XMM MISSION PLANNING: ISO REVISITED?

A.J.C. McDonald(*), G. Gienger(#), R. Kresken(†) & C.G. Petersen(‡)

(*) Logica UK Ltd, ESA/ESOC, Robert Bosch Str.5, 64293 Darmstadt, Germany
Fax: (+49) 6151 902092. email: amcdonal@esoc.esa.de
(#) ESA/ESOC, Robert Bosch Str.5, 64293 Darmstadt, Germany
Fax: (+49) 6151 902271. email: ggienger@esoc.esa.de
(†) EDS Industrien (Deutschland) GmbH, ESA Satellite Tracking Station,
Villafranca del Castillo, PO Box 50727, 28080 Madrid, Spain.
Fax: (+34) 1 8131 139. email:rkresken@vmprofs.vilspa.esa.es
(‡) CRI A/S, ESA Satellite Tracking Station, Villafranca del Castillo,
PO Box 50727, 28080 Madrid, Spain.
Fax: (+34) 1 8131 139. email:cpeterse@vmprofs.vilspa.esa.es

ABSTRACT. During the early months of the mission, ESA's Infra-red Space Observatory (ISO) has demonstrated the reliability and efficiency of the mission planning process: a process characterised by interacting groups of users and operators as well as tight time scales for completing all the planned observations. In developing, under tight budgetary constraints, the mission planning concept for the X-Ray Multi-Mirror Mission (XMM), it is only natural to look critically at the ISO system to identify areas of commonality, and to re-use ISO designs and software wherever applicable.

This paper reviews briefly the operations concepts of the ISO and XMM missions. There follows a short description of the ISO mission planning process. Comparisons are then drawn between the ISO system and that proposed for XMM. As will be seen, while the overall process shows considerable commonality of approach, the longer mission lifetime and longer observation intervals for XMM, move the operations concept away from a rigidly pre-planned approach with automated commanding toward one which allows greater flexibility and manual intervention.

Although the roles of the science and operations teams are discussed, detailed technical descriptions are limited to the areas affecting the Flight Dynamics development at ESOC. In particular, whereas the ISO project maintains a small dedicated team of Flight Dynamics specialists throughout the mission, the XMM team at ESOC will direct effort into producing a flight dynamics system which the spacecraft controller is capable of using for restricted mission planning activities.

1. INTRODUCTION

The European Space Agency's Infrared Space Observatory (ISO) was launched in November 1995 by an ARIANE 4 launch vehicle into a highly eccentric, low inclination orbit. After perigee raising manoeuvres, the nominal orbit had a perigee height of 1000 km and an apogee height of 71000 km giving an orbital period of 24 hours. The mission duration is determined by the cryogenic unit on-board which is continuously boiling off liquid helium to keep the payload at 3-4 degrees Kelvin. Currently, the expected mission duration is approximately 24 months. The on-board scientific experiments, conceived and built by various scientific institutes external to ESA are made available to the scientific community who apply for observing time on a competitive basis. There are four scientific instruments on-board: a short wavelength spectrometer, a long wavelength spectrometer, a photo-polarimeter and an infrared camera.

ESA's X-Ray Multi-Mirror (XMM) satellite is an observatory in the soft x-ray portion of the electromagnetic spectrum (0.1 to 12 keV). It is scheduled to be launched in 1999 by an ARIANE 5 launch vehicle. It will have a highly eccentric, high inclination orbit a perigee height of 7000 km and an apogee height of 114000 km giving an orbital period of 48 hours. The nominal mission duration is planned as 27 months with possible extension to 10.25 years (total duration) depending on consumables. There are three scientific instruments on-board: a photon imaging camera consisting of three co-aligned mirror modules, a reflection grating spectrometer and a telescope working in the visual and ultraviolet spectra.

The *mission planning* of the sequence of scientific observations and basic operations is of fundamental importance to both the ISO and XMM missions.

2. ISO MISSION PLANNING

2.1 SUMMARY OF THE ISO AOCS

The ISO Attitude and Orbit Control System (AOCS) is required to position an astronomical object within the required instrument aperture to an accuracy of 2 arcseconds. During scientific observations, ISO supports two modes: Fine Pointing Mode where a fixed attitude is maintained and Raster Pointing Mode where the spacecraft performs a series of small slews designed to build up a rectangular raster image of an extended object with raster point spacing between 2 to 180 arcseconds. Attitude control in both modes is maintained using a star tracker (aligned with the payload optical axis) and a fine sun sensor (with boresight perpendicular to the star tracker optical axis).

