THE XMM MISSION PLANNING PROCESS AND TOOLS

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ABSTRACT

The X-ray Multi Mirror Module (XMM) spacecraft, an X-ray observatory that was launched on 10th December 1999, is the largest ESA scientific spacecraft ever built, with a mass of nearly 4 tonnes. One of ESA's cornerstone scientific projects, the objective of the XMM mission is to obtain the most comprehensive survey of X-ray sources, in total approximately 1,000,000 celestial targets are expected to be observed. The XMM payload comprises 3 high sensitivity X-ray imaging cameras, 2 high-resolution X-ray spectrometers and one additional instrument covering the optical wavelengths. The instruments are designed to be operated in parallel so that efficient use of observation time is made.

This paper describes the planning constraints of the XMM mission and explains the concept behind the mission planning process, in particular how the activities of the Science Operations Centre (SOC) and the Mission Operations Centre (MOC) are coordinated to make the most of the observing time available for science taking. A detailed description of how proposals for observing time are gathered from members of the scientific community, how they are evaluated and subsequently inserted in the XMM operations schedule, and how telecommands are generated and uplinked to the spacecraft is included.

Keywords: Mission planning, Proposal handling, Web-based system, Scheduling, Simulated annealing.

Introduction

In common with previous scientific ESA missions, the planning and operation of the XMM spacecraft and payload is achieved through the interaction between two geographically distinct bodies. The XMM Science Operations Centre (SOC) is responsible, among other things, for planning scientific observations and processing and archiving the resultant data. The XMM Mission Operations Centre (MOC) controls the operations of the spacecraft and instruments and ensures that the spacecraft's safety is not compromised. A similar high-level planning strategy was also used for ESA's highly successful observatory mission, the Infrared Space Observatory (ISO) launched in November 1995 and operated until April 1998.

XMM is an observatory mission and as such its telescope needs to be pointed towards x-ray sources. Because of the faint nature of the x-radiation, XMM observations are usually long, in the order of a few hours. The spacecraft orbits around the Earth with perigee and apogee of approximately 7,000 and 114,000 km, respectively. Two ESA ground stations, Kourou (in the French Guyana) and Perth (in Australia) are used to command XMM and to receive its telemetry. Except for a short period around perigee, the spacecraft is always visible from one of the ground stations.

The paper describes the constraints imposed on the planning system by the spacecraft, the instruments and the observation strategy. The remainder of the paper describes in detail the end-to-end mission planning process, from the capture of a scientific proposal through to the uplinking of spacecraft and instrument telecommands for execution. In addition, an outline of the main planning tools and techniques used in the SOC planning subsystems can be found.

Most of the MOC and SOC subsystems have been developed for ESA by a consortium of European Industries lead by Logica (UK) that included Dataspazio (I) and GMV (E).

Definitions

Before the planning process is described in detail, it is first useful to define a few terms used throughout the paper:

Proposal - a proposal is defined to be a collection of observations which can themselves be either scientific, calibration, or engineering in nature. Proposals of scientific observations are the principal proposal type and are created and submitted by the X-ray scientific community.

Observation - an observation is the term given to a single, stable 'pointing' of the -X axis of the spacecraft, to which the instrument boresights are nominally aligned. Thus, there is a single designated target (a point on the celestial sphere) associated with each observation. An observation consists of one or more exposures.

Exposure - an exposure is defined to be a single fixed configuration period of an instrument. It is analogous to the notion of an exposure for an optical camera, for which the term defines the camera settings in terms of shutter speed and aperture size required to record an optical image on film. Onboard XMM, exposures on the different instruments can be made in parallel.

Planning Strategy

As there is almost always visibility from the XMM ground stations of Perth and Kourou during science taking periods, the spacecraft has been designed with limited on-board storage capability for both telecommands and telemetry. This implies that the operational concept is to have the control loop closed at the ground. In this context, the planning strategy for the XMM operations is one in which:

- all science observations and associated operations are pre-planned;
- all planned and contingency spacecraft and instrument operations are performed under on-line command from the MOC and the SOC in real-time. That is, there is no onboard time-tagged command schedule to be used for nominal scientific operations. XMM does have an onboard time-tagged command buffer, but this is to be used by the MOC only for safety and security critical situations;
- there is limited onboard storage of science telemetry. All scientific observation data is downlinked to ground in real-time as it is obtained.

