Features of an Onboard, Adaptive, Observation Plan Executive for NASA's Next Generation Space Telescope

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Abstract

Targeted for launch in 2008, NASA's Next Generation Space Telescope (NGST) will be a premiere research tool for extending mankind's understanding of the early universe. Largely because of its planned position at the relatively constraint-free second Earth/Sun Lagrange point (L2), the mission offers a unique opportunity for enhancements in science efficiency and spacecraft operability via the use of an onboard observation plan executive (OPE) that makes real-time plan and schedule adjustments based on immediate mission conditions. The goals for including such a system are to simplify ground system procedures for observatory scheduling and operations, enable more efficient use of observatory resources, and protect against the as-flown characteristics of the vehicle. The OPE's usual function will be the smooth, event-driven execution of a nominal observation plan provided by a ground-based scheduling system, but it will also have the authority and responsibility to autonomously inject standard housekeeping activities as they are needed, and to respond to various anomalous real-time conditions that may arise. The latter may take the form of suspending plan execution while taking corrective actions, deleting elements of the plan that are found to have become nonviable, or perhaps even inserting new elements into the plan as opportunities arise. This paper discusses issues and strategies pertinent to OPE operation. To provide a definite context within which the envisioned OPE will function, we include a proposal for a specific distribution of overall flight software functionality and a description of an interface protocol between the OPE and the other flight software applications. We also discuss both nominal OPE operations, as well as OPE responses to various anomalous conditions.

1. Introduction

The Next Generation Space Telescope (NGST), projected for launch in 2008, is a key component of NASA's origins program (cf. Stockman 1997). Its principal purpose is to enable studies of the cosmological "dark ages" at times and distances from just beyond those probed by the Hubble Space Telescope (HST) to near the "recombination" epoch studied by the Cosmic Background Explorer. Current plans are for NGST to be a large-aperture (~ 8 m) infrared observatory located near the second (i.e., anti-sunwards) Earth/Sun Lagrange point (L2). The technological challenges for creating the required hardware systems are substantial, particularly in areas such as assembly and figure control of the segmented primary mirror, cryogenic operation of complex space systems, and construction and rigidification of large, low-weight space systems.

Placement of the observatory in a halo orbit about L2 offers certain very appealing features for operations. In particular, it eliminates all of the moderate-frequency (i.e., near hourly) orbit-related constraints that plague missions in low Earth orbit, including frequent target occultation by the Earth, increased electronics interference during passage through the South Atlantic Anomaly, and thermal and power stresses related to regular passage through the Earth's shadow. Sun related constraints with year-long periodicity do still pertain. Additional advantages related to L2 placement for most of the proposed NGST mission designs include abundant and continuous solar power and continuous viewing of the Earth by the antenna system.

This paper presents a concept for an event-driven observation plan executive (OPE) that gives a moderate level of planning and scheduling autonomy to the observatory flight system. The goal is to achieve a balanced system that exploits the inherent near-term flexibility associated with the L2 location while at the same time relying on the ground segment's greater computational power to optimize the nominal moderate- and long-term science schedule. This contrasts with most current space observatories, including NASA's four Great Observatories (HST, the Compton Gamma Ray Observatory, the Chandra X-Ray Observatory, and the Space Infrared Telescope Facility), which are essentially purely time-based in their schedule execution design.

The presentation is divided into the following sections: (1) this introduction, (2) a review of the flight systems that constitute the OPE's operational context, (3) a definition of the structure of the observation plan provided by the ground segment as basic input to the OPE, (4) a description of the communications protocol between the OPE and the various spacecraft applications whose activities it coordinates, (5) a description of OPE operations under nominal conditions, and (6) a description of various important OPE responses to anomalous conditions.

2. Spacecraft Systems Overview

For this study, we assume that the NGST systems will be essentially those envisioned by the Goddard Space Flight Center (GSFC) yardstick version of the mission (cf. Stockman et al. 1997). We do so merely to provide a definite context for discussion; the details are not a strong driver for OPE design. Although many design decisions have not yet been finalized, we use present tense in this paper for smoother presentation.