For each observation, an inertial unit vector to a suitable guide star and the target attitude, represented on-board by a quaternion, are uplinked. Once the requested attitude is reached, the AOCS computes the position of the guide star within the star tracker field of view. The star tracker searches for a star at that position within a given search window, the dimensions of which are prescribed from ground and restricted to avoid the possibility of detecting a neighbouring star of similar brightness. Control torques during observations and slews are provided by three reaction wheels. During slews, the active attitude sensors are three gyros and the fine sun sensor.

The AOCS must also ensure an attitude that fulfils the strict requirements stemming from the thermal sensitivity of the cryogenically shielded payload. Since the payload must not be exposed to direct sunlight at any time, the spacecraft sun shield has to be kept pointing toward the sun within close margins and the solar aspect angle of the optical axis of the telescope must be kept between 60 and 120 degrees. To avoid any direct infrared irradiation from the earth, the optical axis has to be kept outside a defined cone around the earth limb. To monitor this constraint, an infrared sensitive earth limb sensor is installed near the telescope aperture. ISO's attitude is permanently checked against these constraints. Any uplinked pointing request violating one of these constraints will be overruled by the AOCS, putting the spacecraft into an autonomous mode.

Routinely during perigee, ISO is maintained without star tracker control in Programmed Pointing Mode (PPM). This mode is also used when ISO is not in a ground controlled pointing or following an unforeseen contingency. In PPM, the spacecraft follows a sequence of typically six different attitudes which are repeated every orbit (approximately 24 hours) and valid for up to three days. The time-tagged commands prescribing the attitudes are generated daily on ground, considering all applicable attitude constraints.

2.2 MISSION PLANNING TEAMS AND PREREQUISITES

The mission planning is performed by staff at the ISO Spacecraft Control Centre (SCC) and Science Operations Centre (SOC). During the first three critical days after launch, operations were performed by the SCC at ESOC in Darmstadt. Thereafter, the SCC joined the SOC at ESOC's satellite tracking station at Villafranca del Castillo, near Madrid, from where all operations are performed (except for the routine orbit determination which is still performed at ESOC).

The SOC consists of several teams handling all scientific aspects of the mission. In the area of mission planning they are responsible for scheduling the scientific observations. As at ESOC the SCC consists of three teams:

- the flight control team, responsible for all aspects of spacecraft monitoring and control
- the flight dynamics team, providing the specialist orbit and attitude support
- the software support team, maintaining the on-ground ISO dedicated control system (IDCS).

The mission planner in the flight control team is responsible for scheduling non-scientific spacecraft platform operations, the generation of the final command schedule and tracking the progress throughout the planning cycle.

Before the formal mission planning process for ISO can begin, flight dynamics must supply the SOC with an orbit prediction file, an eclipse file and a Data Base of Observable Bins (DBOB). The DBOB provides the periods of observability for any direction of the sky over the planned mission lifetime. Within the DBOB, the celestial sphere is sub-divided into non-overlapping 'bins' of either 3x3 degrees or 10x10 degrees, with observability information provided for each bin, namely the time interval within which the entire area of the bin is free of constraints. Based on the DBOB, SOC is able to plan when a specific part of the sky, i.e. a bin, can be observed. The DBOB is valid for the complete mission, but it is re-generated periodically and after any orbit manoeuvre.

2.3 THE ISO MISSION PLANNING CYCLE

The basic planning period in the mission planning system is one orbital period, from perigee to perigee, termed a 'revolution' with a unique number. Mission planning files are identified by this revolution number and a version number, which allows re-planning starting from almost any step in the mission planning cycle. The ISO mission planning cycle (see Figure 1) for a given revolution is summarised as follows:

