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MISSION PLANNING AND SCHEDULING CONCEPT
FOR THE ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

Projected for launch in the latter part of '98, the Advanced X-ray Astrophysics Facility (AXAF), the third satellite in the Great Observatory series, promises to dramatically open the X-ray sky as the Hubble and Compton observatories have done in their respective realms. Unlike its companions, however, AXAF will be placed in a high altitude, highly elliptical orbit (10,000 x 100,000 km), and will therefore be subject to its own unique environment, spacecraft and science instrument constraints and communication network interactions.

In support of this mission, ground operations personnel have embarked on the development of the AXAF Offline System (OPLS), a body of software divided into four basic functional elements: (1) Mission Planning and Scheduling, (2) Command Management, (3) Attitude Determination and Sensor Calibration and (4) Spacecraft Support and Engineering Analysis. This paper presents an overview concept for one of these major elements, the Mission Planning and Scheduling subsystem (MPS). The derivation of this concept is described in terms of requirements driven by spacecraft and science instrument characteristics, orbital environment and ground system capabilities. The flowdown of these requirements through the systems analysis process and the definition of MPS interfaces has resulted in the modular grouping of functional subelements depicted in the design implementation approach. The rationale for this design solution is explained and capabilities for the initial prototype system are proposed from the user perspective.

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MISSION PLANNING AND SCHEDULING CONCEPT FOR THE ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

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Abstract

Projected for launch in September 1998, the Advanced X-Ray Astrophysics Facility - Imaging (AXAF-I) spacecraft, the third satellite in the Great Observatories series, promises to dramatically open the x-ray sky as the Hubble and Compton observatories have done in their respective energy ranges. Unlike its companions, AXAF-I will be placed in a high-altitude, highly elliptical orbit and therefore will be subject to unique environment, spacecraft and science instrument constraints, and communications network interactions.

In support of AXAF-I, Marshall Space Flight Center is developing the AXAF Offline System, software supporting four basic functional areas: 1) mission planning and scheduling, 2) command management, 3) attitude determination and sensor calibration, and 4) spacecraft support and engineering analysis. This paper presents the design concept for the mission planning and scheduling subsystem. The concept derives from the spacecraft and science instrument characteristics; orbital environment; operational activities; and increasing emphasis on decreased development, operations, and maintenance costs. The software provides a unique solution for combined science and spacecraft activity scheduling. The design incorporates multiple independent functions supporting both automated and manual scheduling and a flexible user interface. It takes advantage of advances in automated scheduling techniques while reusing significant amounts of software from previous missions.

AXAF Mission Background

The Advanced X-Ray Astrophysics Facility - Imaging (AXAF-I) is one of the great observatories that will extend man's knowledge of the universe. In energy

sensing range, it falls between the Hubble Space Telescope (HST) and the Gamma Ray Observatory (GRO), also referred to as the Compton Observatory. AXAF-I provides unique scientific capabilities for studying astrophysical objects in the energy range from 0.09 kiloelectronvolts to 10.0 kiloelectronvolts. The facility will be available to scientists in the United States and to members of the international community over an anticipated mission lifetime of 5-years.

AXAF-I is a combination of a spacecraft system, a telescope system, and a set of scientific instruments in a single facility. The spacecraft is capable of maneuvering the facility to point the telescope at targets of interest, providing power for the operation of the facility, storing science and engineering data, and communicating with the ground. The telescope system includes a set of mirrors, the High Resolution Mirror Assembly (HRMA), designed to gather and focus the x-ray image of celestial objects onto the focal plane science instruments (FPSIs). The telescope system also accommodates two objective transmission gratings that can be folded into the HRMA converging x-ray beam. The FPSIs include the AXAF Charge-Coupled Device (CCD) Imaging Spectrometer (ACIS) which provides images and spectra of celestial objects, and the High Resolution Camera (HRC) which provides x-ray images of celestial objects. The ACIS and the HRC cannot observe celestial objects simultaneously.

