Integral – Running the ESA Gamma-Ray Observatory

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This article provides an overview of the planned Integral mission operations, focussing on the role of, and activities to be performed by the Mission Operations Centre (MOC). It identifies ground-segment elements involved in the various operations and the operational concepts underlying the different Integral mission phases. Finally, a short overview of the current status of the mission-operations preparations is given, including the system test activities.

The goals

Integral's contribution to astrophysics will be the observation of various gamma-ray phenomena by combining fine spectroscopy with imaging and accurate positioning of celestial sources of gamma-ray emission. It will also have the capability of simultaneous monitoring at other wavelengths, namely the X-ray and optical bands. In conducting this unique scientific mission, several observation patterns will be applied:

– *Deep exposures of the central Galactic Radian:* Individual pointings on a regular grid with 2.4 and 1.2 deg spacing will cover the core of the our Galaxy (± 30 deg in longitude, ± 20° in latitude). Each such exposure will take 30 minutes.

– *Survey of the Galactic Plane:* A survey will be made of weekly scans following a saw-tooth path to search for as yet unknown persistent sources – such as recent galactic super-novae – and to map our Galaxy's gamma-ray emission. Each scan will consist of a series of individual exposures of 1050 sec duration. The pointing attitude will be separated by 6.0° along the scan path (Fig. 1).

– *Staring observations:* Extended periods of stable pointing will be used to study faint sources and phenomena that are variable in time.