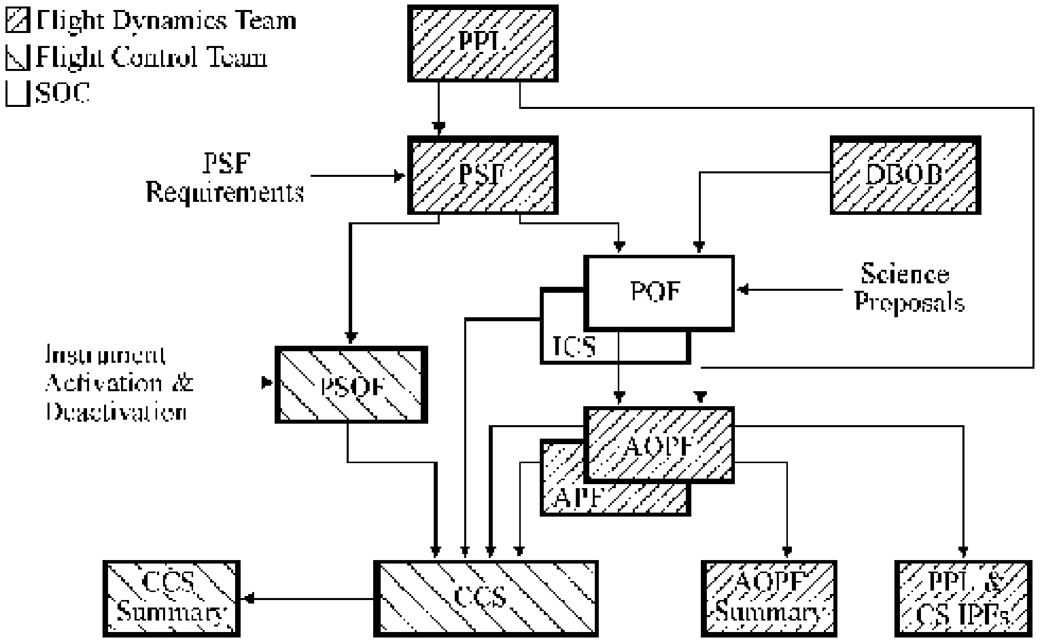

Figure 1. ISO Mission Planning Cycle and Products.

1. Flight dynamics firstly generate a Programmed Pointing List (PPL) containing the sequence of safe PPM attitudes. The generation of a PPL is usually automatic, but attitudes can be specified manually during special operations. The PPL is an internal flight dynamics product at this time.

2. Flight dynamics then produces the Planning Skeleton File (PSF) which includes events for altitude crossings, eclipses, and ground station visibility. It also splits the revolution into non-overlapping windows for scientific observations, calibrations, hand-over between ground stations, uplink of PPL, activation and deactivation of instruments. Requirements for the positioning and length of the windows are jointly defined by the flight control team, flight dynamics and SOC. Figure 2 shows the windows for a typical revolution.

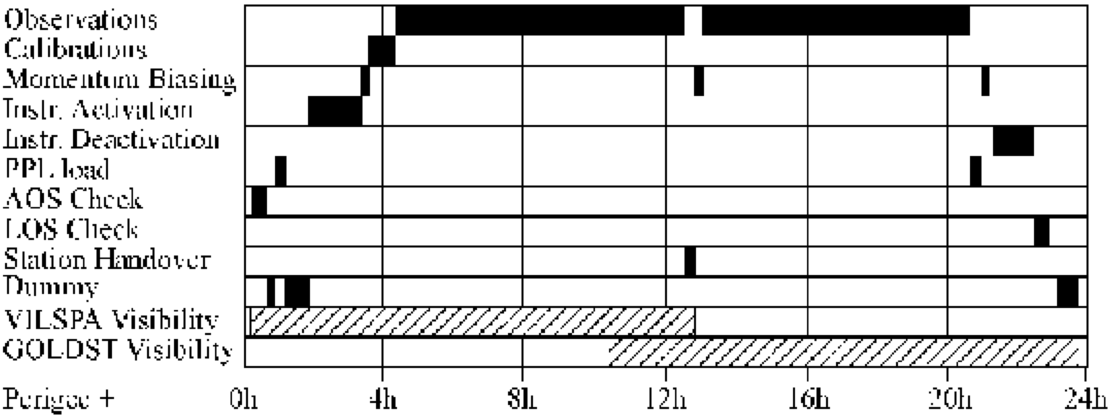

Figure 2. Planning Skeleton File showing typical windows in a revolution.