AXAF-I is scheduled to be launched in September 1998 by the Space Shuttle Program (SSP) orbiter and an upper stage. AXAF-I will be placed in a high altitude, highly elliptical orbit, approximately 10,000 kilometers by 100,000 kilometers. In this orbit, approximately 70 percent of the orbit duration will be above the science data radiation contamination limit of 60,000 km and therefore available for science observations. Operation of the spacecraft will be through on board stored commands. Ground-spacecraft contact will be limited to a 45-minute contact every 8 hours using the Deep

Space Network (DSN) 26-meter network. The spacecraft will be capable of 72 hours of autonomous operations using stored command loads uplinked daily. Science and engineering data will be stored on an onboard solid state recorder (SSR) and dumped to the ground every 8 hours. Onboard reaction wheel momentum buildup will be controlled using onboard thrusters; thruster fuel is the only consumable resource affecting the scheduling of science operations.

Ground System Overview

AXAF-I operations will be controlled from the Huntsville Operations Support Center (HOSC) at Marshall Space Flight Center (MSFC). The AXAF-I ground system, illustrated in Figure 1, is composed of the Operations Control Center (OCC), the Engineering Support Center (ESC), the AXAF Science Center (ASC), the Software Development Facility (SDF), the Flight Software Maintenance Facility (FSMF), and those portions of Nascom and the DSN supporting AXAF-I operations.

The AXAF OCC comprises the Online System (ONLS) for real-time operations and the Offline System (OFLS). It is the focal point for AXAF-I spacecraft operations and includes all the functions for planning and scheduling, command management, command processing, telemetry processing, attitude determination, sensor calibration, and spacecraft support and engineering analysis. The ESC is

collocated with the OCC and provides engineering support to the flight operations team (FOT). The ASC, located at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, is responsible for interfacing with the science community; developing long range science plans; developing 1 month observation lists; monitoring the performance of the FPSIs; developing and maintaining science calibration models; and generating, archiving, and distributing science data products to the user community. The AXAF SDF and FSMF perform flight software maintenance and provide flight software updates to the OCC for uplink to the spacecraft when required.

The OFLS at MSFC complements the ONLS by providing non-real-time support for spacecraft operations and science objectives. The major functions of the OFLS are to 1) plan and schedule science observations and spacecraft and ground system support, 2) generate command loads to be executed onboard the spacecraft, 3) determine spacecraft attitude and perform on-orbit calibration of the attitude sensors, and 4) study spacecraft subsystem performance and support contingency resolution.

This paper concentrates on the first of these functions which has been allocated to the mission planning and scheduling (MPS) subsystem.