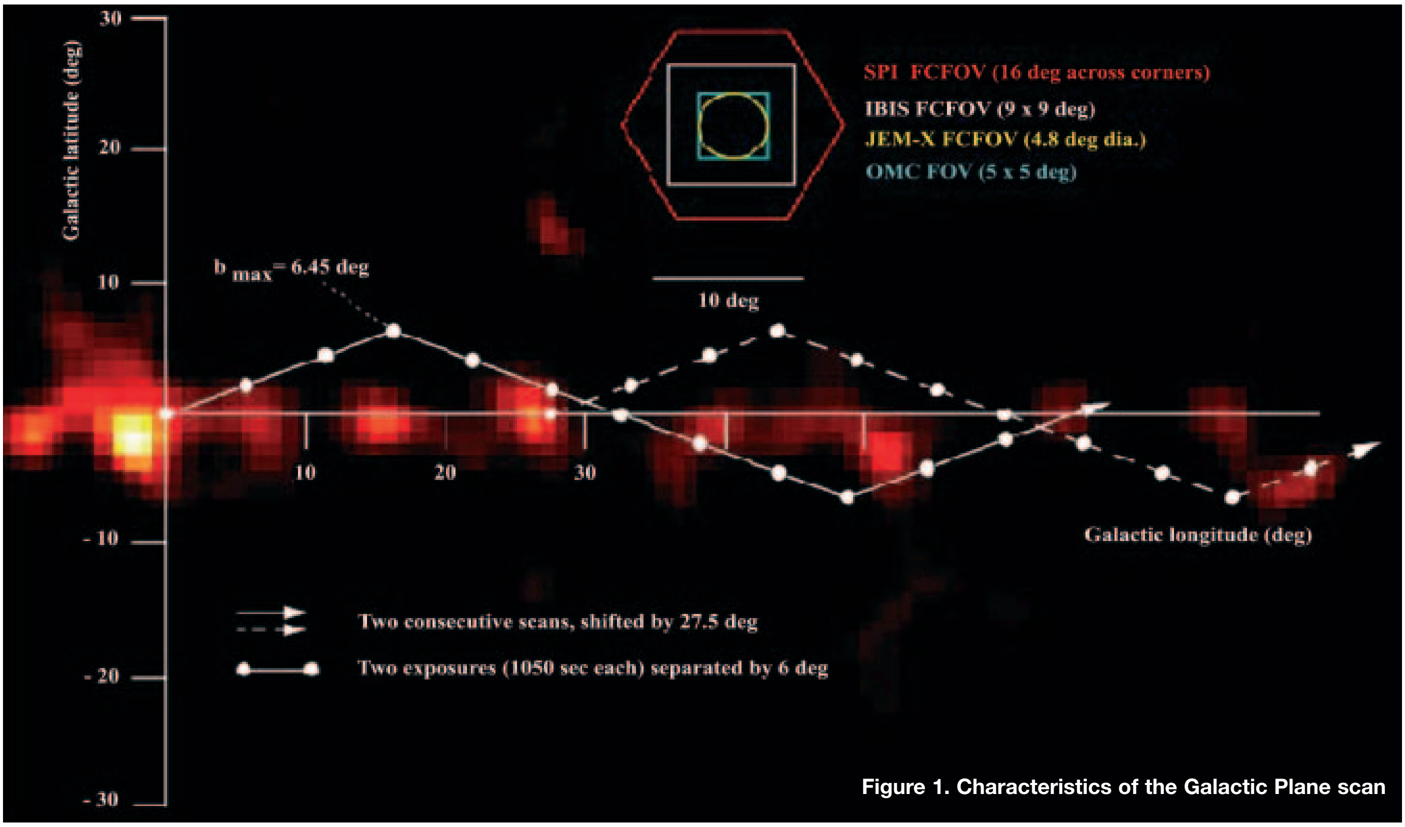

Figure 1. Characteristics of the Galactic Plane scan

Another facet of the mission concerns Gamma-Ray Bursts (GRBs). Integral's instruments and ground segment will allow the identification of GRBs and the provision of key data to the scientific community in near-real-time. Not surprisingly, these mission goals have had a significant influence on the ground-segment set-up and the way in which the Integral operations will be conducted.

The ground-segment elements

Like other observatory missions, Integral can only meet its ambitious scientific goals with the support of its dedicated ground segment. The in-orbit operations are reliant on complex interactions between the various ground-segment elements, which essentially fall into two parts:

- the Operational Ground Segment (OGS) and
- the Science Ground Segment (SGS).

The OGS is responsible for all mission operations, including platform and instruments, and consists of:

- the Mission Operations Centre (MOC)
- the ground stations (Redu in Belgium, and Goldstone in California) and
- the operational network.

The SGS covers all scientific aspects of the mission and itself consists of two components:

- the Integral Science Operations Centre (ISOC), and
- the Integral Science Data Centre (ISDC).

The structure of the complete Integral ground segment and its interfaces is illustrated in Figure 2.

The Mission Operations Centre (MOC) is located at the European Space Operations Centre (ESOC), in Darmstadt, Germany. The MOC is the sole interface to the satellite and is responsible for monitoring and controlling it during all mission phases, following its separation from the Russian Proton launcher. Once the satellite has been commissioned, all operations will be executed according to