3. The mission planner transfers the PSF, via the IDCS to SOC. SOC then plan the scientific observations and, based on the DBOB and science proposals, produces a Planned Observations Files (POF) and a corresponding Instrument Command Sequence (ICS) file. The POF echoes all original PSF entries and adds pointing requests, instrument related commands (via pointers to the ICS) and messages within the windows dedicated for scientific observations. The ICS determines the precise commands to be uplinked to the instruments.

4. The mission planner then transfers the POF back to flight dynamics who add AOCS parameters and commands. Two files are produced; the Augmented Operations Planning File (AOPF), which has the same structure as the POF, and the Attitude Parameter File (APF), which contains parameters for each attitude command used in the AOPF. The principal steps involved in producing the AOPF and APF are the:

    - generation of suitable attitudes and command data to perform routine calibrations in the windows designated for calibrations.
    - generation of raster point series to track any solar system objects requested in the POF
    - final attitude constraint check of all the planned slews and pointings.
    - addition of PPL uplink in designated windows and generation of Intermediate Parameter Files (IPFs) containing the individual pointings from the PPL.
    - addition of reaction wheel biasing commands in designated windows.
    - addition of commands for on-board antenna switching.
    - derivation of attitude parameters including selection of one or more guide stars for each pointing. (Extra confirmation star IPFs are generated in case of guide star ambiguity).

- production of a summary giving an easily readable overview of the planned revolution.

Whereas the APF is a concatenation of all the command parameters for a complete revolution, each IPF contains command data for only one manoeuvre (in this case a PPL pointing) and may be used in contingencies. On-line commanding, when the products from the mission planning cycle are not used, is performed using a wide range of IPFs.

5. In parallel to this activity, the mission planner generates on the IDCS an extension to the PSF called the Planned Spacecraft Operations File (PSOF). This file contains spacecraft platform operations including instrument activation and deactivation sequences.

6. Finally the mission planner transfers the AOPF and APF to the IDCS and merges them with the POF, ICS and PSOF into a Central Command Schedule (CCS). The CCS then contains all planned commands for one revolution.

2.4 OPERATIONAL EXPERIENCE

The experience with the mission planning cycle in the first months of the mission is very positive. Although the nominal mission planning cycle starts some weeks before the revolution in question, a very late re-planning was performed regularly during the commissioning phase and occasionally during routine operations, challenging the flexibility of the mission planning system. All of these re-planning operations went smoothly. A late modification of the observation schedule requires a regeneration of the POF by SOC. If, for example, ground station coverage changes, a new PSF must be generated. In both cases, all subsequent mission planning products for that revolution must also be re-generated.

One problem can occur during the generation of the CCS when additional commands are inserted. The timing of these commands is not completely predictable during the generation of the AOPF. Consequently, there are occasional timing conflicts, so called command clashes, making additional iterations on the AOPF necessary. Since the pointing sequence will not be changed at this point and potential problems in the AOPF generation have usually already occurred and been logged during an earlier iteration, this regeneration has a limited impact. The situation could be improved by providing and implementing complete look-up tables with the time budgets for the uplink of each command. This information is only provided in cases in which the AOPF is not compatible with the planned command sequences defined by the flight control team.

3. XMM MISSION PLANNING

3.1 AOCS DESIGN

Both the ISO and XMM satellites are three-axis stabilised observatories, which are required to slew to pre-defined target attitudes and then dwell there for a period time while the scientific observation is carried out. Both rely on a star tracker and fine sun sensor controlling the attitude during stable observation periods using a system of reaction wheels for slewing. Indeed the star trackers are identical on both spacecraft although the limiting magnitude for the XMM star tracker may be slightly higher. However the attitude control method differs significantly between the two spacecraft in many aspects, particularly during slews.

- ISO maintains an inertial attitude representation on-board as a quaternion. XMM is controlled on the error signals between predicted and measured sensor output alone, without determination of an inertially fixed attitude. XMM uses differing combinations of sensors for attitude control (star tracker, fine sun sensor, sun acquisition sensors, gyros and an attitude anomaly detector) depending on the AOCS mode employed.