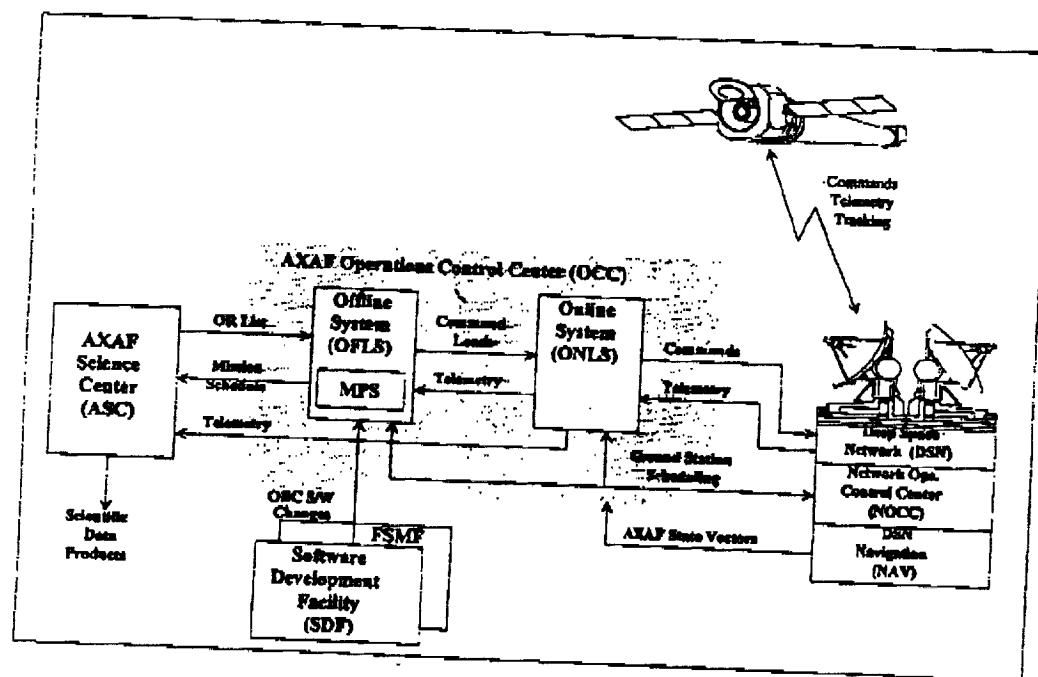


Figure 1. AXAF Ground System

Mission Planning and Scheduling Requirements

The MPS subsystem provides tools for the science operations team (SOT) and the FOT to define and verify the schedule of planned science and spacecraft activities. The goal of the MPS subsystem is to provide maximum science return, while ensuring the health and safety of the spacecraft.

The AXAF-I MPS subsystem is unique among National Aeronautics and Space Administration (NASA) spacecraft ground systems in that it provides completely integrated support for both short range science and spacecraft mission activity planning. Previous missions such as HST and GRO have separated the science planning and mission planning activities into separate systems. This approach has required extensive iterations between science planning systems and the mission planning systems to ensure an optimal schedule of science activities that also meets the needs of engineering support to ensure the health and safety of the spacecraft.

The MPS subsystem requirements can be loosely grouped into science requirements, spacecraft requirements, and operational requirements. Science observations are specified by the ASC in terms of FPSI and transmission grating selection, target location, observation duration and window, and observation priorities. Each observation request can override the default science and spacecraft constraints and constraint values to allow special observations to be performed (e.g., x-ray object occultation by the limb of the Moon). In addition to the standard target constraints (e.g., target occultation), science observation scheduling must also consider minimizing FPSI and transmission grating switching (mechanical motion of the science instrument module and gratings), FPSI science data buffer size, protection from bright x-ray objects, protection from atmospheric contamination (e.g., avoiding pointing the telescope along the orbit velocity vector at lower altitudes), and spacecraft roll constraints to ensure that the ACIS heat radiator is pointed away from the Sun. Finally, science observations can also be constrained by time or observation order.

Spacecraft constraints influencing science schedules include bright object protection for the Sun and the Moon, spacecraft roll constraints to ensure the solar arrays are positioned correctly for battery charging, load shedding during spacecraft night, and management of reaction wheel momentum buildup. The MPS subsystem is also required to select guide stars for controlling the spacecraft attitude and aspect

stars for post facto science data analysis and to schedule all engineering activities required for the continued operation of the facility. These activities may include transmitter management, battery reconditioning, and special maneuvers for calibrating attitude sensors.

Finally, operational considerations that must be incorporated into the schedules include ensuring that DSN contacts are available every 8 hours for dumping SSR data and every 24 hours for command load uplink opportunities, that the commanding required to execute the science schedule does not exceed the available onboard memory, and that consumption of nonrenewable resources is minimized.

The scheduling process must account for the time to maneuver between successive targets, the time to configure the FPSIs for data collection, the time to acquire guide stars, and the actual science observation time, overlapping nonconflicting activities when possible to achieve the most efficient schedule without compromising mission safety or science data integrity. The schedule resulting from application of the observation requirements and the mission constraints must maximize the usage of the available science observation time and the scheduling process must introduce no more than 5 percent idle time into the schedule. The software must provide fully automated scheduling of the science and engineering activities. However, the software must also provide a full range of capabilities for intercepting and manipulating all characteristics of every activity in the schedule.

Operations Concept

The ASC initiates normal mission processing approximately 1 to 1.5 years prior to an operational week. At this time a request for observational proposals is issued to the science community. The ASC receives observation proposals and submits them for peer review for technical feasibility and scientific return. The review committee prioritizes the accepted observation proposals and returns them to the ASC for scheduling and tracking. The ASC lays out the long-term plan of accepted observations (up to 6 months) and provides observation request (OR) lists to the OCC at MSFC for scheduling.

