and GSFC missions and operations, integrate them into the workforce as quickly as possible, and prepare them for more complex and responsible duties that they can perform with increasing independence. Required program activities include an Individual Development Plan (IDP) prepared for each intern by the supervisor, establishment of a mentor relationship with an experienced staff member, various orientation activities, formal and on-the-job training, and completion of a PIP project, which the intern describes in a written report and oral presentations given in Levels I and II to a panel of evaluators.

6.2.1 PIP Level I: Evaluation of Analytical Solutions for an Elliptical Relative Motion Problem (Rivers Lamb)

As part of the New Millennium Program, the Space Technology 5 (ST5) mission is designed to prove several new technologies onboard three identical spacecraft. These spacecraft were to be deployed into a string of pearls configuration in a Geosynchronous Transfer Orbit (GTO). Understanding the relative motion problem is critical for deployment from the launch vehicle as well as for maneuver planning. While the relative motion problem is well understood for circular orbits, motion in this highly elliptical regime is more challenging. The goal was to find an analytical solution to the elliptical relative motion problem since a thorough numerical analysis can be time consuming and inefficient.

Two different analytical solutions were researched, implemented, and compared to a benchmarked numerical model. Neither solution, however, produced completely satisfactory results for the highly elliptical orbit case. In the meantime, the ST5 mission profile changed with the commitment to a Pegasus XL launch vehicle. In this new orbit regime, an analytical solution became more acceptable due to the change in relative motion dynamics at the significantly lower eccentricity. For future analyses in this orbit regime, it will be possible to use either this acceptable analytical solution or a numerical solution.

(Rivers Lamb has been a full-time Goddard employee since August 2003. Prior to that time, he was a Co-op student within the Branch. He received his B.S. degree in Aerospace Engineering from Virginia Tech.)

6.2.2 PIP Level I: The Effects of Attitude Maneuvers on the MMS Formation (Dean Tsai)

The main objective of the MMS mission is to further study the Earth-Sun magnetosphere. The mission consists of four spinning spacecraft flying in tetrahedron formation to capture the spatial and temporal dynamics of the magnetosphere. One of MMS's challenges is to design, for each spacecraft, an optimal orbit that minimizes the number of maintenance maneuvers that are required during the science phase. While the flight dynamics team has spent tremendous efforts in designing the optimized orbits, little effort has gone towards thruster arrangement designs and maneuver scheme designs. The objective of this PIP project was to look at the feasibility of individual spacecraft reaching its optimized orbit while subject to a particular thruster arrangement design, maneuver scheme, and environment perturbations.

The project has the following components:

1. *<u>Develop a Low Fidelity Simulation for MMS spacecraft</u>*
The simulation features spinning dynamic propagation, sensor noise models, a maneuver execution scheduler, a bang-bang attitude controller, a thruster model, 6DOF orbit propagation, and various orbit perturbation models. The simulation has enough complexities for orbit errors and maneuver scheme trade studies. It also has a generic framework that will allow it to become a high fidelity simulation for operations.
2. *<u>Adopt a Thruster Arrangement and a Nominal Maneuver Scheme</u>*
A reorient-and-burn maneuver scheme has been adopted as the nominal scheme. It requires an individual spacecraft to reorient its spin axis before performing orbit maneuvers. An advantage of this scheme is thruster arrangement simplicity. Several thruster arrangements have been considered, and the nominal thruster arrangement design satisfies the attitude performance requirements.
3. *<u>Create the Formation Initialization Maneuver Sequence</u>*
The flight dynamics team has designed the MMS's orbit in terms of instantaneous delta-V. A Matlab optimization algorithm is used to translate the instantaneous delta-Vs to finite burns. The 10-km (inter-spacecraft separation distance) tetrahedron initialization is used as the main test case.
4. *<u>Evaluate the Performance of the Nominal Maneuver Sequence</u>*
Post-maneuver states are examined in the context of evaluating formation integrity. The deviation of semi-major axis is the primary performance indicator because semi-major axis is crucial for period-matching between spacecraft.

This PIP I project was successfully completed on August 04, 2004. It demonstrated that the MMS simulation has the capability of executing a maneuver sequence and generating data for post-maneuver performance studies. The results of the test case showed the nominal maneuver scheme and thruster arrangement designs introduce excessive orbit errors during the tetrahedron initialization. These results have triggered a series of studies, now underway, on alternative maneuver scheme and thruster arrangement designs.

(Dean Tsai started at Goddard in February, 2004. He received his B.S. degree in Mechanical Engineering from University of California.)

6.3 Cooperative Education Program

The Cooperative Education Program integrates academic study with full time meaningful professional experience. This allows the students, through study and work experience, to enhance their academic knowledge, personal development, and professional preparation.

6.3.1 Edwin Dove (Pennsylvania State University)

Edwin Dove started his first cooperative education ("co-op") rotation in January, 2004, and is the Pennsylvania State University's first co-op student in the FDAB. His rotation lasted one year, instead of the standard one semester or summer, and he completed projects in both the attitude and orbit sides of the FDAB.

The first half of his rotation was in the orbit group. He created a comparative analysis between several orbital lifetime prediction programs, such as STK/Lifetime and GTDS. The purpose of the analysis was to find a possible replacement for PC-Lifetime, one of the FDAB's in-house analytical lifetime prediction programs. He presented the results of his analysis at the 2004 STK Users' Conference in Chantilly, Virginia. He found working in the orbit group to be a good educational experience and a lot of fun.

He worked in the attitude group during the second half of his co-op rotation. He learned Simulink, increased his knowledge of Matlab, generated a summary of the thruster modes (delta-V and delta-H) for Solar Dynamic Observatory (SDO), updated SDO's Simulink thruster models, updated duty cycle analysis for SDO, and learned stability analysis related to SDO. As with his orbit group work, he learned new programs and experienced the engineering life of Goddard.

Edwin will return to Penn State in January 2005 to complete his final semester and will graduate in Spring 2005. He hopes to return to the FDAB full-time after graduation.

6.3.2 Stephanie Gil (Cornell University)

Stephanie Gil is a junior majoring in mechanical/aerospace engineering at Cornell University. This is her first co-op rotation, which began in September, 2004, and will end in January, 2005, at NASA Goddard. She is working in the attitude group on the Solar Sail project. In FY 2004, she analyzed the effects that sinusoidal-shaped wrinkles on the sails have on the force imparted on the sails by solar pressure. Using the results of this analysis, she compared the force expected on a sail with no wrinkles versus a sail with wrinkles. This work helped produce an understanding of the Solar Sail spacecraft's actual behavior as a function of wrinkle size and sun incidence angle.