The science mission planning process is an off-line activity and can be broadly broken down into 2 distinct areas: proposal handling and observation sequence planning. These are described in detail later in the paper.

Planning Constraints

There is a number of planning constraints that must be taken into account by the mission planning systems in order to ensure that instrument and spacecraft safety is not compromised. XMM comprises 3 high sensitivity X-ray imaging cameras (EPIC - European Photon Imaging Camera), 2 high-resolution X-ray spectrometers (RGS - Reflection Grating Spectrometer) and one optical instrument (OM - Optical Monitor). To operate the instruments safely and to obtain good scientific data from the instrument, XMM performs scientific observations only when its altitude from the Earth is above the 40,000 km, i.e. above the radiation belts. The pointing constraints that are imposed in order to operate the spacecraft and its on-board instruments within safe operating limits are as follows:

- the angle between the telescopic line of sight (-X axis) and the sun direction must be $90° \pm 20°$;
- the roll angle must be less than 20°;
- during scientific observation periods, the telescopic line of sight must be more than 47° from the earth limb and 22° from the moon limb;
- outside scientific observation periods, the telescopic line of sight must be more than 35° from the earth limb and 3° from the moon limb.

Avoidance criteria are also likely to be applicable for other solar system objects; these are, however undefined at the present time.

The pointing constraints imposed by the physical limitations of the spacecraft sensors and the instruments are not the only constraints that are observed during the planning process. The following considerations fall into the category of operational constraints:

- time to perform routine space and ground segment maintenance operations needs to be allocated as part of the routine planning cycle;
- de-configuration of the instrument and spacecraft subsystems prior to 'unsafe' events such as solar eclipse periods, entry to perigee passage and so on, needs to be scheduled;
- de-configuration of the instrument and spacecraft subsystems prior to the 'apogee gap' experienced once per orbit by the spacecraft. This gap in ground station visibility arises due to the adoption of the highly inclined 40 degree southern orbit and lasts approximately 1 hour each orbit.

Proposal Handling

The start of the mission planning process is the capture, evaluation and enhancement of proposals of scientific observations from the X-ray community. This is called *proposal handling.*

Procedure

Proposal creation occurs in response to the Announcement of Opportunity (AO) made by the XMM Project Scientist. Representatives from the X-ray scientific community, Principal Guest Observers (PGOs), are then invited to submit proposals for scientific observations to the SOC where they are evaluated by SOC staff in the next stage of the planning procedure. Proposals can be created and submitted directly into a database of unevaluated proposals by any scientist with access to a suitably configured World Wide Web (WWW) browser. For those without access to a browser, the procedure involves submitting the required observation details to SOC staff directly (via e-mail or fax) who can enter the information using a similar tool to that available to the external observers.

All submitted proposals must undergo evaluation prior to being made available for scheduling for the following reasons:

- to remove duplicate observations from being scheduled; the XMM observing time is a valuable resource and in order to meet the mission objective to observe 1 million celestial targets, this must not be squandered. Various tools are available to help the SOC staff responsible perform this activity and to enable them to compare an unevaluated proposed observation with evaluated and approved observation requests;
- to 'enhance' the submitted scientific observations to ensure that the maximum scientific return is obtained each individual spacecraft pointing. Enhancing an observation can be achieved by including additional instrument exposures for instruments other than the designated prime one and by tuning the spacecraft