Figure 2 illustrates the detailed schedule generation process. As shown, scheduling is performed in parallel for 3 upcoming weeks. The OCC receives OR lists on a weekly basis that cover a 1 month period and are oversubscribed to ensure scheduling

efficiency. At the OCC, the FOT uses the OFLS MPS subsystem to generate engineering requests (ERs) specifying required spacecraft maintenance activities and to automatically generate the schedules of science observations and accompanying spacecraft activities. Typically, these mission schedules cover 1 week of spacecraft operations at a time. The mission schedules are reviewed by the SOT and the FOT to ensure that both the science objectives and spacecraft engineering requirements are met by the proposed schedule. The schedules may be iterated with the ASC to change observation priorities or characteristics or to add or delete observations in order to meet the overall mission and individual observation objectives. The SOT utilizes the interactive capabilities of the MPS subsystem

software during this process to review the mission schedules and to perform what-if studies of different scheduling scenarios. The MPS subsystem then translates the approved mission schedules into detailed operational timelines (DOTs) of spacecraft activities from which spacecraft command loads can be generated. The final potential user of MPS subsystem software and products is the technical support team (TST), which provide engineering analysis support to the FOT. The TST uses MPS products to compare actual spacecraft performance with planned activities, to analyze hardware usage and predict hardware lifetime, and, potentially, to perform what-if studies for planned operational or hardware configuration changes.