7.0 Outreach Activities

7.1 SAMPEX University Operations

The University of Maryland's Aerospace Engineering Department completed its final year of flight dynamics operations support for the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) spacecraft. This activity was brought to a close with the end of SAMPEX science operations in the summer of 2004. For five years, a team of University of Maryland undergraduate and graduate students provided spacecraft orbit determination, attitude determination, attitude sensor analysis, and flight dynamics product generation. This effort was sponsored and supported by the FDAB, which provided consultation support as needed and periodically reviewed the overall program status. This was a very successful outreach initiative and gave the student team practical experience and training in spacecraft flight dynamics computations, the use of several commercial ground support tools, and analysis of flight data. One of the current FDAB employees, Oscar Hsu, was an early member of the University of Maryland student team prior to his employment with NASA.

[Technical Contact: Thomas Stengle]

7.2 TableSat

TableSat is an interactive, single-axis spacecraft simulator designed as a tool for demonstrating and teaching the process and challenges of designing attitude control systems. It is composed of a 15" diameter disc, balanced on a center spindle, with four coarse sun sensors, a three-axis magnetometer, and a single axis gyro for sensors; two 12-volt computer fans for actuators; wireless Ethernet for communications; a battery pack for power; and an onboard flight processor (see Figure 7.1).

Figure 7-1. TableSat

The table was originally developed as a demonstration tool for the FDAB's "Attitude Control Systems for Non-ACS Engineers" course, but its uses were expanded after receiving positive feedback from class participants. It has been used to explain the fundamentals of controls and control systems to middle- and high-school students. It was also demonstrated to several undergraduate classes at the University of Maryland's Aerospace Engineering Department.

TableSat is currently being upgraded, with help from the University of Maryland, to better serve as a demonstration tool for undergraduate students in linear controls classes. TableSat now has a faster flight processor, larger fans, a more powerful battery, and a new communications system. The TableSat flight code has been rewritten to include more functionality, including variable control, estimation, and actuation rates; onboard state estimation; and three types of actuation: continuous, bang-bang, and pulse-width modulation. The user can either test controllers using a Simulink block diagram or load controllers and state estimators directly to the flight processor. A Matlab Graphical User Interface (GUI) is currently being developed to allow users to easily vary different TableSat parameters.

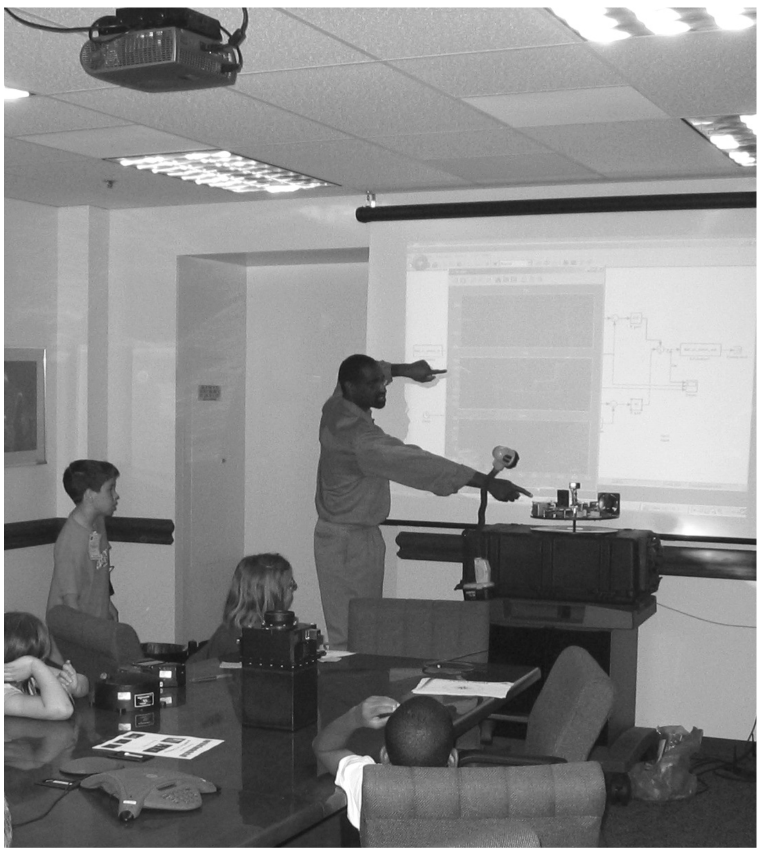

Figure 7-2. TableSat demonstration during "Inspire the Next Generation" Day at GSFC

[Technical Contact: Missie Vess]

8.0 Interagency Activities

8.1 NASA Technical Standards Program

http://www.ccsds.org/
http://standards.gsfc.nasa.gov/

The FDAB supports the NASA Technical Standards Program by contributing to the work of the GSFC standards program, the NASA Data Standards Steering Council (DSSC), and the Consultative Committee for Space Data Systems (CCSDS). The GSFC standards program aims to expand the scope of best practices, and to develop an agency-endorsed database of preferred technical standards for NASA. The DSSC is the hub of the NASA Data Systems Standards Program and is sponsored by NASA Headquarters. The CCSDS is an international organization of space agencies interested in mutually developing standard data-handling techniques to reduce cost, risk and development time and to promote enhanced interoperability and cross-support.

In FY 2004, FDAB personnel participated in the CCSDS navigation workshops that were hosted by the Computer Sciences Corporation, in Lanham, Maryland, during October, 2003, and the Canadian Space Agency facility at Saint Huber, Canada, in May, 2004.

During the first quarter of calendar year 2004, the navigation working group completed another agency wide review of the Orbit Data Message (ODM) Red Book, and conducted exercises with NASA, DLR, and ESA to exchange orbit parameters and ephemeris messages, which is a requirement to qualify the document as a formal CCSDS Recommendation (standard). In September 2004 the CCSDS management council announced its formal approval establishing the ODM as an accepted Recommendation.

FDAB personnel continued discussions, via email and tele-conferences, to advance and revise documentation for attitude data messages, tracking data message, Space Assigned Numbers Authority, Security, and external interfaces. Comments were provided to the CCSDS Cross Support Services (CSS) tracking service white book. Also, CSS personnel are investigating use of streaming media for tracking data transmission, and the navigation working group is investigating whether this concept will effect the definition of a tracking data standard. Updated white book versions were completed for attitude data and tracking data messages, and these documents are currently under review by the working group. Future work will include completion of formal standards for attitude and tracking data exchange and description of XML formats for attitude, orbit and tracking data messages.