NGST consists of three principal components: the spacecraft support module (SSM), the optical telescope assembly (OTA), and the integrated science instrument module (ISIM). Figure 1 shows these three components as envisioned for the GSFC yardstick. The large sunshield deployed from the SSM allows passive cooling of the OTA and ISIM to ~ 30 K. During normal operations, the attitude of the spacecraft is constrained so that the OTA and ISIM remain within the shadow of the sunshield.

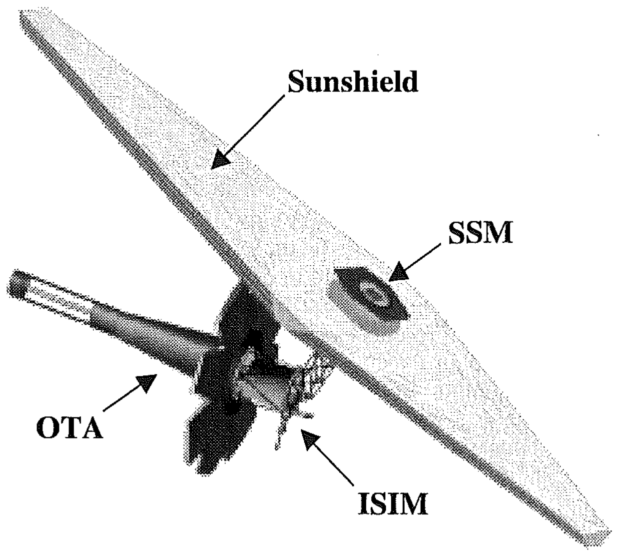

Figure 1 – Yardstick NGST configuration

2.1 – SSM Components

The following SSM systems are important from the OPE's perspective: health and safety control (HSC), communications, command and data handling, and attitude and orbit control (AOC). SSM thermal and electrical power systems also exist, but they are transparent to OPE operations.

HSC is of interest because it has ultimate responsibility for spacecraft health and safety and can therefore deactivate the OPE in emergencies. Communications is important as the conduit of ground-generated control information (observation plans and real-time commands). However, given the L2 mission location, the antenna can be designed to support communications at all valid spacecraft attitudes, which avoids observation schedule constraints associated with communication needs.

Command and data handling provides two services: (1) a command and data interface between the various spacecraft systems, and (2) a data recorder for storing mission observations. The recorder allows simultaneous recording and transmission of data and therefore usually imposes no schedule constraints on the OPE. However, because the data recorder has finite capacity, the OPE must verify that there is sufficient free space available before initiating the collection of new science data. This becomes an issue only in the infrequent event of problems in the ground system that delay ground collection of the recorded data.

AOC consists of hardware and software elements that monitor and control the spacecraft attitude and orbit. AOC hardware includes Sun sensors, star trackers, gyroscopes, reaction wheels, and gas thrusters. The star trackers, gyros, and reaction wheels together are sufficiently accurate to allow determination and control of the SSM attitude to ~ 1" (r.m.s.) during science observations, although significant levels of jitter are present during and just after large slews and momentum dumps. The reaction wheels are also used to absorb momentum resulting from the external torque imposed by solar radiation pressure on the sunshield; the reaction wheels can absorb the equivalent of ~ 24 hours' worth of torque at the worst case attitude. Gas thrusters are used to dump the excess momentum periodically. A separate set of thrusters is used for velocity adjustment roughly once every 23 days to maintain the orbit (cf. Lubow 2000).

2.2 – OTA Components

The OTA consists of the telescope mirrors and the hardware and software elements required to monitor and control them. There are five mirrors. The segmented primary mirror and the secondary mirror are open to free space, while the tertiary mirror, deformable mirror, and fast steering mirror are inside the ISIM box. Adjustments to the control actuators of the primary, secondary, and deformable mirrors are made periodically (say, monthly) to compensate for secular changes in their configuration. The OPE does not make decisions regarding when such adjustments are required; these decisions are based on ground analysis. The fast steering mirror is used to compensate for residual jitter beyond AOC control capability. The error signal used for fast steering mirror control is based on high-rate (~ 30 Hz) guide star observations acquired with one of the science instruments.

