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A New Systems Engineering Approach to Streamlined Science and Mission Operations for the Far Ultraviolet Spectroscopic Explorer (FUSE)

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ABSTRACT

The Mission Operations and Data Systems Directorate (MO&DSD, Code 500), the Space Sciences Directorate (Code 600), and the Flight Projects Directorate (Code 400) have developed a new approach to combine the science and mission operations for the FUSE mission. FUSE, the last of the Delta-class Explorer missions, will obtain high resolution far ultraviolet spectra (910 - 1220Å) of stellar and extragalactic sources to study the evolution of galaxies and conditions in the early universe. FUSE will be launched in 2000 into a 24-hour highly eccentric orbit. Science operations will be conducted in real time for 16-18 hours per day, in a manner similar to the operations performed today for the International Ultraviolet Explorer.

In a radical departure from previous missions, the operations concept combines spacecraft and science operations and data processing functions in a single facility to be housed in the Laboratory for Astronomy and Solar Physics (Code 680). A small mission operations team will provide the spacecraft control, telescope operations and data handling functions in a facility designated as the Science and Mission Operations Center (SMOC). This approach will utilize the Transportable Payload Operations Control Center (TPOCC) architecture for both spacecraft and instrument commanding. Other concepts of integrated operations being developed by the Code 500 Renaissance Project will also be employed for the FUSE SMOC. The primary objective of this approach is to reduce development and mission operations costs.

The operations concept, integration of mission and science operations, and extensive use of existing hardware and software tools will decrease both development and operations costs extensively. This paper describes the FUSE operations concept, discusses the systems engineering approach used for its development, and the software, hardware and management tools that will make its implementation feasible.

MISSION DESCRIPTION

The FUSE science program will address fundamental problems in such diverse areas as composition and properties of interstellar gas and dust, stellar explosions and mass loss, galactic dynamics, active galactic nuclei, and planetary magnetospheres. Many of these problems require long exposures (15-50 hours) of faint objects. Among the most important and demanding FUSE science is the study of trace species in interstellar and intergalactic gas using absorption spectroscopy of faint, distant sources, such as active galactic nuclei and quasars. The deuterium-to-hydrogen (D/H) abundance ratio is a critical parameter for understanding the Big Bang and the chemical evolution of the universe. FUSE will address this problem by measuring the D/H ratio in a wide range of astrophysical conditions representing different evolutionary histories, degree of stellar development, and chemical mixing. These problems require high spectral resolution and instrument sensitivity in the wavelength range 910 to 1220 Angstroms. The mission design lifetime is three years to provide sufficient observation time to meet the science exposure time requirements; the mission goal is five years.

The FUSE Principal Investigator at the Johns Hopkins University(JHU), Baltimore, Maryland, leads a university-government team which will build and test the FUSE instrument. The instrument team includes JHU, University of Colorado at Boulder, University of California at Berkeley, and the GSFC Engineering Directorate (Code 700). Canada and France are partners in the FUSE mission and are providing critical elements of the instrument to JHU. FUSE operations are the responsibility of the GSFC Laboratory for Astronomy and Solar Physics.

Since the start of the Phase B there have been major changes in the FUSE mission concept in order to meet programmatic requirements while maintaining scientific performance. The result is a new, innovative normal-incidence optical design, a dedicated spacecraft to be built at GSFC, a Delta II launch, and a 24-hour highly-eccentric, geosynchronous orbit (600 km perigee, 71000 km apogee) which provides about 18 continuous hours of unocculted, low radiation background science time per day (see Figure 1). This occurs when the spacecraft is at altitudes greater than about 30,000 to 40,000 kilometers.