- ISO slews under closed loop control using three gyros and a fine sun sensor as attitude sensors. Due to the risk of gyro failure over the potentially 10 year mission, XMM will operate routinely without gyros, performing slews using only a fine sun sensor. This allows closed loop control around two axes, but relies on open loop control around the third axis where the reaction wheel speed profile is commanded from ground. XMM will use dynamically tuned gyros for autonomous safety modes and during eclipses where no fine sun sensor information is available.

- There is no equivalent of ISO’s Programmed Pointing Mode (PPM) for XMM, avoiding the use of a PPL. Because of XMM’s higher perigee height, the earth avoidance region through perigee is considerably smaller. XMM can therefore adopt a more 'relaxed' approach to the perigee region and select only one safe attitude. At the end of an observation, XMM will remain at the current attitude until otherwise commanded or the emergency sun acquisition mode triggers due to sun-pointing constraints.

3.2 OPERATIONS CONCEPT

XMM will use the same team structures as ISO, although the names and locations may differ.

- The Mission Operations Centre (MOC) will perform all aspects connected with the operations and safety of the spacecraft. It will be situated at ESOC in Germany throughout the mission. The MOC contains three dedicated teams (as for the ISO SCC): the flight control team, the flight dynamics team and the software support team for the real-time XMM Mission Control System (XMCS).
- The Science Operations Centre (SOC) will be developed at ESOC and ESTEC in the Netherlands. It will however be situated during operations at Villafranca in Spain, taking over the ISO facilities when that mission is complete.

A very significant difference between the two missions lies in the durations of the individual observations, due to the different wavelengths involved. ISO's infrared observations are typically only a few minutes long, whereas XMM's x-ray observations will last several hours. The consequence for ISO is that the observation sequence for a revolution is carefully planned in advance with no opportunity to manually intervene in an automatic schedule of commanding. If for any reason, an object fails to be at the prescribed attitude, there is no time to perform a trim manoeuvre or to initiate manual search procedures. A new observation would have to be scheduled at a later date. This allowed the flight dynamics team to prepare the mission planning products during normal working hours. Consequently, there was a clear separation of activities between the flight control team, using the ISO dedicated control system (IDCS) and the flight dynamics team, using the flight dynamics system (FDS).

For XMM, however, the SOC will have the opportunity to monitor the scientific output during their scheduled observation and propose small attitude trim manoeuvres optimising the instrumental pointing. With such long exposure times, if one observation has to be aborted, the SOC may need to re-plan new observations within the same revolution; requiring a faster mission planning turnaround, possibly outside normal working hours. This leads to a more flexible approach being adopted for XMM whereby the mission planner or spacecraft controller from the flight control team will have sufficient access to the FDS, in addition to the flight dynamics team, to perform mission planning.

The longer orbital period of XMM has little impact on the operational principles of mission planning. The number of ground stations supporting routine operations will differ however. ISO maintains two: at Villafranca (Spain) and Goldstone (USA), whereas XMM will maintain only one at Redu (Belgium).

3.3 THE XMM MISSION PLANNING CYCLE

Similarly to ISO, all scientific observations must satisfy the spacecraft pointing constraints to protect the payload instruments from exposure to direct sunlight at all times. The solar aspect angle of the optical axis must be kept in the range 70 to 110 degrees. Additional constraints also exist to avoid earth pointing and to orient the fixed solar panels at the sun. A more relaxed set of constraints is allowed through perigee.

The nominal XMM mission planning cycle will take a similar approach to that described in the previous section for ISO. Except for the DBOB, all mission planning products are generated for one and only one revolution as for ISO.

1. The Data Base of Observable Bins (DBOB), orbit and eclipse files will be generated by flight dynamics and delivered to SOC as for ISO.

2. The mission planner will prepare a Planning Skeleton File (PSF) on the FDS containing a time line of orbit dependent events and other general house-keeping activities, in a similar manner to ISO. Flight dynamics will perform off-line checking. Since XMM contains no Programmed Pointing List (PPL), the single safe attitude for the perigee region will be computed while generating the PSF.

   In both missions, it is necessary to deactivate the scientific instruments during perigee. However XMM differs from ISO in the need to deactivate the scientific instruments during eclipse. The operational sequence for activation and deactivation of the instruments is a clearly definable set of commands which can be uplinked as a sequence without manual intervention. Consequently, the XMM PSF generation software will insert the relevant command sequence pointers with a default time separation within special activation and deactivation windows. By doing this, the need to generate a Planned Spacecraft Operations File (PSOF) as for ISO is removed, along with the need to merge such a file with the other mission planning products. The risk of getting a command scheduling clash with the subsequent re-planning activities is therefore reduced.