2.3 – ISIM Components

The ISIM consists of the three science instruments (SIs) and the hardware and software required to monitor and control them. (Strictly speaking, the software elements and much of the control hardware are located on the SSM side of the truss used to isolate the ISIM and OTA from thermal and mechanical disturbances, but this is a mere architectural "detail" from the perspective of the OPE.) The three SIs are the near infrared camera (NIRC), the near infrared spectrograph (NIRS), and the combined mid infrared camera/spectrograph (MIRC/S). Each of the SIs has a multi-configuration optical/mechanical system for transmission of the light and a focal plane array (FPA) detector system for measuring the incident light.

The NIRC serves double duty. Its 8k×8k FPA consists of 64 separate chips. During science observations, one of the chips is selected to serve as a fine guidance sensor and configured for readout at 30 Hz, with data accumulated from only a pre-selected 100×100 pixel region of the chip. The remaining 63 chips can be used for science data collection. The NIRC actually consists of four cameras, each with a separate optical system and FPA. A broadband filter can therefore be specified for use with the quadrant containing the chip to be used for fine guidance, while narrow band filters are used in the other three quadrants.

The NIRS and MIRC/S both have camera and spectrograph modes. The camera modes can be used either directly for science or as target location devices in support of spectrographic science. For the latter purpose, special target acquisition processing is used to identify desired targets and adjust either the configuration of the science instrument or the spacecraft attitude to place the target(s) in one or more selected apertures.

The ISIM flight software modules to which the OPE typically issues command directives are fine guidance support (FGS), to acquire and hold guide stars; NIRS and MIRC/S target acquisition support (TAS), to place targets in designated spectrograph apertures; and NIRC, NIRS, and MIRC/S science data collection (SDC), to collect and process data during science exposures. Each of these in turn makes use of two SI-specific utility modules: an SI configuration monitor and control (CMC) module, and an SI FPA data processing (FDP) module. The CMC modules are used for issuing configuration change commands (e.g., move focus relay mirror, change filter, activate test lamp, and activate FPA high voltage) and monitoring SI engineering telemetry to verify that the commands have executed properly. The FDP modules are used for applying basic data processing functions to the FPA data in support of the various high-level operations.

The duration of science exposures is limited by the level of cosmic ray background radiation at L2. The background flux is estimated to be such that ~ 10% of image pixels would be contaminated in exposures lasting 1000 s, which is currently taken as an approximate upper limit for exposure times (cf. Isaacs, Legg, and Tompkins 1999). Occasional solar flares or coronal mass ejections raise the background particle flux sufficiently to render observations useless, or even endanger the SI FPAs if detector high voltage remains active. Consequently, a radiation monitor is included that informs the OPE regarding the level of the background flux to allow it to either postpone observations or deactivate the SI FPA high voltage, as appropriate.

3. Observation Plan Structure

The ground-based planning and scheduling system constructs an observation plan for the OPE to execute on a regular (say, weekly) basis. The new plan is uplinked and appended to the end of the currently executing plan, so there is no break in execution. Each plan is composed of the following progressively smaller structures: visits, groups, activity sequences, and activities. These components have the following definitions and attributes.

Activity: The smallest logical unit uploaded from the ground for dissemination by the OPE. Some typical activities are *Slew*, *Acquire Guide Star*, *Acquire NIRS Target*, and *Acquire NIRC Exposure*. Each activity has a number of associated parameters, both generic and specific. Generic parameters include the ID of the target application (e.g., AOC for a *Slew* activity), and a flag indicating whether successful completion of the activity is required for the visit as a whole. Specific parameters are those required to define the activity, such as target attitude for a slew, as well as special conditions that must be met before the activity starts, such as sufficiently low spacecraft jitter for a guide star acquisition.

Activity sequence: A set of one or more activities to be executed sequentially, e.g., [*Slew*, *Acquire Guide Star*, *Acquire NIRC Exposure*].

Group: A set of one or more activity sequences to be executed in parallel. This allows, for example, a NIRS dark current calibration in parallel with a NIRC science exposure. All activity sequences within a group must be complete before the next group begins.

Visit: A logically complete set of one or more groups. Visits typically consist of a slew to a particular target attitude, followed by a number of science or engineering activities at that attitude. A visit may also have associated parameters, in particular a set of three time parameters: an earliest permitted start time, latest permitted start time, and latest permitted end time. These can be used, for example, to synchronize the visit with an anticipated astronomical event or with related observations by other observatories. Being logically complete, a visit is the natural unit to drop if one of its required components is found to be nonviable.