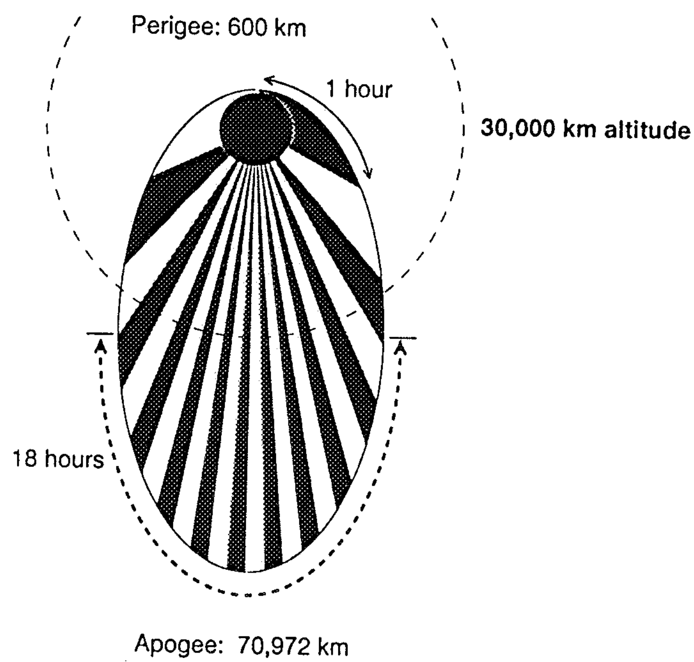

Figure 1

FUSE Orbit Geometry

FUSE OPERATIONS CONCEPT

Through a series of trade studies involving the instrument, spacecraft, and ground system, a new operations concept was developed. In addition to lowering total mission costs, low-cost mission operations was a major objective of this process.

The principal characteristics of the FUSE operations concept are summarized as follows:

- Science operations take place 18 hours per day, and only when the spacecraft is at altitudes above 30,000 km.
- Spacecraft telemetry rate is 64 kbps, using one of two omni-directional antennas.
- Two ground stations can provide coverage of 19-20 hours per day; only a 10m dish is required to provide adequate link margin (3db). This coverage requires one station in the Northern Hemisphere and one in the Southern. Wallops Island, VA, and Canberra, Australia, were used for analysis purposes. This wide geographical separation is required due to the high eccentricity of the orbit.
- Spacecraft and instrument command and control is generated and executed in real time.
- All ground system functions are located in the Science and Mission Operations Center (see Figure 2).
    - Data capture and level zero processing
    - Spacecraft and instrument command and control
    - Science/mission planning and scheduling
    - Orbit determination (flight dynamics function)
    - Trend and performance analysis (with support of instrument and spacecraft teams)
    - Science data processing, calibration, distribution, archiving
    - Science program management
    - Guest Observer proposal support
- A number of functions and processes are automated in order to reduce the work complement of the ground operators.
    - Spacecraft and instrument health and safety functions in flight software
    - Health and safety monitoring in ground system
    - Data capture and data retransmission
    - Level Zero processing
- Constraints imposed to simplify operations
    - No operations will take place during the lower portion of the orbit when FUSE traverses the trapped electron and proton belts.
    - No spacecraft maneuvers outside periods of direct contact.
    - No science operations required during shadow periods.