[Technical contact: Felipe Flores-Amaya]

8.2 Global Positioning System (GPS) Modernization

The GPS, a space-based radio-navigation system providing highly accurate position, velocity, and time information, was developed in the 1970s and 80s by the U.S. Department of Defense. NASA uses GPS for a wide range of navigation, timing, attitude determination, and scientific applications. With very few exceptions, the GPS signals available to users have remained essentially unchanged since the first GPS satellite was launched in 1978. There are two L-band carrier signals used for navigation: L1 at 1575.42 MHz and L2 at 1227.60 MHz. There is a Coarse Acquisition (C/A) code on the L1 frequency that is available to anyone, as well as a Precision (P(Y)) code available to authorized (military) users on L1 and L2. The great leaps in digital communications technology since the early 1980s have led to a push to modernize the GPS constellation in order to incorporate more modern signal structures and expand the level of services provided to civil users, who now greatly outnumber the military users for whom the system was originally developed.

A number of new capabilities will be available to civil users such as NASA after the launch of the first in a series of "modernized" GPS satellites in 2005. First, a new "precision" civil signal is being added on the L2 carrier that will allow civil users to directly measure and correct for ionospheric errors by tracking signals on both L1 and L2. Furthermore, the new L2C signal has better cross-correlation properties than the C/A signal and has a component that is not modulated by a data message. This makes the new signal advantageous for weak signal tracking applications, such as the capabilities being developed in NASA's Navigator GPS receiver. In 2007, GPS satellites will include a third navigation signal, L5 at 1176.45 MHz, which is being developed to meet the specific needs of aviation users. These new capabilities onboard the GPS satellites coupled with improvements to the GPS ground segment will significantly improve the performance of GPS for civil users.

The Air Force is also currently conducting detailed architecture studies for GPS III, the next series of GPS satellites that will begin launching early in the next decade. The GPS III program will include a number of new improvements to both the ground and space segments of the GPS system, including a cross-link ranging system that will allow near real-time satellite ephemeris and clock updates to be transmitted to users, a new integrity signal, critical for aviation users, that will provide real-time information regarding satellite anomalies or degradations in service, and a modernized navigation signal on the L1 carrier that will be compatible with the new European Galileo Satellites. To ensure their navigation needs are met over the next decades, NASA and other civil agencies have an important role on the GPS III team. Specifically NASA has responsibility to help define the GPS system requirements for space users and has incorporated changes into the GPS III System Specification that, for the first time, spell out signal power and availability requirements for space users. The modernization of GPS will mean improved navigation performance for all Earth-orbiting spacecraft, particularly missions in high Earth orbits.

[Technical contact: Mike Moreau]

8.3 NASA Engineering and Safety Center (NESC) Support

http://nesc.nasa.gov

NESC was formed in the wake of the Space Shuttle Columbia accident to serve as an independent technical resource for NASA managers and employees. The objective of the NESC is to improve safety by performing in-depth independent engineering assessments, testing, and analysis to uncover technical vulnerabilities and to determine appropriate preventative and corrective actions for problems, trends or issues within NASA's programs, projects, and institutions.

FDAB personnel have been supporting the NESC Guidance, Navigation, and Control Super Problem Resolution Team (GNC SPRT) in numerous capacities ranging from core members to technical-team support members. There are fourteen FDAB members on the GNC SPRT: one senior engineer who serves as the core team member, ten engineers who serve as sub-discipline experts, and three junior engineers serving as technical-team support members.

During FY 2004, the FDAB personnel have been involved with the following NESC GNC SPRT activities:

- Face-to-Face Meeting at the AIAA Guidance, Navigation, and Control Conference in Providence, RI.
- Past SPRT Support
    - MER, Calipso, International Space Station (ISS) Control Moment Gyro Anomaly
- Current SPRT Support
    - Independent Technical Assessment/Investigations: ISS & Shuttle Recurring Anomalies, Orbiter Repair Manuever, Genesis Re-entry Observation
    - Consultations: Cassini Orbit Insertion, Cassini-Huygens Probe Entry, Genesis, Shuttle Reentry/Aero Flight Control Technical Interchange Meeting, Hubble Space Telescope System Health

8.3.1 Space Shuttle Recurring Anomalies Review

The Space Shuttle Recurring Anomalies review effort includes engineers from the NASA centers and from private industry. The review effort is intended to apply independent technical resources to Shuttle problems, uncover technical vulnerabilities, and perform independent engineering trend analysis and risk assessment. The teams are mechanisms (dynamic mechanical systems, actuators, and pyrotechnics), structures (static mechanical systems, thermal protection, materials),fluids, propulsion, electrical /avionics, software, and human factors. The teams perform a structured review of existing Shuttle anomaly reports, along with further searches of the Shuttle's Problem Reporting and Corrective Action Database. All of the identified issues are documented and reported to the NESC Systems Engineering Office.

The electrical/avionics team, in particular, is tasked with the review of all the Shuttle guidance, navigation, and control issues along with all the electrical issues. This includes wire splices, connector savers, metastability, particle and debris sealed devices, servo valve oscillations, gyros, star trackers, IMU, single event upsets, pyro firing failures, Kapton wiring, shuttle and SRB umbilical, CE-07 trending, bent connector pins, crimping processes, exceptions to standard repairs, microswitch contacts, issues with ET doors, single-use cables, capacitor and power supplies, water spray blower motor, flash evaporator, redundancy, flood-light seals, insulation, staking of screws with potting compound, AC motor valve, corrosion, EVA and ground operations.

GNC-specific issues that have been documented to date relate to problems with the IMU, the solid rocket booster gyros, and the star trackers. The items with the highest criticality are the IMU and gyro issues. Problems related to wiring, lubricants, shipping, restraint drift, accelerometer bias, power supply issues, noisy/high rate/spikes/instability in output, spin motor rotation detector issues, test failures, electrical/bent pin issues, and metal issues have been documented and reported. The Shuttle review effort will end in October, 2004, and will be followed by a similar review effort for the International Space Station.

[Technical contact: Dave Mangus, Oscar Hsu, Julie Thienel]

8.4 Low-Thrust Working Group

GSFC continued its participation in the interagency Low Thrust Working Group. The working group, funded by NASA HQ and managed by MSFC, is developing a new state-of-the-art suite of low-thrust tools. The five tools, called MALTO, Mystic, OTIS, SNAP, and Copernicus, will meet the needs of our internal and external customers, who are planning ever more complex missions that require low-thrust propulsion. The tools are also designed to be compatible with each other. GSFC will receive preliminary versions of the tools in early FY 2005 and will participate in Beta testing. The target release date for Version 1.0 of these tools is at the end of FY 2005. Academia and industry will have, to the maximum extent possible, access to the tools in this suite for use in research and business.

The working group has held three yearly Technical Interchange Meetings (TIMs). GSFC personnel participated in the recent 2004 NASA Intercenter Low-Thrust (LT) TIM held at JPL in August, 2004. The next LT TIM, which coincides with the planned release of the suite of tools, will be held at MSFC in September, 2005.

[Technical contact: Steven Cooley]

Appendix A: Conferences and Paper Abstracts

Given below are abstracts from professional papers and technical presentations that were prepared and delivered in FY 2004 by branch members.