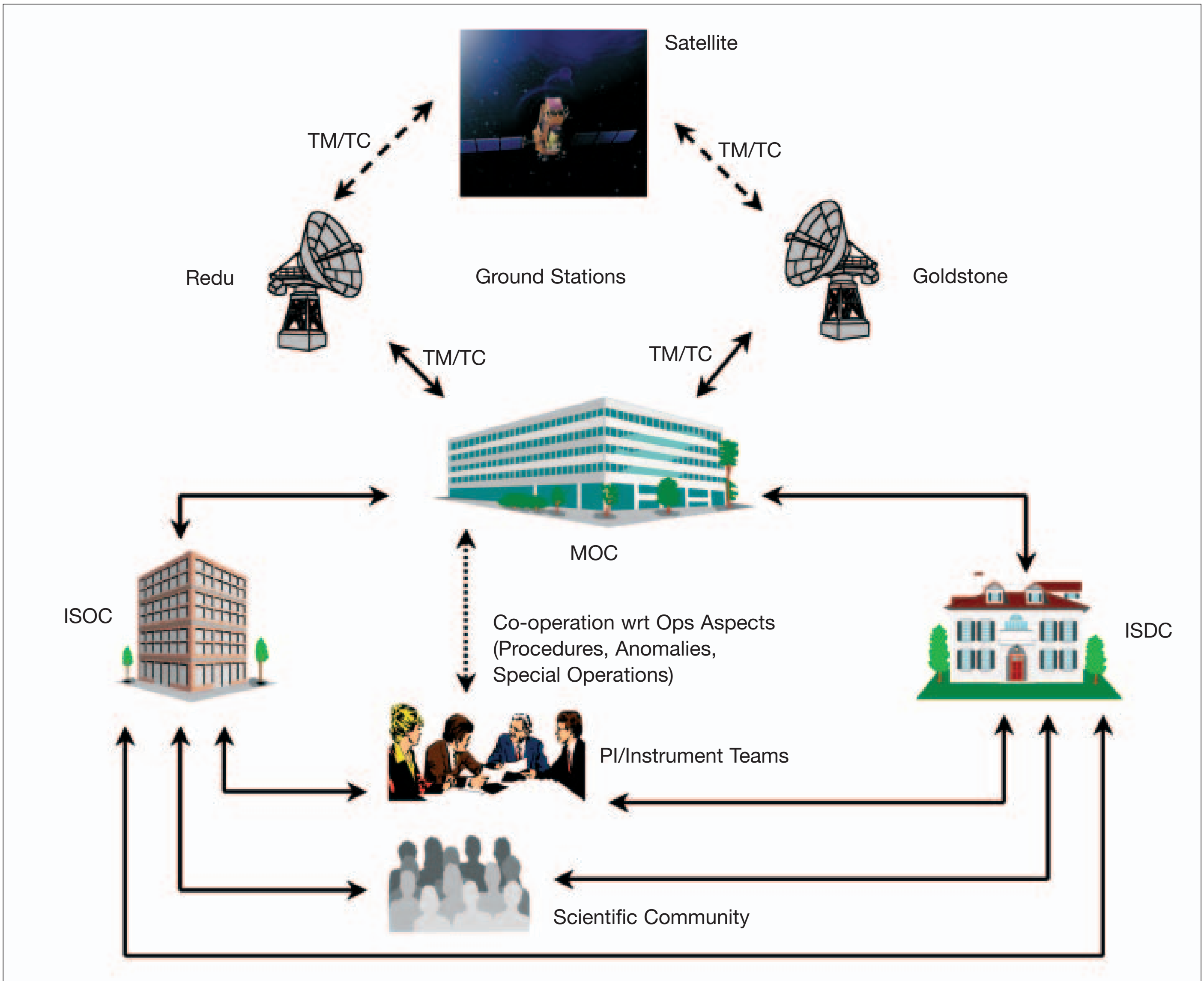

Figure 2. The configuration of the Integral Ground Segment

operational timelines, each segment of which covers a full three-day orbital revolution and is produced by the MOC based on planning inputs provided by the Integral Science Operations Centre (ISOC).

The ISOC is located at the European Space Research and Technology Centre (ESTEC), at Noordwijk in The Netherlands. It is mainly responsible for the collection of the observation requests from the scientific community and the generation of the observation plan that drives the utilisation of the Integral payload.

The Integral Science Data Centre (ISDC) is located in Versoix, near Geneva (CH) and is a non-ESA institution. It is mainly responsible for the processing of the science data - including the maintenance of the scientific archive - and the generation and distribution of the scientific products.

The Integral satellite has only limited on-board time-tag command capabilities, and so this capacity is used only for safety aspects. Since Integral is to be controlled in real-time from the ground, a network of stations has been implemented that allows permanent contact with the satellite during the scientifically useful part of the orbit. The two primary ground stations are located at Redu in Belgium, which is a station provided by ESA, and at Goldstone in California (USA), which is a station provided by NASA/Jet Propulsion Laboratory (JPL).