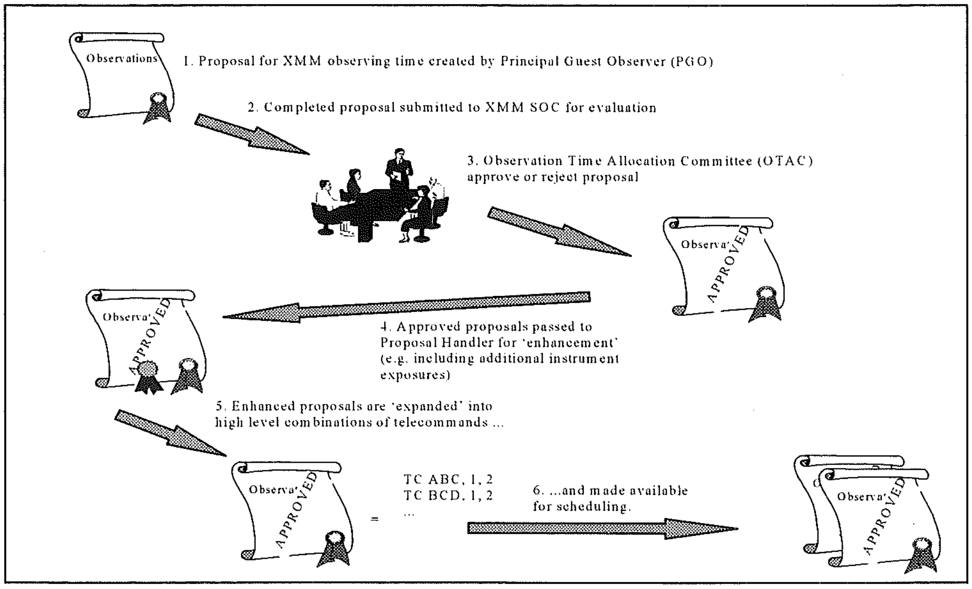

Figure 1: Proposal Handling Stages

attitude to include objects of interest in the instrument field of views additional to the designated observation target.

The evaluation procedures are carried out by Proposal Handlers, SOC staff members, and by the Observation Time Allocation Committee (OTAC). Approved observations are assigned a scheduling priority that is used at the sequence generation stage of the process to ensure that the highest priority observations are included in the spacecraft operations. The principal stages of the proposal handling process are shown in Figure 1.

Proposal Handling Tools

The Proposal Handling Subsystem (PHS) is the name given to the collection of tools available to support the proposal handling process. These are described below.

Remote Proposal Submission (RPS) - this is a WWW site available to the scientific community and which provides proposal creation, editing and validation functions. The RPS comprises a set of Active Server Pages (ASP) written in Visual Basic and which use an Open Database Connectivity (ODBC) interface to an underlying ORACLE database, which stores the temporary proposal information. By building certain instrument configuration 'rules' into the database and linking the ASPs to the database the tool provides on-line validation at each stage of proposal creation. Following the completion of the temporary proposal details, the PGO can 'submit' the proposal, which effectively places the information under configuration control within the main Proposal Database (PDB) of the SOC. At this stage, the status of all observations in the proposal is set to 'Entry'.

Proposal Editor (PE) - this is the name given to the tool available for use by the SOC staff only. This tool can be accessed via any WWW browser and is based on the RPS in an attempt to ensure the maximum commonality and re-usability of software. The functions of the PE are however, much more sophisticated and enable the Proposal Handler to specify instrument modes and configurations not available to the scientific community. The PE is used by the Proposal Handler to enhance a submitted proposal following approval of the proposal from the OTAC. All modifications to the original proposal are configuration controlled, so that previous edits can be reinstated if required. In addition, the tool provides functions to create new proposals; this enables instrument scientists at the SOC to store 'calibration' and so-called 'engineering' proposals in the PDB for inclusion in the routine mission planning observation sequence. For instance, it is possible to carry out calibration of one instrument by using its internal calibration source, while another one is being used to observe a scientific target. In this manner, less 'down-time' of the instruments is required, thus increasing the scientific efficiency.

Proposal Tools (PT) - there are a number of stand-alone tools which are used by the Proposal Handler to evaluate the scientific merit of an observation and to calculate additional information required to configure the instruments for the series of exposures within the observation. These are collectively called the Proposal Tools and the various functions have been integrated into a single Man Machine Interface (MMI) to provide the Proposal Handler with a uniform procedure to control this activity.

Observation Sequence Planning

Observation Sequence Planning is the term given to the selection of approved observations scheduling them in a time-ordered sequence within a planning period (i.e. a period of time for which spacecraft and instrument operations are being planned).

Procedure

The cycle for generating observation sequence schedules revolves around a 2 week planning period and is based on the concept of 'filling in' a skeleton, or outline, plan with increasing levels of detail at each processing stage, until finally a complete operational plan is created.

A number of different subsystems are involved in the evolution of the skeleton plan into the final sequence of time-ordered telecommands ready for uplinking to the spacecraft. The primary systems involved in this process are:

- Flight Dynamics System (FDS), located at the MOC;
- Sequence Generation Subsystem (SGS), located at the SOC;
- Mission Planning Subsystem (MPS), part of the XMM Control System (XMCS) located at the MOC.