Journal Articles

2004 Classical and Quantum Gravity, Volume 21, S635-S640, February, 2004

"Pointing Acquisition and Performance for the Laser Interferometry Space Antenna Mission," Hyde, Maghami, Merkowitz

ABSTRACT: The laser interferometer space antenna (LISA) mission, a space-based gravitational wave detector, uses laser metrology to measure distance fluctuations between proof masses aboard three spacecraft. Each spacecraft has two incoming and two outgoing laser beams for a total of six laser links. These links are established sequentially at the start of the mission, and the spacecraft control systems must aim their lasers at each other with pointing motions less than 8 nrad/Hz$^{-1/2}$ in the frequency band 1100 mHz. The process for acquiring the laser links as well as the simulated performance is described.

Conferences

NASA/Goddard Space flight Center Flight Mechanics Symposium, Greenbelt, Maryland, October 28-30, 2003

"Nonlinear Observers for Gyro Calibration," Thienel, Sanner

ABSTRACT: Nonlinear observers for gyro calibration are presented. The first observer estimates a constant gyro bias. The second observer estimates scale factor errors. The third observer estimates the gyro alignment for three orthogonal gyros. The convergence properties of all three observers are discussed. Additionally, all three observers are coupled with a nonlinear control algorithm. The stability of each of the resulting closed loop systems is analyzed. Simulated test results are presented for each system.

"Applications of a Semiparametric Statistical Method to Spacecraft Sensor and Calibration Data," Kedem, Thienel, Harman

ABSTRACT: A semiparametric statistical method is applied to spacecraft sensor data. The method stipulates a reference distribution and deviations from it and the problem is to estimate the reference distribution and the distorted distributions from all available data. That is from the combined data obtained from all the sources under consideration. The problem can be solved by assuming a distortion form and independent data.

"Gyroless Attitude and Rate Estimation Algorithms for the FUSE Spacecraft," Harman, Thienel, Oshman

ABSTRACT: The Far Ultraviolet Spectroscopic Explorer (FUSE) is equipped with two ring laser gyros on each of the spacecraft body axes. In May 2001 one gyro failed. It is anticipated that all of the remaining gyros will also fail, based on intensity warnings. In addition to the gyro failure, two of four reaction wheels failed in late 2001. The spacecraft control now relies heavily on magnetic torque to perform the necessary science maneuvers and hold on target. The only sensor consistently available during slews is a magnetometer. This paper documents the testing and development of magnetometer-based gyroless attitude and rate estimation algorithms for FUSE. The results of two approaches are presented, one relies on a kinematic model for propagation, a method used in aircraft tracking, and the other is a pseudo-linear Kalman filter that utilizes Euler's equations in the propagation of the estimated rate. Both algorithms are tested using flight data collected over a few months after the reaction wheel failure. Finally, the question of closed-loop stability is addressed. The ability of the controller to meet the science slew requirements, without the gyros, is analyzed.

"Formation Tetrahedron Design for Phase I of the Magnetospheric Multiscale Mission," Hughes

ABSTRACT: The Magnetospheric Multiscale Mission (MMS) is a NASA mission intended to make fundamental advancements in our understanding of the Earth's Magnetosphere. There are three processes that MMS will study including magnetic reconnection, charged particle acceleration, and turbulence. There are four phases in the nominal mission and this work addresses some of the outstanding issues in phase I. The nominal Phase-I orbit is a 1.2 x 12 R_e, highly elliptic orbit with four spacecraft nominally forming a regular tetrahedron. In this paper we investigate the relative dynamics of the four MMS spacecraft about an assumed reference orbit. There are several tetrahedron dimensions required in Phase I of the mission and in this work we design optimal tetrahedrons for the 10 km baseline. The performance metric used in the optimization process is directly related to the science return, and is based on an extension of previous work performed by Glassmeier. The optimizer we use is a commercially available Sequential Quadratic Programming (SQP) routine. Multiple optimal solutions are found, and we characterize how the performance of the formation varies between different regions of the reference orbit.

"Disturbance Reduction Control Design for the ST7 Flight Validation Experiment," Maghami, Hsu, Markley, Houghton

ABSTRACT: The Space Technology 7 experiment will perform an on-orbit system-level validation of two specific Disturbance Reduction System technologies: a gravitational reference sensor employing a free-floating test mass, and a set of micro-Newton colloidal thrusters. The ST7 Disturbance Reduction System is designed to maintain the spacecrafts position with respect to a free-floating test mass to less than 10 nm/vHz, over the frequency range of 1 to 30 mHz. This paper presents the design and analysis of the coupled, drag-free and attitude control systems that close the loop between the gravitational reference sensor and the micro-Newton thrusters, while incorporating star tracker data at low frequencies. A full 18 degree-of-freedom model, which incorporates rigid-body models of the spacecraft and two test masses, is used to evaluate the effects of actuation and measurement noise and disturbances on the performance of the drag-free system.

AAS Guidance and Control Conference, Breckenridge, Colorado, February 4-8, 2004

"Nonlinear Observers for Gyro Calibration," Thienel, Sanner

ABSTRACT: Nonlinear observers for gyro calibration are presented. The first observer estimates a constant gyro bias. The second observer estimates scale factor errors. The third observer estimates the gyro alignment for three orthogonal gyros. The observers are then combined. The convergence properties of all three observers, and the combined observers, are discussed. Additionally, all three observers are coupled with a nonlinear control algorithm. The stability of each of the resulting closed loop systems is analyzed. Simulated test results are presented for each system.

"Orbit Design for Phase I and II of the Magnetospheric Multiscale Mission," Hughes

ABSTRACT: The Magnetospheric Multiscale Mission (MMS) is a NASA mission intended to make fundamental advancements in our understanding of the Earth's magnetosphere. There are three processes that MMS is intended to study including magnetic reconnection, charged particle acceleration, and turbulence. There are four phases of the MMS mission and each phase is designed to study a particular region of the Earth's magnetosphere. The mission is composed of a formation of four spacecraft that are nominally in a regular tetrahedron formation. In this work, we present optimal orbit designs for Phase I and II. This entails designing reference orbits such that the spacecraft dwell-time in the region of interest is a maximum. This is non-trivial because the Earth's magnetosphere is dynamic and its shape and position are not constant in inertial space. Optimal orbit design for MMS also entails designing the formation so that the relative motion of the four spacecraft yields the greatest science return. We develop performance metrics that are directly related to the science return, and use Sequential Quadratic Programming (SQP) to determine optimal relative motion solutions. While designing for optimal science return, we also consider practical constraints such as maximum eclipse time and minimum inter-spacecraft separation distances. Data are presented that illustrates how long we can ensure that the formation remains in the relevant region of the Earth's magnetosphere. We also draw general conclusions about where in the orbit acceptable tetrahedron configurations can be provided and for how long.