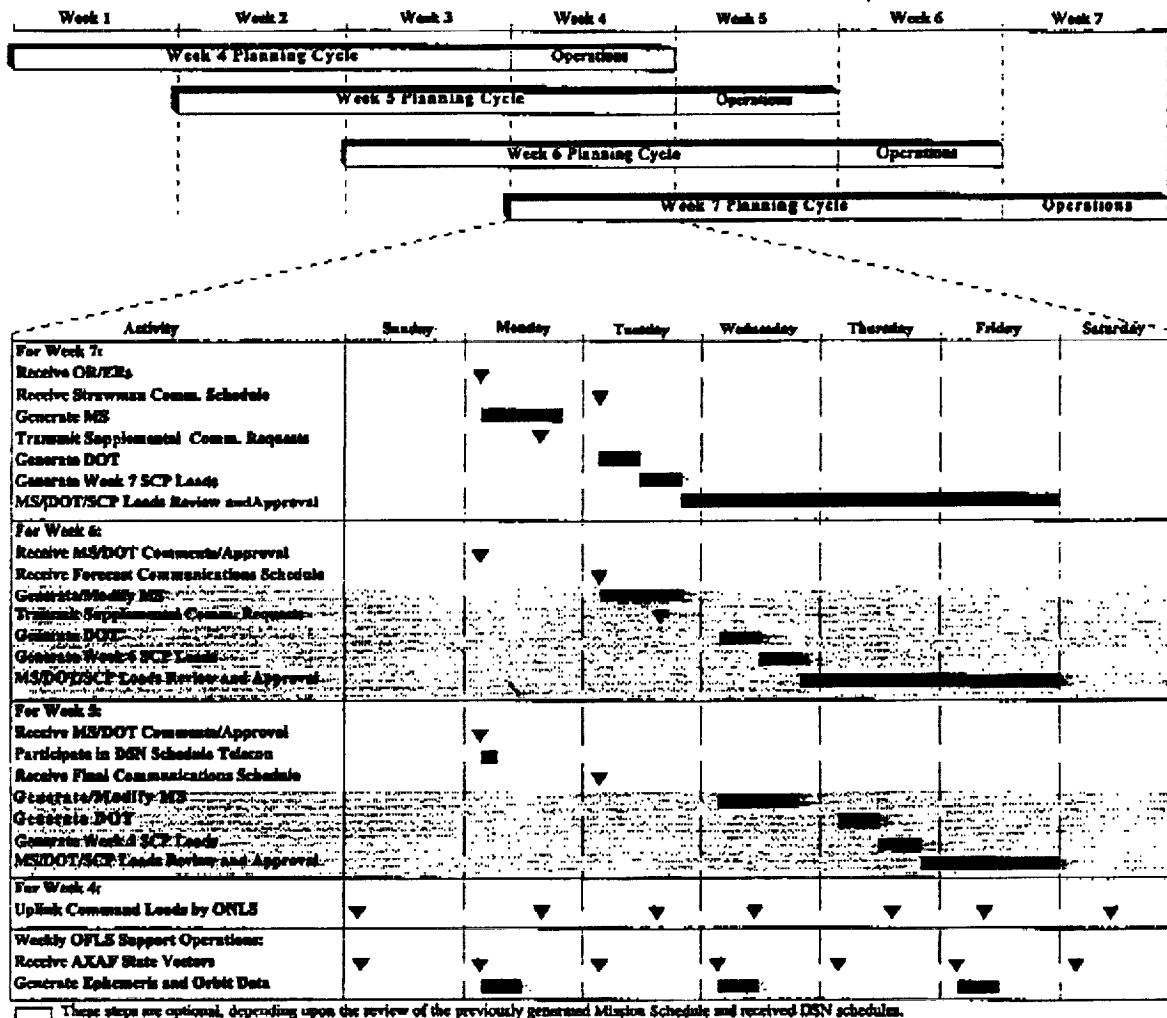


Figure 2. Mission Planning Operational Timeline

Design Drivers

Several programmatic issues drive the MPS subsystem requirements and the final MPS subsystem design. The major factors are decreasing NASA development and operations budgets, the proposed mission lifetime and the diverse audience for MPS software and products. Table 1 summarizes the major programmatic drivers and the resulting design issues.

Table 1. Major OFLS MPS Subsystem Design Drivers

Driver	Implication
Shrinking operations budgets	Automated software (reduced operator interaction) High performance (reduced turnaround time)
Shrinking development budgets	Software reuse Flexible software (reduced maintenance) Software reusability for future missions
5-year mission	Flexible, modular software (easy adaptation to changing mission conditions)
Diverse operational community	Flexible, modifiable user products

Shrinking operations budgets require missions and supporting software that can be supported by fewer operations personnel over the life of the mission. This in turn implies a greater degree of software automation and a need for reduced operator intervention to obtain the desired results. Shrinking development budgets require increasing levels of software reuse as well as software reusability for future missions. Shrinking maintenance budgets imply software that can be rapidly and inexpensively tailored to changing mission and operations personnel requirements. Flexible, modular software and a complete set of tools for manual intervention in the schedule are required to support the different needs of each of the mission phases, the changing environment over a 5-year mission, and rapid response to spacecraft contingencies in a cost-effective manner. Finally, the software interface and products must support the needs of users whose primary interest is the science return of the mission and those whose primary concern is the continued operation of the spacecraft. The output products must be easily

accessible in a variety of formats to support long term spacecraft performance analysis as well as rapid turnaround analyses in contingency situations.

Mission Planning and Scheduling Design

Figure 3 illustrates the proposed MPS subsystem software architecture. The software has been designed with each major function assigned to a separate executable process. A single, unified interface provides access to automated schedule generation, interactive schedule review and modification, and each individual process. The processes can be executed sequentially from observation request processing through schedule and DOT generation for normal automated processing. However, each process will be invoked independently as required to perform constraint checking during manual schedule modification. Likewise, each module can be accessed independently by the user for special analyses.

Building the software as separate, sequentially invoked processes allows the order to be easily tailored to changing mission priorities. For example, science operations are currently independent of ground station contacts. However, the failure of an antenna could require that the spacecraft return to attitudes that place a DSN ground station within the line of sight of the remaining antenna at regular time intervals. To support this, antenna processing could be moved earlier in the sequence and the results used in the scheduling algorithm to judiciously schedule observations or to interrupt observations as necessary. This type of approach decreases development costs by eliminating the need for the software design and scheduling algorithms to accommodate, a priori, all possible contingencies, while minimizing the cost and time required to adapt to changes during the mission.