The data flows between these systems and the associated timings are shown in Figure 2. The process is initiated 28 days before the period being planned is due to start, by the production of seven Planning Skeleton Files (PSF) by the Flight Dynamics System (FDS) at the Mission Operations Centre (MOC). Each PSF contains 'windows' of time for a single orbit, in which the SOC Sequence Generation Subsystem is able to schedule observation time. Other periods of time not available for scientific planning purposes (e.g. for spacecraft or ground segment maintenance) are identified in the file, along with orbit related events, such as eclipse information and star-tracker operational characteristics, that must be used during the planning of the observation sequence.

PSFs are received at the SOC by the SGS and are used, together with the database of schedulable observations and the planning constraint information, to produce a set of Preferred Observation Sequence (POS) files and Instrument Command Parameters (ICP) files. The POS is essentially an extended PSF, since it contains all the PSF information, but includes additional data defining the spacecraft attitudes required for each observation in the sequence and the time-related observation and exposure commanding details. The ICP is an auxiliary file used to contain the instrument command parameters. Like the PSF, each POS and ICP pair contains information pertaining to a single revolution. POS and ICP files, 7 pairs of files corresponding to 7 orbits, are sent back to the MOC, 14 days prior to the planing period starting. This is received by the FDS, which checks that the observation sequence defined in the POS is feasible with regard to the spacecraft pointing and operational constraints. The FDS also generates the necessary commands and parameters that are required by the spacecraft Attitude Orbit Control System (AOCS) and Startracker (STR) on-board systems to manoeuvre the spacecraft between the different observation attitudes. The result of this processing is an additional file pair, called the Enhanced Preferred Observation Sequence (EPOS) and the Attitude Parameter File (APF). These are basically extensions of the POS and ICP files described earlier, and again, there is one file pair per orbit being planned. The EPOS and the APF files are submitted to the XMCS Mission Planning System less than one week after reception of the POS/ICPs. There, they are placed under configuration control and validated one final time against the telecommand database before being used to generate the Timeline and the Timeline Summary File (TSF). The timeline is submitted to the XMCS Telecommanding Subsystem (TCS) for uplink to the spacecraft and the TSF is transferred to the SOC as a confirmation of the acceptance of the observation sequence.

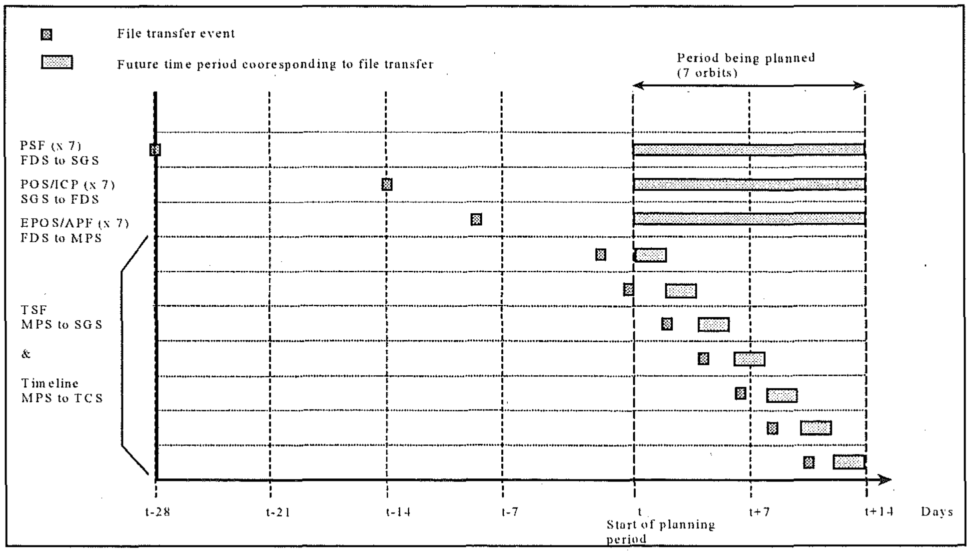

Figure 2: Mission Planning Data Flows

Sequence Generation Tools

The Sequence Generation Subsystem (SGS) comprises a set of manual and automatic tools to enable the Mission Planner at the SOC to define the observation sequence. They are briefly introduced below.