A communications network has been set up under ESOC's responsibility which ensures communication between the various centres and between the MOC and the ground stations.

Figure 3. The Integral Dedicated Control Room during System Validation Test activities

The MOC's role

The Integral Mission Operations Centre will be responsible for all mission operations. This covers the preparation and execution of operations during:
- the Launch and Early-Orbit Phase (LEOP)
- the Satellite Commissioning Phase, and
- the Routine Mission Phase.

The individual tasks include:
- provision of a Planning Skeleton File (PSF) to the ISOC
- generation of the operations timeline
- execution of all satellite operations
- execution of platform and instrument maintenance operations
- monitoring of satellite (spacecraft and instruments) safety and health
- determination and control of the satellite's orbit and attitude
- maintenance of the satellite's on-board software
- provision of telemetry and auxiliary data to the ISDC.

In order to perform the above tasks, the MOC relies heavily on the existing ESOC infrastructure, including the control rooms, communications facilities, and computer hardware. The most intensive use of these facilities will be made during the Launch and Early-Orbit Phase (LEOP), as this is the most critical period of the mission and thus the most demanding in terms of resources (facilities and manpower). The LEOP operations will mainly be performed from ESOC's Main Control Room (MCR) and Flight Dynamics Room (FDR). The Routine Mission Phase operations will be conducted from the Integral Dedicated Control Room (DCR); see Figure 3.

The Flight Control Team (FCT) is responsible for all mission operations. Led by the Spacecraft Operations Manager, it consists of:
- an engineering team: five engineers who are responsible for controlling and monitoring the satellite subsystems, the on-board software maintenance, the mission planning and the preparation/execution of the operational time-lines
- a spacecraft-analyst team: two analysts who are responsible for the maintenance of the Operational Database and other operational tools, and also support the engineering team
- a spacecraft-controller team: six controllers who are responsible for the routine operation of the satellite.

Various other ESOC personnel support the FCT during the different mission phases, not only in terms of optimally exploiting the ESOC internal infrastructure (communications, computer hardware/software, etc.), but also in monitoring and controlling the external communications and the ground stations. The ESOC-provided infrastructure also includes the Integral Mission Control System (IMCS), based on the generic SCOS 2000 system, and the Integral Flight Dynamics System (IFDS), based on the existing ORATOS infrastructure. The ESOC Flight Dynamics Team has been an important contributor to the mission planning for the satellite and its attitude and orbit control philosophy.

The LEOP and Commissioning Phases

The satellite has been transferred to the Baikonur launch site about two months before launch. Communications links with Baikonur will allow the pre-launch activities to be followed from ESOC. ESOC is providing facilities to accommodate teams from the Principal Investigators (PI), the spacecraft manufacturer and the Project from three months before until three months after the launch. It will also allow the Instrument teams to analyse their instrument data from ESOC during the Integral Commissioning Phase.

The critical Launch and Early Orbit Phase activities will start in earnest about 8 hours before launch. The MOC will remain in contact with the satellite until the launch, but during the launch phase itself no link will be available to the satellite. The next contact with the satellite will be established via ESA's Villafranca (E) ground station about 10 minutes before Integral's separation from the Proton launcher. A few minutes later, the Redu (B) ground station will also make contact with the satellite, and both stations will be used to support the post-separation operations. At separation, the MOC will establish the command link and will monitor the activation of the satellite.

The initial in-orbit phase will last about 6 h, ending with the transition into the Inertial Pointing and Slew (IPS) mode. At this point the spacecraft platform will be fully activated and the satellite in a stable pointing state. The following days will be devoted to checking-out all platform subsystems and the activation and check-out of the scientific instruments.