AAS/AIAA Space Flight Mechanics Meeting, Wailea, Hawaii, February 8-12, 2004

"Use of Invariant Manifolds for Transfers between Three-Body Systems,"
Howell, Patterson, Beckman, Folta

ABSTRACT: The Lunar L1 and L2 libration points have been proposed as gateways granting inexpensive access to interplanetary space. To date, only individual solutions to the transfer between three-body systems have been found. The methodology to solve the problem for arbitrary three-body systems and entire families of orbits does not exist. This paper presents the initial approaches to solve the general problem for single and multiple impulse transfers. Two different methods of representing and storing 7-dimensional invariant manifold data are presented. Some particular solutions are presented for the transfer problem, though the emphasis is on developing methodology for solving the general problem.

Astronomical Telescopes and Instrumentation, Glasgow, Scotland, June 21-25, 2004

"Pointing Control System Design and Performance Evaluation of TPF Coronagraph,"
Liu, Blaurock, Mosier

ABSTRACT: The Terrestrial Planet Finder (TPF) project aims to detect and characterize extra-solar Earth-like planets. The coronagraph telescope is one of the two mission concepts being studied. To reject the star flux and detect the planet flux in the visible light range, the coronagraph telescope must achieve a rejection ratio on the order of a billion to one. Dynamic jitter, introduced by environmental and on-board mechanical disturbances, degrades the optical performance, as characterized primarily by contrast ratio. The feasibility of using passive vibration isolation combined with active attitude and line-of-sight (LOS) control systems to stabilize the spacecraft and the optical components to the requisite level is being studied. The telescope is also required to slew between targets or rotate around the LOS. The slew mode control law must be designed to balance the need for efficient large-angle maneuvers while simultaneously avoiding the excitation of flexible modes in order to minimize settling time.

This paper provides an overview of the current control design concept and sensor/actuator topology for TPF Coronagraph and illustrates the fine pointing performance of the telescope. This performance is primarily a function of the rejection of high-frequency dynamic disturbances, in this case due to reaction wheel disturbance forces/torques transmitted through the passive isolation stage. Trade studies between isolator force rejection and disturbance level reduction via wheel redesign are also presented to illustrate the requirements imposed on current technologies. Finally, the paper summarizes preliminary results on the slew/settle performance of the telescope.

"Requirements Formulation and Dynamic Jitter Analysis for the Fourier-Kelvin Stellar Interferometer," Tupper, Liu, Blaurock, Bolognese, Howard, Danchi

ABSTRACT: The Fourier-Kelvin Stellar Interferometer (FKSI) has been proposed to detect and characterize extra solar giant planets. The baseline configuration for FKSI is a two-aperture, structurally connected nulling interferometer, capable of providing null depth less than 10-4 in the infrared. The objective of this paper is to summarize the process for setting the top level requirements and the jitter analysis performed on FKSI to date. The first part of the paper discusses the derivation of dynamic stability requirements, necessary for meeting the FKSI nulling demands. An integrated model including structures, optics, and control systems has been developed to support dynamic jitter analysis and requirements verification. The second part of the paper describes how the integrated model is used to investigate the effects of reaction wheel disturbances on pointing and optical path difference stabilities.

40TH AIAA JOINT PROPULSION CONFERENCE, FORT LAUDERDALE, FLORIDA, JULY 11-14, 2004

"Propulsion Options for the LISA Mission," Cardiff, Marr

ABSTRACT: The LISA mission is a constellation of three spacecraft operating at 1 AU from the Sun in a position trailing the Earth. After launch, a propulsion module provides the DV necessary to reach this operational orbit, and separates from the spacecraft. A second propulsion system integrated with the spacecraft maintains the operational orbit and reduces non-gravitational disturbances on the instruments. Both chemical and electrical propulsion systems were considered for the propulsion module, and this trade is presented to show the possible benefits of an EP system. Several options for the orbit maintenance and disturbance reduction system are also briefly discussed, along with several important requirements that suggest the use of a FEEP thruster system.

SPACE SYSTEMS OPTOMECHANICS AND DYNAMICS CONFERENCE, 49TH SPIE ANNUAL MEETING, DENVER, COLORADO, AUGUST 4-6, 2004

"Control Modes of the ST7 Disturbance Reduction System Flight Validation Experiment," Maghami, Hsu, Markley, O'Donnell

ABSTRACT: Space Technology 7 (ST7) experiment will perform an on-orbit system-level validation of two specific Disturbance Reduction System technologies: a gravitational reference sensor employing a free-floating test mass and a set of micronewton colloidal thrusters. The ST7 Disturbance Reduction System (DRS) is designed to maintain the spacecrafts position with respect to a free-floating test mass to less than 10 nm/vHz over the frequency range of 1 to 30 mHz. This paper presents the overall design and analysis of the spacecraft drag-free and attitude controllers. These controllers close the loop between the gravitational sensors and the micronewton colloidal thrusters. There are five control modes in the operation of the ST7 DRS, starting with the attitude-only mode and leading to the science mode. The design and analysis of each of the control modes as well as the mode transition strategy are presented.

AIAA/AAS Astrodynamics Specialists Conference, Providence, Rhode Island, August 16-19, 2004

"Orbit Optimization for the Geospace Electrodynamics Connections (GEC) Mission," Mesarch

ABSTRACT: Part of NASA's Solar Terrestrial Probe line of missions, the Geospace Electrodynamics Connections (GEC) mission will deploy a formation of three spacecraft to perform in-situ atmospheric research in the low Ionosphere-Thermosphere region. These spacecraft will fly together in a "string-of-pearls" formation with variable separations ranging from 10 seconds to one-quarter of an orbit at perigee. Over the course of its two-year mission, the three spacecraft will perform ten, 1-week dipping campaigns whereby they maneuver to lower their perigee to near 134 km. Using available launch vehicle performance data, an optimal parking orbit of 222 x 1525 km was found to maximize the dry mass available while providing enough propellant to perform the ten deep-dipping campaigns over its two-year mission. The results were used to create multi-variable contour plots containing the orbit perigee, the orbit apogee, spacecraft dry mass, propellant mass, and T500 (a science data collection figure of merit that tabulates the cumulative time spent below 500 km). These plots illustrate how the mission can trade off science return relative to the cost in dry mass and propellant. Other optimal solutions such as minimum propellant or maximum T500 were found to either limit the science data collection or to be dry mass limiting, respectively. Sensitivity analyses were performed to find new optimal (maximum dry mass) solutions if the number of campaigns changed, if the coefficient of drag (C_D) were different, and if the propellant specific impulse were increased. A surprising result showed that the dry mass and T500 were both increased if the number of campaigns decreased. Changes in C_D provided the expected results – raising C_D lowered both the dry mass and T500 while lowering C_D raised both the dry mass and T500. Increases in the propellant specific impulse had the expected outcome of raising the dry mass and lowering the propellant load but there was no change in the T500 figure of merit. The orbit optimization was performed parametrically using a Matlab™ script and validated using FreeFlyer™, a commercial orbit analysis tool.