Session Manager (SM) - this controls the mission planning session and provides a number of high level functions. For example, an interface is provided to support

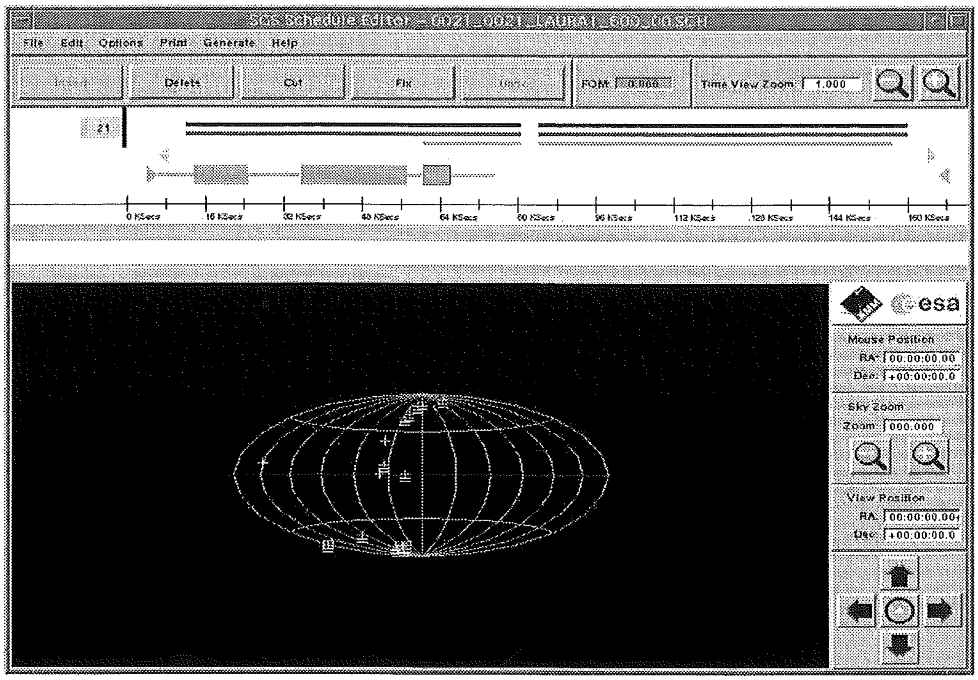

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Figure 3: Snapshot of the XMM SGS Schedule Editor

the introduction of the PSFs from the MOC along with simple viewing functionality to inspect the files. In addition, the SM validates the POS/ICP files produced by the Schedule Editor (see below) against the telecommand database and initiates the transfer of the files to the MOC for further processing.

Schedule Editor (SE) - this is the primary planning tool used by the Mission Planner. It is essentially a GUI editor, providing the Mission Planner with visualisations of the planning and observation data and also provides him/her with the functions to create and manipulate an observation sequence, whilst enforcing all planning constraints. The SE comprises 3 main displays: the Timeline View, which is a temporal representation of the planning constraint information and the observation sequence for the current planning period; the Sky View, which is a spatial representation of the celestial sphere (2 projections are provided, Aitoff and Orthographic Sin), showing candidate and scheduled observations; and the List View, which as the name suggests, is a text list of candidate observation details. A snapshot of the main window that includes the Timeline and the Sky views of the SGS SE tool is given in Figure 3. These views give the Mission Planner all the information s/he requires to produce and evaluate an observation sequence. When used in manual mode, the SE enables the Mission Planner to add and remove observations from the sequence, or to change the order of existing observations, simply by selecting observations in any of the views and pressing the button to perform the desired operation.