All processing is input driven. Observation and engineering request input processing is controlled by a set of tables defining the syntax, parameters, and allowable parameter values for each type of request. Additional tables link the input requests to the internal software processing and the output parameters required to command the spacecraft activities. For example, a single input request format can be used to request 1) a maneuver, 2) a maneuver and guide star acquisition, or 3) a maneuver, guide star acquisition, and science observation simply by referencing a different set of processing rules (and supplying all necessary information, such as FPSI configuration). Likewise, because the software carries multiple formats internally to support different users, the output can be switched from commanding a maneuver using right ascension, declination, and roll

to using a quaternion simply by changing the command output rules. This approach divorces the detailed processing software from the external MPS interfaces, facilitates adding new capabilities, and reduces the cost of modifying capabilities to adapt to changing mission requirements.

The scheduling algorithm selected for the OFLS MPS is based on advanced hybrid-optimizing techniques. In this approach, specific scheduling goals are selected (e.g., maximize time on science targets, minimize consumption of thruster fuel, minimize maneuver time). Heuristics are used to limit the set of targets to be placed in the schedule and an optimizing algorithm is used to time-order the limited set of targets. This approach provides a balance between the high performance of heuristic scheduling algorithms and the high efficiency of optimizing algorithms. Several such goals can be implemented at a relatively low cost (typical algorithms require 300 to 3000 lines of code). This allows several algorithms to be prototyped and the results analyzed during the design phase, avoiding surprises late in the development cycle if the algorithms do not respond as predicted. Likewise, it allows algorithms to be developed from the beginning to support basic,

expected contingency scenarios (see earlier discussion for related issues).

The content and format of all reports (online or hard copy) can be specified by the user. Templates for basic reports will be developed and delivered with the system. However, the user will have the capability to modify these templates or build new templates to meet the changing needs over the life of the system. This approach allows each of the operations groups: FOT, SOT, and TST, to tailor the interface to meet its special requirements. It also allows immediate access to all data required to resolve unexpected problems and avoids the costly report maintenance involved with traditional systems over an extended 5-year mission.

Finally, the design concept takes advantage of existing software from previous NASA missions, primarily HST. Approximately 55 percent of the MPS software will be reused. The reuse software will provide the bulk of the detailed spacecraft algorithms (e.g., maneuvers, low gain antenna (LGA)-DSN visibility, communications support), the input observation request parsing software, and the schedule processing shell. The majority of the