"Results of the Magnetometer Navigation (MAGNAV) Inflight Experiment,"
Thienel, Harman, Bar-Itzhack

ABSTRACT: The Magnetometer Navigation (MAGNAV) algorithm is currently running as a flight experiment as part of the Wide Field Infrared Explorer (WIRE) Post-Science Engineering Testbed. Initialization of MAGNAV occurred on September 4, 2003. MAGNAV is designed to autonomously estimate the spacecraft orbit, attitude, and rate using magnetometer and sun sensor data. Since the Earth's magnetic field is a function of time and position, and since time is known quite precisely, the differences between the computed magnetic field and measured magnetic field components, as measured by the magnetometer throughout the

entire spacecraft orbit, are a function of the spacecraft trajectory and attitude errors. Therefore, these errors are used to estimate both trajectory and attitude. In addition, the time rate of change of the magnetic field vector is used to estimate the spacecraft rotation rate. The estimation of the attitude and trajectory is augmented with the rate estimation into an Extended Kalman filter blended with a pseudo-linear Kalman filter. Sun sensor data is also used to improve the accuracy and observability of the attitude and rate estimates. This test serves to validate MAGNAV as a single low cost navigation system which utilizes reliable, flight qualified sensors. MAGNAV is intended as a backup algorithm, an initialization algorithm, or possibly a prime navigation algorithm for a mission with coarse requirements. Results from the first six months of operation are presented.

"A Survey of Earth-Moon Libration Orbits: Stationkeeping Strategies and Intra-Orbit Transfers," Folta, Vaughn

ABSTRACT: Cislunar space is a readily accessible region that may well develop into a prime staging area in the effort to colonize space near Earth or to colonize the Moon. While there have been statements made by various NASA programs regarding placement of resources in orbit about the Earth-Moon Lagrangian locations, there is no survey of the total cost associated with attaining and maintaining these unique orbits in an operational fashion. Transfer trajectories between these orbits required for assembly, servicing, and positioning of these resources have not been extensively investigated. These orbits are dynamically similar to those used for the Sun-Earth missions, but differences in governing gravitational ratios and perturbation sources result in unique characteristics.

We implement numerical computations using high fidelity models and linear and non-linear targeting techniques to compute the various maneuver delta-V and temporal costs associated with orbits about each of the Earth-Moon Lagrangian locations (L_1, L_2, L_3, L_4, and L_5). From a dynamical system standpoint, we speak to the nature of these orbits and their stability. We address the cost of transfers between each pair of Lagrangian locations

"Formation Control of the MAXIM L_2 Libration Orbit Mission," Folta, Hartman, Howell, Marchand

ABSTRACT: The Micro-Arcsecond X-ray Imaging Mission (MAXIM), a proposed concept for the Structure and Evolution of the Universe (SEU) Black Hole Imager mission, is designed to make a ten million-fold improvement in X-ray image clarity of celestial objects by providing better than 0.1 micro-arcsecond imaging. Currently the mission architecture comprises 25 spacecraft, 24 as optics modules and one as the detector, which will form sparse sub-apertures of a grazing incidence X-ray interferometer covering the 0.3-10 keV bandpass. This formation must allow for long duration continuous science observations and also for reconfiguration that permits re-pointing of the formation. To achieve these mission goals, the

formation is required to cooperatively point at desired targets. Once pointed, the individual elements of the MAXIM formation must remain stable, maintaining their relative positions and attitudes below a critical threshold. These pointing and formation stability requirements impact the control and design of the formation.

In this paper, we provide analysis of control efforts that are dependent upon the stability and the configuration and dimensions of the MAXIM formation. We emphasize the utilization of natural motions in the Lagrangian regions to minimize the control efforts and we address continuous control via input feedback linearization (IFL). Results provide control cost, configuration options, and capabilities as guidelines for the development of this complex mission.

"Pseudo-Linear Attitude Determination of Spinning Spacecraft," Bar-Itzhack, Harman

ABSTRACT: This paper presents the overall mathematical model and results from pseudo linear recursive estimators of attitude and rate for a spinning spacecraft. The measurements considered are vector measurements obtained by sun-sensors, CCD head star trackers, horizon sensors, and three axis magnetometers. Two filters are proposed for estimating the attitude as well as the angular rate vector. One filter, called the *q-Filter*, yields the attitude estimate as a quaternion estimate, and the other filter, called the *D-Filter*, yields the estimated direction cosine matrix. Because the spacecraft is gyro-less, Euler's equation of angular motion of rigid bodies is used to enable the estimation of the angular velocity. A simpler Markov model is suggested as a replacement for Euler's equation in the case where the vector measurements are obtained at high rates relative to the spacecraft angular rate. The performance of the two filters is examined using simulated data.

"Implicit and Explicit Spacecraft Gyro Calibration," Bar-Itzhack, Harman

ABSTRACT: This paper presents a comparison between two approaches to sensor calibration. According to one approach, called explicit, an estimator compares the sensor readings to reference readings, and uses the difference between the two to estimate the calibration parameters. According to the other approach, called implicit, the sensor error is integrated to form a different entity, which is then compared with a reference quantity of this entity, and the calibration parameters are inferred from the difference. In particular this paper presents the comparison between these approaches when applied to in-flight spacecraft gyro calibration. Reference spacecraft rate is needed for gyro calibration when using the explicit approach; however, such reference rates are not readily available for in-flight calibration. Therefore the calibration parameter-estimator is expanded to include the estimation of that reference rate, which is based on attitude measurements in the form of attitude-quaternion. A comparison between the two approaches is made using simulated data. It is concluded that the performances of the two approaches are basically comparable. Sensitivity tests indicate that the explicit filter results are essentially insensitive to variations in given spacecraft dynamics model parameters.

"Linear State-Space Representation of the Dynamics of Relative Motion, Based on Restricted Three BodyDynamics," Luquette, Sanner

ABSTRACT: Precision Formation Flying is an enabling technology for a variety of proposed space-based observatories, including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), Stellar Imager (SI) and the Terrestrial Planet Finder (TPF). An essential element of the technology is the control algorithm, requiring a clear understanding of the dynamics of relative motion. This paper examines the dynamics of relative motion in the context of the Restricted Three Body Problem (RTBP). The natural dynamics of relative motion are presented in their full nonlinear form. Motivated by the desire to apply linear control methods, the dynamics equations are linearized and presented in state-space form. The stability properties are explored for regions in proximity to each of the libration points in the Earth/Moon - Sun rotating frame. The dynamics of relative motion are presented in both the inertial and rotating coordinate frames.