Schedule Optimiser (SO) - this is an important automatic scheduling tool available to the Mission Planner. It provides the means to automatically create different observation sequence solutions, based on a Simulated Annealing (SA) algorithm, which is a simple extension to the 'hill-climbing' algorithm (see next bullet). The schedule optimiser can be invoked by the mission planner at any time while a schedule is being edited by the schedule editor described above. The optimiser works by taking a copy of the current schedule and then producing incrementally 'better' solutions while it runs as a background activity. Each time an improved schedule is created, it is saved to a different electronic file, which is thus available subsequently for manual editing using the schedule editor. When the mission planner invokes the optimiser, there are a number of 'directives' that can be selected to ensure that certain manual scheduling decisions are not overruled by the automatic scheduling. For example, a time period which the optimiser is to work on can be specified, so that other parts of the schedule remain unaffected. Another example concerns the nature of the automatic algorithm itself; during the optimisation the algorithm might choose to remove an observation already in the schedule and replace it with another observation from the candidate pool. This behaviour can be prevented by manually 'fixing' individual observations in the schedule prior to running the optimiser.

In addition, the 'cost function' of the algorithm (described in the bullet point below) can be manually configured before running the optimiser and the results compared with those produced by other cost functions. One operational example of when a different cost function might be used is if an instrument on board the spacecraft fails, or its performance starts to degrade. In this scenario, the cost function can be easily replaced with another one which prioritises the use of the remaining operational instruments.

Simulated Annealing (SA) algorithm – it works by mimicking the annealing process in a cooling metal, whereby the energy level of the metal's molecules is analogous to the energy level, or 'cost', of a particular observation sequence solution. The solution cost is evaluated by calculating a numeric value based on metrics of the schedule which are deemed to contribute positively, or negatively, to the quality of the sequence. For example, slew time, the time spent by the spacecraft manoeuvring between observation targets, should be minimised in order to spend the maximum amount of time obtaining quality scientific data. However, this must be offset against the requirement to schedule high priority observations, which might be in a portion of the sky further away from the ideal, minimal slew path. By evaluating how the cost of a solution changes in response to variations, or perturbations, which are randomly introduced, the algorithm can increase the quality of the solution. A number of other controlling influences, or parameters, conditions the decisions taken by the algorithm. Probably the most important of these is the definition of a 'cooling curve'. The cooling curve, as its name suggests, mimics the natural process of reducing temperature over time. This is used by the algorithm to determine the probability that a perturbation that reduces the quality of a schedule will be accepted before continuing with the next perturbation on the schedule. This feature enables the algorithm to (potentially) converge on a globally optimal solution in the domain, or solution space, rather than simply converging on a localised solution, as occurs in other techniques. The rate at which the algorithm 'cools' can impact the effectiveness of the algorithm; if it cools to quickly the potential to find an optimal solution is reduced; cooling too slowly might mean that the algorithm takes a very long time to converge. The definition of the cooling curve is configurable in the schedule optimiser code, enabling the mission planners to experiment with different curves and to determine a suitable one for the XMM planning problem.

Conclusion

The XMM mission planning process is based on the concept of distributed responsibility. The SOC mission planning components are responsible for scheduling observation time such that they meet the safety and operational constraints imposed by the spacecraft systems and instrument payload. Planning information is added incrementally at different planning stages by MOC and SOC subsystems until an operational schedule is produced. In this manner, the complex planning problem is simplified into a number of less complex and more manageable activities. Efficiency of the XMM mission planning process can be assessed at a number of levels. First, the number of data transfers (and system interfaces) has been reduced from that used for the ISO model, thus reducing the number of system interactions and making the overall system more efficient procedurally. Second, where possible within the cost constraints of the project, the SOC planning tools have been designed with useful automatic functions to assist in the more time-consuming aspects of the process. In addition, verification and validation is performed as early in the planning process as possible to reduce the number of instances where re-planning might be required due to incorrect or incomplete data. Third, the mix of automatic and manual tools to achieve good use of the observing time available, is key to the design of the Sequence Generation Subsystem; human operators provided with sophisticated visualisation tools, are capable of creating good scheduling solutions. Together with the automated support from the simulated annealing algorithm, it is envisaged that very good efficiency will be achieved. Finally, the design of the XMM spacecraft systems and instruments ensures that as much useful information as possible is obtained through parallel operation of the instruments. For some instruments, serendipitous data may even be acquired during slews, which are also scheduled via the SGS.

As of the time of writing this paper, the XMM mission planning is being used to plan the actual mission since January 4th 2000. Despite the limited experience that could be accumulated in this short period, the mission planning process and the associated tools are performing as expected with no major problem to report. Currently, most of the XMM operations are executed using the timelines generated using the planning process and tools described in this paper. This confirms that our system can do the job for XMM!

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