Auxiliary Visits: Although not expected to be used for the NGST mission, a natural extension of the OPE concept is the use of an onboard pool of auxiliary visits, provided by the flight operations team (FOT), that the OPE can use to fill gaps in the plan that may arise as a consequence of the OPE dropping one or more nonviable visits that precede a fairly tightly time constrained visit. We do not examine this extension here; see Welter, Legg, and Cammarata 1999 for further discussion.

4. OPE Communications Protocol

Four types of information exchange are of interest for the OPE: OPE control directives, activity validation dialog, activity execution dialog, and state change notifications. For the following discussion, a "directive" is a high-level instruction from some control entity (e.g., the OPE) to an application (e.g., AOC) to perform some function.

The OPE control directives are the mechanism by which a higher level authority (i.e., the FOT or HSC) controls the behavior of the OPE. In addition to the basic directive for appending a new observation plan to the current one, there are OPE control directives to suspend and restart the OPE's ability to issue directives, to cause it to suspend or terminate any outstanding directives that it has issued, and to cause it to smoothly shut down its own function.

An activity validation dialog takes the form of the OPE directing a flight software application to confirm that an activity is valid for execution. For each defined activity directive, the application has rules for ascertaining whether or not the activity is currently valid. For example, AOC is able to ascertain whether a slew target attitude violates Sun constraints. Each application responds to an activity validation directive with an indication of *valid* or *invalid.*

An activity execution dialog consists of the OPE directing an application to execute a specified activity. For safety, the application reapplies its validation procedure to confirm that the activity is valid. If it is valid, the application attempts to execute the activity. Upon completing the activity, the application issues a response message indicating that the activity *succeeded, failed*, or was *terminated prematurely* (e.g., by a subsequent OPE directive).

State change notifications are spontaneously generated messages issued by the various flight software applications that inform the OPE of important system state changes that are not the specific consequence of an earlier OPE execution directive. These include such notifications as *spacecraft jitter in low range*, *guide star lock lost*, *system momentum in high range*, and *external radiation in medium range*. This state information is used by the OPE to coordinate observation plan execution flow as well as possible insertion of appropriate response actions.

5. OPE Operations for Normal Conditions

The normal flow for OPE processing of observation plan visits is as follows. The NGST OPE does not review the plan as a whole immediately upon completion of uplink from the ground, rather it validates each visit only immediately before its execution. At that time, the OPE conducts a validation dialog with each of the flight software applications to which an activity in the visit is addressed. Any activity found to be invalid at that time is marked as such by the OPE and suppressed from the plan. If an activity found to be invalid was also marked as required for the visit as a whole (e.g., the slew to the visit target), the visit as a whole is rejected and the OPE moves on to the next visit.

If the visit has not been rejected, the OPE checks to determine whether current time is within the specified permitted start time window for the visit. If current time precedes the permitted window, the OPE delays further processing of the visit until the window is entered. If current time is within the window, the OPE proceeds to the next step of evaluation. If current time falls after the window, the OPE proceeds to the next visit.

After time window verification, the OPE checks on the need for insertion of any house-keeping tasks that (1) will be necessary before the end of the visit and (2) could interfere with the visit. The most significant such house-keeping task is the use of the AOC thrusters to dump angular momentum. Although the details for the NGST momentum management strategy have not yet been formalized, we have assumed the following variation as an example of OPE house-keeping insertion.

A constraint on nominal visit duration is imposed through the ground-based scheduling segment so that the momentum predicted to be accumulated during any visit will be less than the diameter of the permitted angular momentum sphere. With support from an AOC analysis utility, the OPE determines whether the expected momentum accumulation for the visit added to the current momentum load would cause violation of the permitted momentum sphere. If no violation is predicted, no momentum dump is inserted. If a violation is predicted, the analysis utility also computes the minimum dump necessary, actually the associated post-dump target momentum, such that the momentum load will just reach the permitted momentum sphere at the end of the visit. To allow for modest schedule deviations, the momentum sphere for this test is padded inwards slightly to a "yellow" limit, with the pad the equivalent of, say, two science exposures. The parameters for the dump are then packaged as an activity to be executed in parallel with (i.e., combined as a group with) the initial activity of the visit, typically a slew. To allow for the possibility that the initial activity is not compatible with a parallel dump, the OPE has a list of activities that are compatible with parallel momentum dumping. If the initial activity is not on the list, the OPE inserts the dump before the first planned activity of the visit.