As the launcher does not deliver the satellite directly to its final operational orbit, perigee-raising burns will be conducted using Integral's on-board thrusters at the apogees 3, 4 and 5. As soon as the last manoeuvre has been performed, the verification of instrument performances will commence, which will last until two months after the launch. When all checks have been successfully completed, the satellite will be declared operational and the Scientific Mission phase can begin.

The operations concept and its implementation

For the Integral mission operations to be conducted safely and efficiently, several critical constraints have to be respected, typical examples of which are summarised in Table 1. All such constraints had to be considered at the planning stage to arrive at an operational timeline that can be executed safely.

Table 1. Mission constraints

Pointing	The star-tracker bore sight shall be no closer than 15 deg to the Earth's limb and separated by at least 10 deg from the Moon's limb.
Wheel Speeds	The wheel speeds shall not exceed specified limits and shall be outside the zero-speed region (± 120 rpm)
Solar Aspect Angle (SAA)	The SAA shall be less than 40º (30º when the power supply from the solar array is degraded) for power reasons.
Roll Angle	The roll angle is to be less than 5º for thermal reasons.
Slews	Several constraints have to respected here, e.g. a max. slew speed, to ensure proper slew performance.

The routine mission operations are preceded by comprehensive mission-planning activities. About 6 months before the execution of operations, the MOC provides requests to NASA/JPL regarding utilisation of its Goldstone station. The next step concerns the generation of the skeleton plan needed by the ISOC to plan the observations. The Flight Dynamics Team generates a set of Planning Skeleton Files (PSF) covering a one-month period, about one month in advance. Each PSF concerns one orbital revolution and identifies the time windows that are available for science operations. The PSFs are provided to the ISOC, which uses them to prepare the Preferred Observation Sequences (POS). Each POS identifies the required pointings and the corresponding instrument configurations for a single orbit.

A set of five POS is provided about two weeks in advance to the Flight Dynamics Team, which enhances them by including the necessary satellite operations, in particular the inputs needed to control the spacecraft's attitude. The products of this activity are the Enhanced Preferred Observation Sequences (EPOS).

The EPOS are provided to the FCT, which then generates the Operational Timelines, which are the reference for the generation of the command schedule. The Timeline for a satellite revolution is available one week in advance to Operations. A Timeline summary is sent to the ISOC for confirmation.

An overview of the main planning activities is shown in Table 2.

The command schedule will be loaded during the satellite's perigee passage before the orbital revolution concerned. The commands will be executed automatically by the command system, and manual commanding is only envisaged under special circumstances. The same is true for on-board time-tag commands, which are only used to execute operations that are to be performed outside ground coverage, e.g. during eclipse and perigee passages. The Spacecraft Controller on shift monitors the operations and the safety/health of the platform and instruments.

All telemetry and auxiliary data (e.g. attitude data or operations log) needed to evaluate the scientific data are provided to the ISDC in real-time. The data are further processed by the ISDC and used for a quick assessment of the science. If necessary, the ISDC will send requests for an update of the instrument configuration to the ISOC. Subject to the ISOC's approval, the requested replanning will be started, and the turnaround time for such an activity will be less than 36 h. The consolidated telemetry data are provided by the MOC to the ISDC (on CD-ROM) within some days after a particular orbit's completion. They will be used to generate the appropriate scientific products for onward distribution to the scientific community.

Implementation of the operations

The Integral mission has very particular requirements in terms of satellite attitude control, which call for some special functions within the MOC. Because its main instruments use masks to suppress background radiation effects, Integral must slew frequently around the target in order to monitor the sources from various angles. In addition, the mission's scientific objectives include systematic monitoring of the sky. These demands lead to various types of observation patterns:

Hexagonal Dither Pattern
- Hexagon around the nominal source location, i.e. 7 pointings (a number of cycles can be observed together)
- Closed-loop slew of 2° between two pattern points
- Duration of each pointing 30 min.

Raster Dither Pattern
- m x n raster around the target, i.e. m x n pointings (a number of cycles can be observed together)
- Closed-loop slew of 2° between two pattern points
- Duration of each pointing 30 min.