2ND INTERNATIONAL SYMPOSIUM ON FORMATION FLYING, CRYSTAL CITY, VIRGINIA, SEPTEMBER 14-16, 2004

"Formation Control for the MAXIM Mission," Luquette, Leitner, Gendreau, Sanner

ABSTRACT: Over the next twenty years, a wave of change is occurring in the space-based scientific remote sensing community. While the fundamental limits in the spatial and angular resolution achievable in spacecraft have been reached, based on today's technology, an expansive new technology base has appeared over the past decade in the area of Distributed Space Systems (DSS). A key subset of the DSS technology area is that which covers precision formation flying of space vehicles. Through precision formation flying, the baselines, previously defined by the largest monolithic structure which could fit in the largest launch vehicle fairing, are now virtually unlimited. Several missions including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), and the Stellar Imager will drive the formation flying challenges to achieve unprecedented baselines for high resolution, extended-scene, interferometry in the ultraviolet and X-ray regimes. This paper focuses on establishing the feasibility for the formation control of the MAXIM mission. MAXIM formation flying requirements are on the order of microns, while Stellar Imager mission requirements are on the order of nanometers. This paper specifically addresses: (1) high-level science requirements for these missions and how they evolve into engineering requirements; and (2) the development of linearized equations of relative motion for a formation operating in an n-body gravitational field. Linearized equations of motion provide the ground work for linear formation control designs.

18TH INTERNATIONAL SYMPOSIUM ON SPACEFLIGHT DYNAMICS, MUNICH, GERMANY, OCTOBER 11-15, 2004

"Hardware-in-the-Loop Testing of Continuous Control Algorithms for a Precision Formation-Flying Demonstration Mission," Naasz, Burns, Gaylor, Higinbotham

ABSTRACT: A sample mission sequence is defined for a low earth orbit demonstration of Precision Formation Flying (PFF). Various guidance navigation and control strategies are discussed for use in the PFF experiment phases. A sample PFF experiment is implemented and tested in a realistic Hardware-in-the-Loop (HWIL) simulation using the Formation Flying Test Bed (FFTB) at NASA's Goddard Space Flight Center.

"Exchange of Standarized Flight Dynamics Data,"
Martin-Mur, Berry, Flores-Amaya, Folliard, Kiehling, Ogawa, Pallaschke

ABSTRACT: Spacecraft operations require the knowledge of the vehicle trajectory and attitude and also that of other spacecraft or natural bodies. This knowledge is normally provided by the Flight Dynamics teams of the different space organizations and, as very often spacecraft operations involve more than one organization, this information needs to be exchanged between Agencies. This is why the Navigation Working Group within the CCSDS (Consultative Committee for Space Data Systems) has been instituted with the task of establishing standards for the exchange of Flight Dynamics data. This exchange encompasses trajectory data, attitude data, and tracking data. The Navigation Working Group includes regular members and observers representing the participating Space Agencies. Currently the group includes representatives from CNES, DLR, ESA, NASA and JAXA. This Working Group meets twice per year in order to devise standardized language, methods, and formats for the description and exchange of Navigation data. Early versions of some of these standards have been used to support mutual tracking of ESA and NASA interplanetary spacecraft, especially during the arrival of the 2003 missions to Mars. The Navigation Working Group is currently in the process of developing a common Extensible Markup Language (XML) specification for all the navigation messages. This paper provides a summary of the activities carried out by the group, briefly outlines the current and envisioned standards, describes the tests and operational activities that have been performed using the standards, and lists and discusses the lessons learned from these activities.

"Control of the Laser Interferometer Space Antenna," Maghami, Hyde, Kim

ABSTRACT: The Laser Interferometer Space Antenna mission is a planned gravitational wave detector consisting of three spacecraft in heliocentric orbit. Laser interferometry is used to measure distance fluctuations between test masses aboard each spacecraft to the picometer level over a 5 million kilometer separation. The Disturbance Reduction System comprises the pointing and positioning control of the spacecraft, electrostatic suspension control of the test masses, and point-ahead and acquisition control. This paper presents a control architecture and design for the Disturbance Reduction System to meet the stringent pointing and positioning requirements. Simulations are performed to demonstrate the feasibility of the proposed architecture.

Appendix B: Reviews Supported

Below is a list of various reviews that were supported by FDAB personnel during FY2004.

APL Honeywell MIMU Failure Briefing
APL New Horizons/Pluto Attitude Determination Review
Aura Flight Dynamics Peer Reviews
Aura OD Peer Review
Dean Tsai PIP Review
FUSE gyro-less Flight Actual Review
FUSE gyro-less Flight Reading Review
GLAST Flight Software Critical Design Review
GLAST Ground System SDR Review
GLAST Mission Operations Center (MOC) Design Peer Review
GLAST Orbital Lifetime Review
GLAST Pointing Knowledge Review
GLAST Pointing Knowledge Review, #2
GLAST Re-Entry Peer Review
GPM Peer Review
HRV DM SEB
HST 2-gyro Science Mode System PDR Review
HST 2-gyro Science Peer Review
HST Pointing Control System Review
INFOCUS Peer Review
JWST ISIM System Requirements Review
Messenger Mission Readiness Review
New Horizons Mission Design Review
SDO Ground System Preliminary Design Review
SDO Mission Operations Center Peer Review
SDO Peer Review
Sentinels Science Definition Team Meeting
ST-5 Mission Design Review
ST7 HiFi Stimulation Tabletop
STEREO Mission CDR Single-Point Failures Review
STEREO Mission Operations Review
STEREO Review
Sun Solar Systems Connections Roadmap Meeting
Swift FOR Review Board
THEMIS Flight Dynamics Operations Peer Review
THEMIS Peer Review
THEMIS Preliminary Design Review

Appendix C: Acronyms and Abbreviations

AAS	American Astronomical Society
AC	Afternoon Constellation
AC	analog current
ACE	Active Coronal Explorer
ACS	attitude control system
AETD	Applied Engineering and Technology Directorate
AGI	Analytical Graphics, Inc.
AIAA	American Institute of Aeronautics and Astronautics
ALMA	Atacama Large Millimeter Array
ANTS	Autonomous NanoTechnology Swarm
AO	Annoucement of Opportunity
APL	Applied Physics Laboratory
AR&C	Autonomous Rendezvous and Control
AU	Astronomical Unit
AutoFDS	Autonomous Flight Dynamics System
BSS	Boeing Satellite Systems
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite
CCB	configuration control board
CCD	Charge Coupled Device
CCS	Constellation Coordination System
CDA	Command and Data Acquisition
CDGPS	Carrier-phase Differential GPS
CDR	critical design review
CERES	Coalition for Environmentally Responsible Economies
CMNT	colloidal micronewton thruster
CNES	Centre National d'Etudes Spatiales
co-op	Cooperative Education
COS	Cosmic Origins Spectrograph
COTS	Commercial-off-the-shelf
CSC	Computer Sciences Corp.
CSOC	Consolidated Space Operations Contract
CSS	Cross Support Services
dB	decibel
DCS	Dynamics Control System
deg	degree
DM	De-orbit Module
DOF	degree of freedom
DOWD	differenced one-way doppler
DRS	Disturbance Reduction System
DSN	Deep Space Network
DSS	Distributed Space System
DUO	Dark Universe Observatory
EAVCS	Enhanced Auto-track Computer Vision System