3. The mission planner transfers the PSF, via the XMCS to SOC. SOC then plan the scientific observations and produce the Preferred Observation Schedule (POS) and corresponding Instrument Command Sequence (ICS) in a similar manner to the Planned Observation File (POF) for ISO. As for ISO, it is the SOC's responsibility to ensure that the pointing requests do not violate any attitude constraints during the slews as well as the stable pointing mode.

4. The mission planner then transfers the POS back to the FDS. The flight dynamics team will process the POS to produce an Enhanced Preferred Observation Schedule (EPOS) and associated Attitude Parameter File (APF) similarly to ISO. (The equivalent file to the EPOS for ISO is the Augmented Operations Plan File (AOPF)). The EPOS echoes all the original entries in the POS, after checking for constraint violations, and inserts additional events with pointers to relevant command data in the APF.

5. The mission planner transfers the EPOS and APF back to the XMCS and merges them with the POS and ICS into the Central Command Schedule (CCS), but without the additional overhead of merging them with an ISO-like PSOF.

3.4 ON-LINE RE-PLANNING AND COMMAND ACTIVITIES

In the case of operational difficulties, it will be necessary after the difficulty is resolved, to re-join the schedule as soon as possible. This will imply using the flight dynamics system to compute a safe path to slew to the next appointed observation.

A re-planning request by the SOC may include aborting the current observation and choosing an alternative before re-joining the original schedule, or slewing to a 'Target of Opportunity' such as a supernova within a few hours. The SOC will deliver a new re-planned POS to the MOC. This will have to be processed by the spacecraft controller (using the flight dynamics system) to produce an EPOS in the same manner as for routine mission planning. Although the change to the schedule may only affect one observation, it is nevertheless necessary to examine all subsequent observations until perigee to ensure that the reaction wheel speeds are never close to zero during a scientific observation. If a new observation results in an attitude where this will occur later in the revolution, further re-planning will be necessary to allow for a reaction wheel biasing command to be sent. This command would use the thrusters to impart momentum to the individual wheels while maintaining a constant attitude.

As described in Section 3.1, large angle slews by XMM are performed with closed loop control around only two axes. Open loop control is performed around the third axis using a ground-calculated reaction wheel speed profile. At the start of the mission, before in-flight calibration of the reaction wheels and moments of inertia, large slews could result in significant attitude errors around the axis under open loop control. The AOCS will therefore autonomously command the star tracker to map its field of view on completion of the slew. The flight dynamics system can then be used to determine the current attitude and compute a small adjustment manoeuvre to attain the final target.

During the early stages of the mission, it will be necessary to re-compute attitude parameters if significant differences between the measured wheel speeds prior to a slew and wheel speeds expected in the EPOS/APF mission plan are seen. The flight dynamics system must then be used to re-compute and re-transfer these parameters to the XMCS. These new parameters must replace those originally given in the APF and be incorporated in the command schedule.

4. CONCLUSIONS AND ACKNOWLEDGEMENTS

This paper has summarised the mission planning processes for both the ISO and XMM missions with emphasis on those aspects affecting the flight dynamics system and team.

The careful work done for ISO by all parties has resulted in a very successful and efficient process, despite the operational complexities. It is therefore only natural to adapt the ISO experience to the XMM mission, without following slavishly everything which was done.

The different geographic locations of MOC and SOC for XMM as well as the additional need for a fast re-plan option, gives rise to new requirements and a greater reliance on electronic interfaces. ISO maintains a dedicated flight dynamics team of three people in Spain to operate the flight dynamics system during normal hours. The need for XMM re-planning and attitude trim manoeuvres at any time of day has prompted the desire to develop a restricted flight dynamics system which requires less specialist support and can be operated by the spacecraft controller in an efficient and safe manner, throughout a hopefully long and successful mission.

As stated in this paper, mission planning involves many different teams other than those involved in flight dynamics. The authors are therefore pleased to acknowledge the contributions of many colleagues within the mission operations and science operations centres of both ISO and XMM to the definition and implementation of these processes.