Galactic-Plane Survey
- Saw-tooth path along the Galactic Plane with an inclination of 21° (arcs covering a subset of the Galactic Plane will be observed together)

Table 2. Overview of the main mission planning activities

Time	Activity	Initiator	Data Product	Remarks
T0 – 6 months	Long Term Planning	MOC/FD	Long-Term Event Plan	
T0 – 6 months	Goldstone Scheduling Request	MOC/SO	Schedule Request	Period of 6 months covered, 6 months in advance
T0 – 1 month	Generation of PSF Provision of PSF to ISOC	MOC/FD	Planning Skeleton File	Period of 1 month covered, 1 month in advance
T0 – 2 weeks	Generation of POS Provision of POS to MOC	ISOC	Preferred Observation Sequence	Period of 2 weeks covered, 2 weeks in advance
T0 – 2 weeks	Processing of POS & generation of EPOS	MOC/FD	EPOS	Period of 2 weeks covered, 2 weeks in advance
T0 – 1 week	Generation of Operational Timeline	MOC/FCT	Operations Timeline	Period of 1 week covered, 1 week in advance
T0 – 3 days	Generation of Command Schedule	MOC/FCT	Command Schedule	Period of 1 orbit, 1 orbit in advance
T0	Start of Operations			

– Open-loop slew of 6 deg between two pattern points
– Duration of each pointing 1050 sec.

Galactic-Centre Radian Deep Exposure
– 21 x 31 pointings raster, i.e. 651 pointings (selected subsets will be observed together)
– Closed-loop slew of 2° between two pattern points
– Duration of each pointing 30 min.

The above observation patterns require the execution of a slew manoeuvre typically every 30 min. An important feature to be considered in this context is that the nominal operations are to be performed in a gyroless manner, which has implications for both the open- and closed-loop slews.

Closed-loop slews can be performed when the slew angle is such that the guide star remains within the Field of View (FOV) of the star tracker. The advantage of this type of slew manoeuvre is that the accuracy of the pointings remains within very strict limits. Open-loop slews are to be chosen in the case of bigger slew angles, considering the various constraints applicable, such as the maximum slew speed.

The accuracy of the pointing after an open-loop slew depends on the duration of the manoeuvre. Since a sequence of several open-loop slews can lead to an increasing attitude inaccuracy, a real-time attitude reconstruction is performed by the Integral Flight Dynamics System (FDS). The IFDS determines the deviations from the planned attitudes and provides corrections for the upcoming slews to the Mission Control System (IMCS), in a fully automated process. The Integral File Transfer System (IFTS) takes care of the transfer of files between the IFDS and the IMCS.

Depending on the observations planned, there may be more than 100 slews during a single revolution. Since the satellite is controlled using reaction wheels, the momentum is to be carefully determined in order to perform momentum dumps at the appropriate times. The FDS determines an adequate momentum profile (Fig. 4) for each revolution at the planning stage. Regular checks are performed to ensure that the actual wheel speeds do not deviate significantly from those planned, otherwise the on-board Autonomous Momentum Dumping (AMD) mechanism will be triggered for safety reasons when the allowed wheel-speed boundaries are breached.

Apart from the AOCS operations, the MOC also controls the platform's on-board subsystems (power, thermal, on-board data handling, etc.) as well as the various instruments.

The platform operations are planned and executed solely by the MOC. The instrument-related operations are a shared activity between the MOC and ISOC. While the ISOC plans the instrument configurations that are relevant for the various observations, the MOC plans the routine instrument operations that are required during an orbit. The operations planning is done using the so-called 'Event Designators' (EDs), which are keywords put by Flight Dynamics into the planning files to identify the appropriate command activities.