EFF	Enhanced Formation Flying
EKF	extended Kalman Filter
ELV	Expendable Launch Vehicle
EM	Ejection Module
EO	Earth Observing
EOS	Earth Observing System
EPIC	Extrasolar Planet Imager Coronagraph
ES	Earth Science
ESA	European Space Agency
ESMO	Earth Sciences Mission Operations
ESSP	Earth System Science Program
EVA	Extra-Vehicular Activity
FAA	Federal Aviation Administration
FD	flight dynamics
FDAB	Flight Dynamics Analysis Branch
FDF	Flight Dynamics Facility
FDS	Flight Dynamics System
FFTB	Formation Flying Testbed
FOT	flight operations team
FOV	field of view
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	Fiscal Year
GEC	Geospace Electrodynamic Connections
GEONS	GPS-Enhanced Orbit Navigation System
GLAST	Gamma Ray Large Area Telescope
GMAT	Goddard Mission Analysis Tool
GMSEC	Goddard Mission Services Evolution Center
GMT	Greenwich Mean Time
GN	Ground Network
GNC	Guidance, Navigation, and Control
GOES	Geostationary Operational Environmental Satellite
GOTS	Government-off-the-shelf
GPB	Gravity Probe B
GPM	Global Precipitation Mission
GPS	Global Positioning
GRACE	Gravity Recovery and Climate Recovery mission
GRS	Gravitational Reference Sensor
GSFC	Goddard Space Flight Center
GTDS	Goddard Trajectory Determination System
GTO	geostationary transfer orbit
GUI	graphical user interface
HEO	High Earth Orbit/ Highly Elliptical Orbit
HiFi	High Fidelity
HLDRI	HST Laser Dynamic Range Imager
HME	Hierarchical mixture-of-experts

HP	Hewlitt-Packard
HQ	Headquarters
HRV	Hubble Robotic Vehicle
HST	Hubble Space Telescope
Hz	hertz
IAD	Interface Agreement Document
ICD	Interface Control Document
IMDC	Integrated Mission Design Center
IMU	Inertial Measurement Unit
ISS	International Space Station
IT	Ionosphere-Thermosphere
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
km	kilometer
KSC	Kennedy Space Center
L&EO	launch and early orbit
LEO	Low Earth Orbit
LIDAR	Laser Detector and Ranging
LISA	Laser Interferometer Space Antenna
LPO	Libration Point Orbits
LRO	Lunar Reconnaisance Orbiter
LT	Low Thrust
m	meters
MagCon	Magnetospheric Constellation
MagNav	Magnetometer Navigation
mas	milliarcsecond
mbps	megabit-per-second
MC	Morning Constellation
MDR	MacDonald-Dettwiler Robotics
MESA	Mission Engineering and Analysis Branch
min	minute
MIT	Massachusetts Institute of Technology
MLT	mean local time
MMS	Magnetospheric Multiscale Mission
MOC	mission operations center
MOMS	Mission Operations and Mission Services Contract
MOU	Memorandum of Understanding
MSASS	Mission Spin-Stabilized Spacecraft
MSFC	Marshall Space Flight Center
MTASS	Mission Three-Axis Stabilized Spacecraft software
Mv	visual magnitude
NESC	NASA Engineering and Safety Center
NFIR	Natural Feature Image Recognition
NOAA	National Oceanic and Atmospherics Administration

NRA	NASA Research Announcement
NSG	Network Support Group
OATS	orbit and attitude tracking system
OCO	Orbiting Carbon Observatory
OD	Orbit Determination
OOO	Organics Origins Observatory
OS	Operating System
PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PCS	pointing control system
PDR	preliminary design review
PI	Principal Investigator
PIP	Professional Intern Program
PiVoT	Position-Velocity-Time
PLT	post-launch testing
QA	Quality Assurance
R&D	Research and Development
Re	Earth Radius
RSDO	Rapid Spacecraft Development Office
RTADS	Real-Time Attitude Determination System
RTF	Return to Flight
RXTE	Rossi X-Ray Timing Explorer
s	second
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SDO	Solar Dynamics Observatory
sma	semi-major axis
SN	Space Network
SOCC	Spacecraft Operations Control Center
SOHO	Solar and Heliospheric Observatory
SORCE	Solar Radiation and Climate Experiment
SOW	Statement of Work
SPAD	Solar Pressure and Aerodynamic Drag
SPDM	Special Purpose Dexterous Manipulator
SPECS	Sub-millimeter Probe for the Evolution of Cosmic Structure
SPIE	International Society for Optical Engineering
SPIRIT	Space Infrared Interferometric Telescope
SPRT	Super Problem Resolution Team
SRB	Solid Rocket Booster
SRP	solar radiation pressure
SRR	System Requirements Review
SSMO	Space Science Mission Office
ST	Space Technology
STEREO	Solar-Terrestrial Relations Observatory
STK	Satellite Tool Kit
STP	Solar Terrestrial Probe

STS	Space Transportation System
TDRS	Tracking and Data Relay Satellite
TDRSS	TDRS system
TGS	Two-Gyro system
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Technical Interchange Meetings
TIP	Task Implementation Plan
TPF	Terrestrial Planet Finder
TPF-C	Terrestrial Planet Finder Coronagraph
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmospheric Research Satellite
UCB	University of California, Berkeley
UMR	University of Missouri, Rolla
US Stratcom	United States Strategic Command
USGS	United States Geological Survey
USN	Universal Space Network
VSE	Vision for Space Exploration
VESPER	Venus Sounder for Planetary Exploration
VHF	very high frequency
VRB	virtual rigid body
WIRE	Wide-Field Infrared Explorer

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13. SUPPLEMENTARY NOTES

14. 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) 2004. 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; attitude analysis; attitude determination and sensor calibration; and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology

15. SUBJECT TERMS

NASA, Goddard Space Flight Center, GSFC, flight dynamics, flight projects, technology development, Flight Dynamics Analysis Branch, FDAB, mission support, attitude control subsystem, ACS, spacecraft, navigation, trajectory design, maneuver planning, attitude analysis, attitude determination, sensor calibration, FY 2004, accomplishments

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