The OPE then proceeds to issue the various activity directives for the activities of the visit. This process proceeds on an event-driven basis, thereby alleviating the ground-based scheduler of the need to model activity execution in detail or insert execution time pads into the observation plan. As activity sequences proceed, the next activity can only be started after the OPE has received an activity completed notification from the application executing the preceding activity. Furthermore, even if the prior activity has completed, the OPE delays directing the execution of any activity until required observatory state conditions specified for the activity have been realized. For example, an *Acquire Guide Star* activity can specify that the SSM jitter must be within a "green" range before acquisition can begin, which will have been reported via a state change notification message by AOC. The OPE also requires completion of all parallel activity sequences within a currently active group before any activities in the next group are initiated.

6. OPE Responses to Anomalous Conditions

The OPE responds to various anomalous conditions. We present five examples pertaining to NGST operations: loss of guide star lock, violation of permitted momentum limits during visit execution, extreme background particle flux, visit end time violation, and attitude constraint violation.

To support the first three types of violations, each of the high-level ISIM applications (i.e., FGS, SI TAS, and SI SDC) support two special generic directives: *Suspend* and *Resume.* A *Suspend* directive causes the application to stop whatever process it is currently doing, reset itself to begin the process again at a natural starting point, issue a directive to the associated FDP utility to stop any support computations, and finally notify the OPE that the *Suspend* directive has succeeded. If an application is not currently active, it remains in the same state and issues the required notification of success.

For most applications, the natural starting point is simply the beginning of the activity, so the whole activity will be repeated. For FGS, the natural starting point is either (1) the beginning of the activity (i.e., to include a search for and verification of the candidate guide star) if the guide star has not yet been acquired, or (2) a simple reacquisition based on the known location of the guide star if the guide star has been acquired.

A *Resume* directive causes an application to proceed forward from its starting point if it is in a suspended state and issue a success or failure response notification message to the OPE. With the exception of FGS, all applications immediately respond to a *Resume* directive with a success notification. If FGS had not yet acquired a guide star, it too responds immediately with a success notification; a subsequent failure to acquire will be reported as a failure of the not yet completed *Acquire Guide Star* activity. However, if the guide star had already been successfully acquired, FGS postpones notifying the OPE regarding the outcome of the *Resume* directive until after it has succeeded or failed in its reacquisition attempt and then respond accordingly.

An anomalous event can result in activity failure. If a failed activity is marked as required for the visit as a whole, e.g., if FGS is unable to acquire a guide star, the OPE terminates the visit and moves immediately to the next visit. To accommodate this design, each application is required to autonomously perform any necessary clean-up tasks and place itself and associated hardware elements in one of a small number of easily identified standard states at the end of any activity.

6.1 Loss of Guide Star Lock

Upon being notified by FGS that a loss-of-lock has occurred, the OPE activates a script that causes *Suspend* directives to be sent to all ISIM applications. After all applications have reported success, the OPE issues a *Resume* directive to FGS. If FGS succeeds in acquiring the star, the OPE issues *Resume* directives to all of the remaining ISIM applications; otherwise, the OPE terminates the visit. To prevent a possible infinite loop of guide star loss-of-lock events followed by temporarily successful reacquisition attempts, the OPE keeps track of the number of loss-of-lock events that occur in each visit and terminates the visit if the number becomes excessive.

6.2 Violation of Momentum Limits

In addition to the yellow momentum limit, two other limits are defined: orange and red. The red limit is sufficiently close to actual reaction wheel saturation that the OPE must immediately respond to it. The orange limit, while still high, is sufficiently below the red limit that there is time to complete any exposures currently in progress, but no more. Given the logic for insertion of house-keeping momentum dumps previously described, it should only be possible for an orange or red limit violation to occur if some real-time anomaly has delayed completion of the visit.