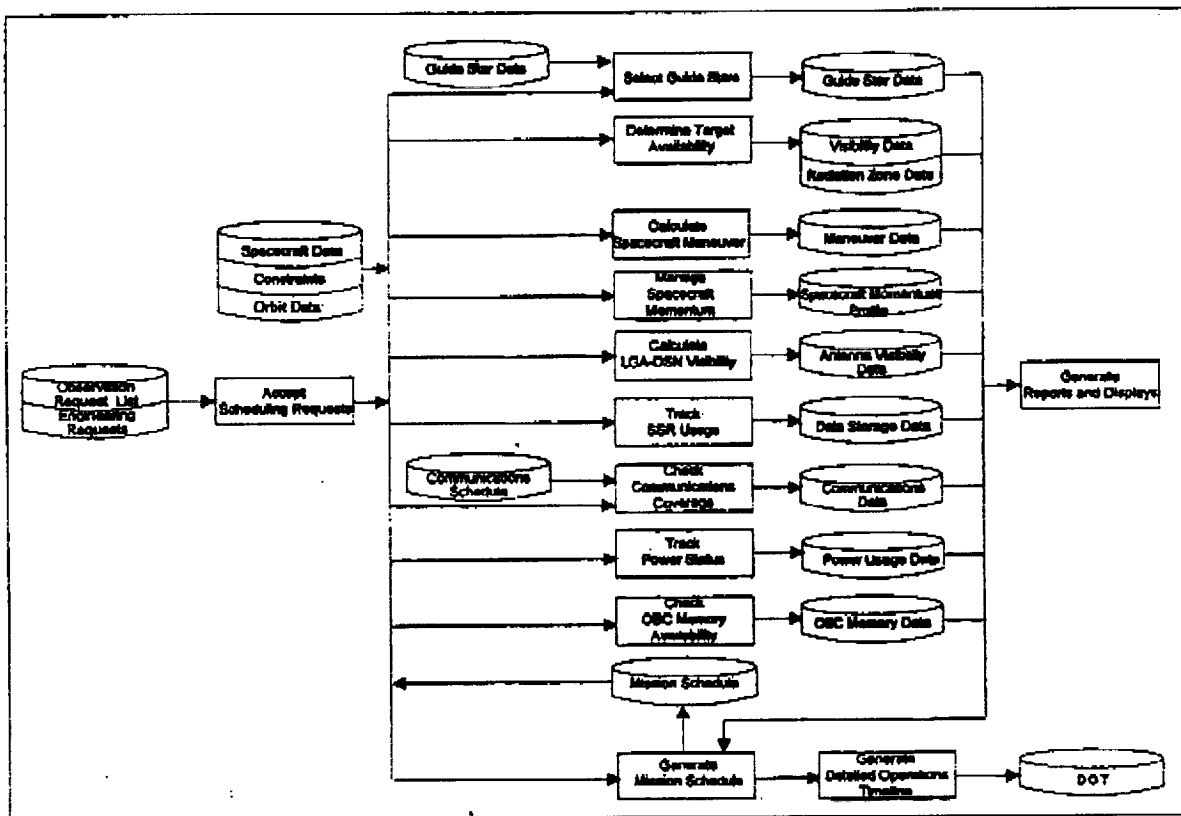


Figure 3. Mission Planning and Scheduling Software Architecture

development effort will be concentrated on developing the AXAF-I scheduling algorithms, integrating the components into a cohesive system, providing AXAF-I unique constraints (e.g., bright x-ray object avoidance regions, fuel consumption models, and aspect star selection).

Ongoing Design Activities

Work is currently in progress to confirm the MPS design concept. Detailed scheduling goals are being defined in conjunction with the FOT and the science planning team at the ASC. Prototypes of the basic science, spacecraft, and operations algorithms are being developed based on the reuse software. The scheduling algorithms will be used in conjunction with the prototyped software to validate the proposed scheduling approach and to ensure that the design will meet AXAF-I operational and performance requirements. This effort will be based on realistic science observing scenarios developed by the ASC. In a parallel effort, sample displays for generating ORs and editing mission schedules are being developed for review by the FOT and the SOT to ensure that the user interface provides the flexibility required by both operational groups.

Summary

The OFLS MPS is still in the early stages of the design process. However, the basic design concept derived from the science, spacecraft, and operations requirements is complete. This design combines science and spacecraft requirements to provide scheduling support for all routine mission activities. The design is intended to decrease long-term costs for operations by minimizing and facilitating operator interactions. Combining science and mission planning and working closely with both the SOT and the FOT to develop scheduling algorithms minimizes the need for iterating science schedules between the OCC and the ASC, also decreasing long-term operations costs. The MPS design facilitates maintenance over the 5-year mission by recognizing and providing the flexibility to easily adapt to common changes over the life of the mission. The design also allows the user to tailor the interface to meet different and changing operational needs.

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Acronyms

ACIS	AXAF CCD Imaging Spectrometer
ASC	AXAF Science Center
AXAF	Advanced X-Ray Astrophysics Observatory
AXAF-I	AXAF - Imaging
CCD	charge coupled device
CSC	Computer Sciences Corporation
DOT	detailed operations timeline
DSN	Deep Space Network
DSN NAV	DSN Navigation
ER	engineering request
ESC	Engineering Support Center
FOT	flight operations team
FPSI	focal plane science instrument
FSMF	Flight Software Maintenance Facility
GRO	Gamma Ray Observatory
HOSC	Huntsville Operations Support Center
HRC	High Resolution Camera
HRMA	High Resolution Mirror Assembly
HST	Hubble Space Telescope
LGA	low gain antenna
MPS	mission planning and scheduling
MS	mission schedule
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NOCC	Network Operations Control Center
OBC	onboard computer
OCC	Operations Control Center
OFLS	Offline System
ONLS	Online System
OR	observation request
SCP	stored command processor
SDF	Software Development Facility
SOT	science operations team
SSP	Space Shuttle Program
SSR	solid state recorder
S/W	software
TST	technical support team