Integral's instruments require a lot of routine operations because they have to be put into a safe configuration for each perigee and eclipse passage. The platform-related operations are less complicated. Its thermal subsystem does not require a lot of ground intervention because most of the thermal-control cycles are implemented on-board. The power subsystem requires some eclipse-related operations, such as battery charging. These operations can be pre-planned, which is also true for the On-Board Data Handling (OBDH) subsystem, including the selection of the appropriate antenna depending on satellite attitude and station visibility. The FDS pre-integrates the corresponding EDs into the EPOS.

The MOC is also responsible for the On-Board Software (OBS) and conducts a regular assessment of satellite functions and performance to identify any needs for OBS upgrades.

The MOC processes only the satellite housekeeping data. The processing of the science data is the task of the ISDC. The MOC performs a pre-processing of the telemetry received from the various ground stations and provides it, together with some ground-reception-time and data-quality annotations, to the ISDC. To generate the science products, however, the ISDC also requires information about the satellite's attitude and the execution of the operations, which is provided in form of auxiliary data files by the MOC in near-real-time.

Operations preparation status

At the time of writing, the development and testing of the ground segment has been largely completed and the simulation campaign is in progress. In addition to the testing at subsystem level, many system tests have been conducted, including the System Validation Tests (SVTs) involving the flight-model satellite. These SVTs focused on the validation of the MOC functions and operational procedures, as

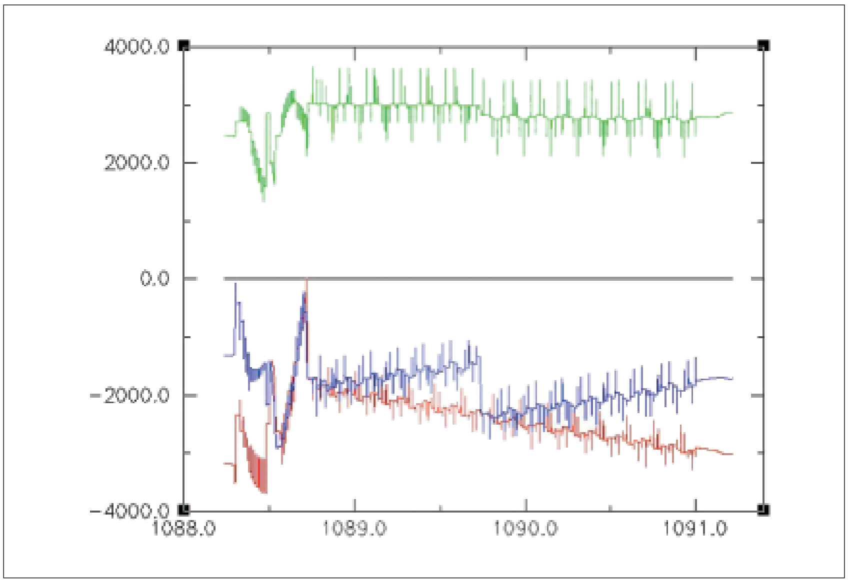

Figure 4. A typical profile for momentum wheels 2, 3 and 4 during a single satellite orbit. The x-axis indicates the days (reference is 1 January 2000), and the y-axis the wheel speeds in rpm

well as providing a platform for performing the overall ground-segment end-to-end tests, involving the ISOC and ISDC. The latter, together with the Ground Segment Integrated Tests (GSITs) form the main basis for validating the overall Integral Ground Segment. All SVTs and GSITs performed so far have been successfully completed and the test goals were fully achieved. The main results of the system test programme are:

- validation of the functions of the Mission Control System
- validation of the interfaces from/to the Mission Control System
- validation of the overall Ground Segment Operations Concept and Interfaces
- verification (*no complete validation*) of the Operational Database
- verification (*no complete validation*) of nominal flight procedures
- verification (*no complete validation*) of major flight-contingency procedures.

The ongoing work related to the preparation of the mission operations mainly concerns the consolidation of the Flight Operations Plan (FOP) and the Operational Database (ODB) and the training of the operations teams.