Upon being notified by AOC that an orange momentum limit violation has occurred, the OPE activates a script that will suspend all ISIM applications after any currently outstanding activities have been completed. After all of the ISIM applications have been suspended, the OPE uses the AOC analysis utility previously described to determine parameters for a momentum dump that will reduce the momentum load sufficiently below the yellow limit so that the yellow limit will just be reached again at the predicted end time of the visit. Because the momentum dump will induce vehicle jitter, the script instructs the OPE to refrain from issuing an FGS *Resume* directive until after the "green" jitter range has been reachieved. Thereafter the script is the same as the end of that used for responding to a guide star loss-of-lock.

If the red limit is crossed, the OPE's response is the same except that it does not wait for the outstanding activities to run to completion before issuing the *Suspend* directives. To avoid interference between the red violation response script and the orange script that will have already been activated, the OPE deactivates the orange script when the red script starts.

6.3 Extreme Background Particle Flux

Three background particle flux ranges are of interest: low, medium, and high. Valid SI measurements can be made for low background flux. The SIs are safe but measurements are invalid for medium background flux. The SI FPAs are in danger of high-voltage arcing damage if the background flux is high and the FPA high voltage is on.

When informed of a low-to-medium or medium-to-high particle flux transition, the OPE activates a script that suspends all ISIM applications. If the flux is high, the OPE also issues high-voltage deactivation directives to the three CMC applications to deactivate FPA high voltage. When a high-to-medium transition occurs, the OPE issues high-voltage activation directives and sets a timer to delay progress in the response script for a specified period. When a medium-to-low transition occurs, the OPE issues an FGS *Resume* directive, followed in due course by *Resume* directives to the remaining ISIM applications.

6.4 Combined Response Scripts

Given the similarity of the various responses just described, one can combine them into a single script with appropriate state condition checks to determine whether certain elements of the script (i.e., momentum dumping or FPA deactivation) should be used. The reception of any one of the anomaly notification messages appropriate to activation of the script would result in termination of any previous version of the script that may already be running and reactivation of the script from the beginning.

6.5 Visit End Time Violations

Delays in the completion of a visit resulting from anomalies such as those described in the previous subsections could result in the violation of the visit-specified latest permitted end time. If this occurs, the OPE terminates the current visit and proceeds to the next visit.

6.6 Attitude Constraint Violations

If the ground-based scheduler does not specify latest permitted end times for all visits, delays in visit completion could result in the spacecraft remaining so long at its current attitude that Sun constraints are violated. Upon detecting an attitude violation, AOC slews the vehicle to a local valid attitude and notifies the OPE. The OPE then terminates the current visit and proceeds to the next.

Summary

We have presented a proposal for an onboard observation plan executive (OPE) tailored for use on the Next Generation Space Telescope. The goal is to produce a system that provides flexible and efficient event-driven execution of observation plans generated by a ground-based planning and scheduling system, as well as robust response to real-time anomalies. The various sections of the paper have described the NGST flight systems that constitute the context within which the OPE will be operating, the structure of the observation plan provided by the ground segment as basic input to the OPE, the communications protocol between the OPE and the various spacecraft applications whose activities it coordinates, OPE operations under nominal conditions, and a set of example OPE responses to anomalous conditions.

Acknowledgements

Variations on the ideas reported here have been evolving over a number of years. We acknowledge, in particular, our colleagues on the NGST Software Operations Working Group, all of whom contributed to the evolving OPE concept. We have also made free use of the related ideas explored in Cammarata et al. 1998, Doxsey et al. 1998, Legg and Welter 1999, and Welter, Legg, and Cammarata, 1999.

Acronym List

AOC	attitude and orbit control
CMC	configuration monitor and control
FGS	fine guidance support
FDP	FPA data processing
FOT	flight operations team
FPA	focal plane array
GSFC	Goddard Space Flight Center
HSC	health and safety control
HST	Hubble Space Telescope
ISIM	integrated science instrument module
MIRC/S	mid infrared camera / spectrograph
NGST	Next Generation Space Telescope
NIRC	near infrared camera
NIRS	near infrared spectrograph
OPE	observation plan executive
OTA	optical telescope assembly
SDC	science data collection
SI	science instrument
SSM	spacecraft support module
TAS	target acquisition support

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