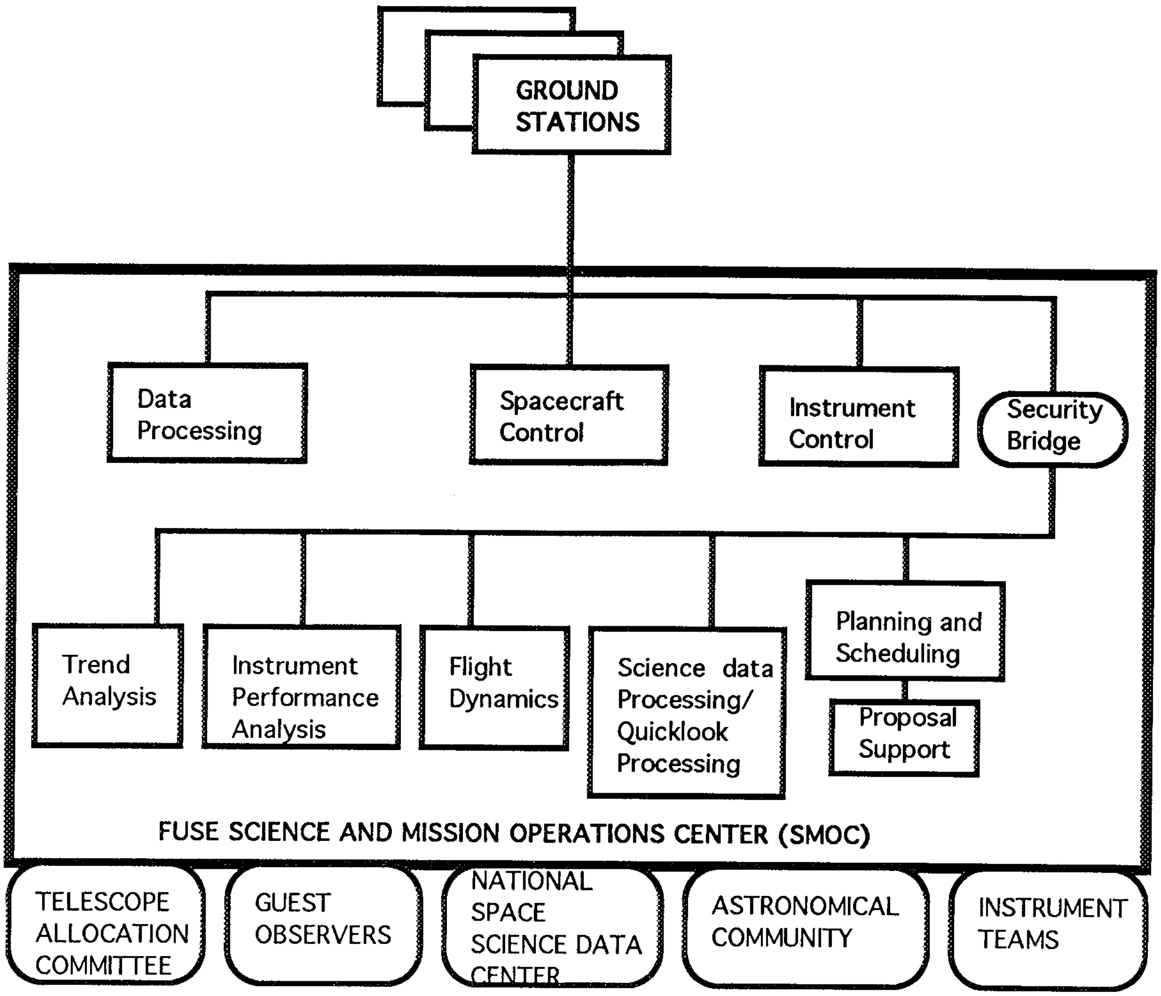

Figure 2
FUSE Science and Mission Operations Center

Real time requirements include the ability to execute interactive, real-time control of the instrument and spacecraft. The daily real-time contact must occur when the spacecraft is at altitudes above 30,000 km to use the low radiation portion of the orbit. Health and safety, housekeeping and science data will be monitored autonomously in real-time to avoid possible data loss due to anomalies or improper operations. The target and guide star identification and acquisition process is interactive with the ground. Adjustments to the instrument fine alignment are required every two hours or less; commanding the spacecraft and instrument will occur on a frequent basis.

FUSE Guest Observers and the Instrument Team will have electronic connections to the SMOC for proposal submission, observation planning and execution, and science data evaluation and retrieval. Level zero data will be available to scientists shortly after receipt in the SMOC and processed science data within 2 days. The mission data will be archived at the National Space Science Data Center (NSSDC).

FUSE DEFINITION PROCESS

Ground and flight segment engineers and scientists have been heavily involved throughout the FUSE definition process. This breadth of involvement has allowed mission-wide and life-cycle trade studies to be conducted and informed design decisions made based on study results. A team consisting of the Project Scientist, the Spacecraft Manager, Instrument System and Operations Engineers, Ground Data Systems Engineers, Operations Scientist, Mission Operations Manager, and Flight Dynamics Systems Engineer was established to create a flight and ground system concept that meets the mission requirements. The revised concept was reviewed periodically by the Principal Investigator and the FUSE Project. The ground system concept described above was ultimately one result of this process. Since operational considerations were an integral part of the mission and life cycle trade studies, the operations and ground system concept developed continuously with the rest of the mission concept.