Acknowledgments
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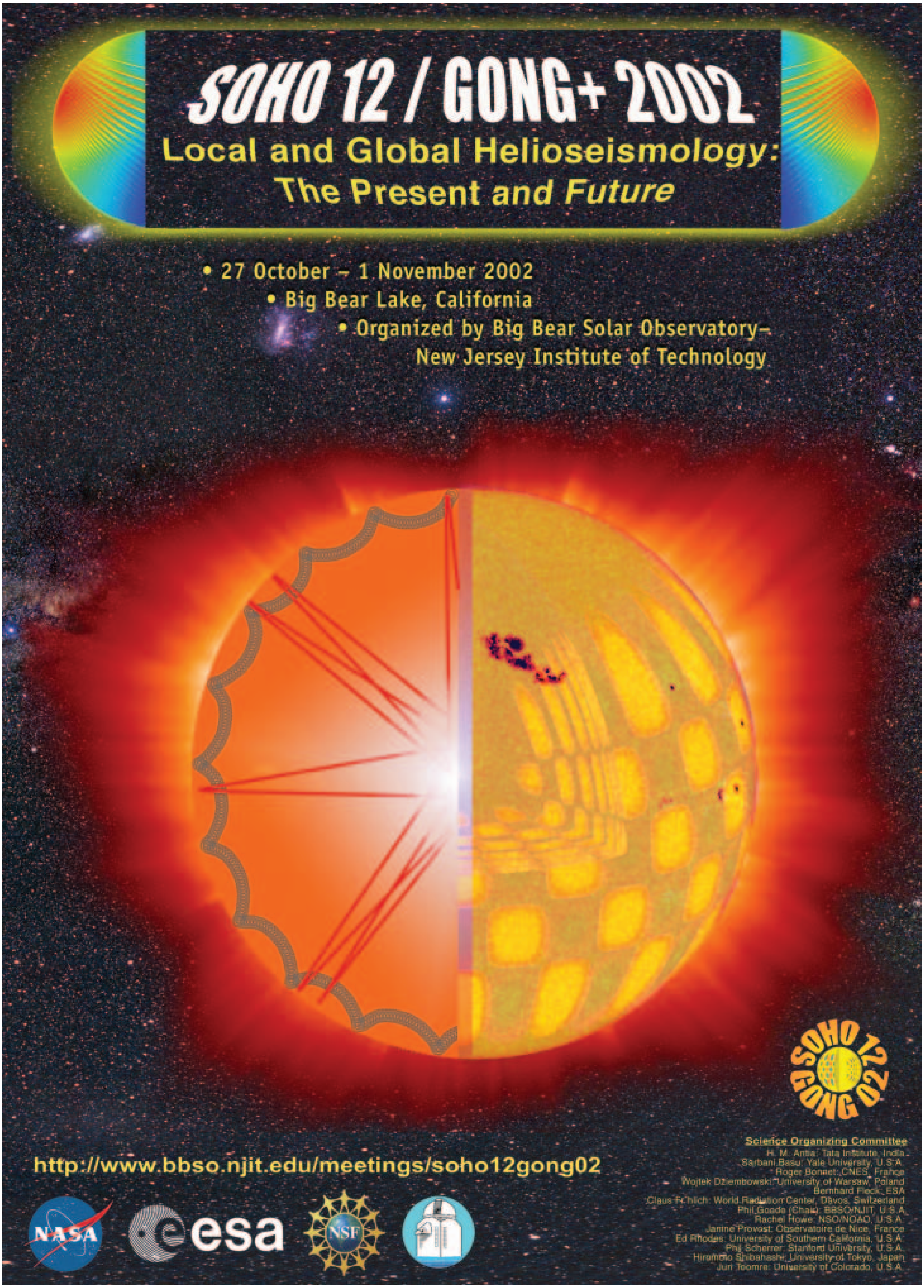

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