The orbit selection was the first major trade study. The 24-hour orbit described above provides several significant advantages over a low-earth orbit for the FUSE mission. This orbit decision minimizes the mission lifetime for the mission's science program, lowers mission complexity (operations, spacecraft, and instrument), maximizes time outside the radiation belts for low background science by providing 2 to 3 times the observing efficiency of LEO, provides a 100X improvement in target visibility, radically simplifies science and mission scheduling, provides continuous observing periods for long observations, and simplifies faint-object target acquisition.

These factors, combined with the utilization of real-time control of the instrument and spacecraft, reduce the number of functions and subsystems in the flight and ground segments. Such simplifications lower system complexity, lower development and testing costs, lower software maintenance costs, and reduce operations support staff. Specifically, a high-rate data downlink, command management system, planning and scheduling system, and automated target and guide star acquisition system were either deleted from the FUSE mission concept or significantly simplified. Many other design trades were made to optimize the mission design concept and reduce cost.

The fact that FUSE is operated in real time, has one instrument, one common destination for all data, and a low rate for data downlink made possible the consolidation of the spacecraft and science operations. A single Mission Operations Team will be trained to perform both science and spacecraft operations. The current concept plans to staff each operational shift with two console operators (one for the spacecraft, one for the instrument) and one resident astronomer. The operations staff will be assisted by autonomous functions in the ground system for health and safety monitoring, data capture and retransmission, and Level Zero processing. These are very significant, because by automating these activities the operations staff will have significant portions of their time freed for more intellectually challenging and critical work, such as calibration, planning and scheduling, preparing for the next science observation, and of course spacecraft and instrument commanding.

The SMOC will be a joint development by Codes 600 and 500 and the FUSE instrument team. The objective is to reduce documentation (e.g., a single requirements document for the FUSE ground system), reduce and simplify interfaces, and reduce staffing and facility requirements. The SMOC will be one of the missions to be implemented utilizing services and products of the Code 500 Renaissance system.

FUSE DEFINITION METHODOLOGY

The FUSE Project has adopted a Functional Analysis methodology to achieve an end-to-end systems approach to mission concept development. FUSE is the first project at GSFC to employ this process across the entire mission starting in the definition phase. Functional analysis is the process of identifying, describing and relating the functions a system must perform in order to fulfill its goals and objectives. The primary analysis tool is the functional flow block diagram. These diagrams show the network of actions that lead to the completion of a function. It is part of the end to end flow of level one activities that leads to the system definition. The process starts with requirements, followed by functional analysis, and ends with system definition.

The mission phases that were defined to be studied were development, prelaunch, launch, mission operations, and end of mission. Each mission phase was further broken into sub-phases, and sub-phases into functions. This allows the systems engineers to evaluate the functional relationships and dependencies across subsystems and between flight and ground segments. In addition, the interdependencies at the function level can be traced to higher levels. The functional flow diagrams will be used to allocate and validate requirements at the subsystem level.

This process helped to identify major areas of the mission for further study, such as the critical topics for the FUSE End-to-End Data System Study. The main objectives of this study are: to characterize the space to ground link, the command and data handling memory sizing and the on board bus traffic; and to establish a baseline of the data rates and identify "tall poles" in the instrument, observatory and ground data systems. Among the important outcomes of this type of study are the identification of missing requirements, the identification of the requirements that drive the complexity of the system in terms of data and the validation of the operations concept. In parallel, the FUSE Operations Concept Document was written. Through this process the mission operations concept is "engineered" like the other components of the mission.

CONCLUSION

Because of its need to dramatically reduce costs, and its success in achieving this goal, the FUSE mission is a pathfinder for NASA's low-cost mission operations objectives. A tightly integrated team and consideration of end-to-end operations issues in all phases of the FUSE mission contributed substantially to the development of this approach.