The Integral Operational Ground Segment

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Integral will be launched in October this year by a Russian Proton rocket into a highly elliptical orbit. The mission will be controlled from the Integral Operational Ground Segment, which will take charge of the satellite's operation from its separation from the launcher until the end of the mission. This article describes the ground-segment architecture and specifically the functionality of the Integral Operational Ground Segment. The latter's design is based on the latest ESA infrastructure develpments in the fields of mission-control systems (SCOS 2000), station modulation, demodulation and tracking systems, and interoperability between ESA and NASA/JPL for cross-support of the mission.

The mission profile

The International Gamma-Ray Astrophysics Laboratory (Integral) is designed for two years of in-orbit operation, with the on-board consumables sized for a possible mission extension of a further three years. The Proton launcher will deliver Integral into a highly elliptical transfer orbit, similar to the final operational orbit, but with a lower perigee at 685 km. During the subsequent Early Orbit Phase, the spacecraft will be gradually injected into its final orbit by a series of manoeuvres performed using the on-board resources (fuel and thrusters).

Table 1. Integral operational-orbit parameters and supporting ground stations

Parameter	Operational Orbit
Apogee altitude	153 000 km
Perigee altitude	10 000 km
Inclination	51.6 deg
Argument of perigee	300 deg
Orbital period	72 hours
RP ground stations	ESA Redu
	DSN Goldstone
	ESA Villafranca (backup)
EOP ground stations	ESA Villafranca
	ESA Redu
	DSN Goldstone
	ESA Perth

The nominal operational orbit parameters for Integral are given in Table 1, together with the combination of ground stations planned to support the Routine Phase (RP) of the mission and the stations that will be used in the Early Orbit Phase (EOP).

The driving requirement in the selection of the ground stations to support the routine phase of the mission was that the satellite is to be operated in real time from the ground (no on-board data storage provided). The combination of the ESA Redu and DSN Goldstone ground stations will provide coverage of the complete operational orbit above the Earth's radiation belts (approximately 90% of the total orbit), i.e. the part of the orbit of scientific interest in which the on-board Instruments can be operated.

Integral is an observatory-type mission and as such will be operated based on a pre-planned command schedule for each orbit, containing all scientific observations and spacecraft operations activities to be carried out during the orbit. The command schedule will be automatically executed within the Integral Mission Control System at the Mission Operations Centre.

The ground-segment architecture

The mission's ground segment consists of two distinct elements: the Integral Operational Ground Segment and the Integral Science Ground Segment (Fig. 2). The former will be responsible for spacecraft and instrument operations throughout the satellite's lifetime, from its separation from the launcher until the end of the mission. The latter includes the Integral Science Operations Centre (ISOC) located at ESTEC, Noordwijk in the Netherlands, and the Integral Science Data Centre (ISDC) located at Versoix in Switzerland. The ISOC is responsible for planning the scientific utilisation of the satellite, based on inputs from the gamma-ray science community and taking into account the on-board instrument characteristics. The ISOC will also

Figure 1. The Redu Integral ground station: central monitoring and control position and IFMS racks

maintain a copy of the archive generated by the ISDC, thereby providing an additional interface to the science community for the distribution of the mission's scientific products.

The ISDC is responsible for the scientific processing of the satellite telemetry and for the archiving of the mission's scientific products and distribution to the science community. In addition, the ISDC will detect Targets of Opportunity (TOOs) and Gamma-Ray Bursts (GRBs) from the telemetry received in real-time from the Operational Ground Segment. TOO alerts will be provided to the ISOC for the possible re-planning of observations during the current or future orbits. GRBs are transient phenomena, which will be detected in real time from the incoming science telemetry and will automatically generate real-time commands to the satellite, for specific setting of the Optical Monitoring Camera (OMC), and real-time alerts to the science community, so as to allow additional specific observations using Integral and other space and/or ground-based observatories. The ISDC is supported by the Principal Investigator teams, who are providing instrument-specific software and expertise for processing of the received scientific data.

The Integral Operational Ground Segment

The main architectural elements of the Integral Operational Ground Segment (OGS) are the ground stations, the Mission Operations Centre (MOC), and the communications system. The OGS is the sole interface to the satellite; all commands to the spacecraft and on-board instruments are generated at the MOC, and all telemetry from the satellite (spacecraft and instruments, housekeeping and science telemetry) is received at the MOC and distributed within the Ground Segment as necessary.

In the nominal mission scenario, the OGS will take charge of Integral's operation 1 h 32 min after lift-off, when the satellite separates from the Proton upper stage, within visibility of the Villafranca (E) and Redu (B) ground stations. The OGS's role will terminate with the end of the mission.

The ground stations will acquire the satellite via the radio-frequency communications at S-band (2 GHz), and track it during its pass over the station. They constitute the front-end interface between the OGS and the satellite. It is through this interface that the commands received from MOC and processed at the ground station are modulated in accordance with the relevant ESA Standards, frequency up-converted and transmitted to the satellite. On the receiving side, the telemetry received from the satellite is frequency down-converted, demodulated, decoded and pre-processed at the station to extract its main components (satellite housekeeping and science telemetry virtual channels) before transmission to the MOC. In addition, the ground stations will measure the satellite range and range-rate. The measurement data will be sent to the MOC, where they will be used for satellite orbit determination and maintenance. During the Early Orbit Phase of the mission in particular, range and range-rate measurements are essential for the initial orbit determination and for the calculation and verification of the manoeuvres required to achieve the final operational orbit.

The MOC is the heart of the OGS. It is from the MOC that all satellite operations, remote operation of the ESA ground stations, and communication-network operations are performed. The main building blocks of the MOC are the Integral Mission Control System (IMCS), the Flight Dynamics System and the Integral Simulator.

The IMCS provides the functionality required for satellite operations, including the final step of the mission-planning process, satellite monitoring and control, and transmission in real-time of the received satellite telemetry to the ISDC, together with the appropriate auxiliary data. In addition, the IMCS provides the facilities required for handling the on-board software-maintenance activities and the short- and long-term archiving of telemetry, telecommand and auxiliary data. The archive will be regularly consolidated with the satellite playback telemetry received from the ground stations after the pass; the consolidated archive will be regularly dumped (in portions of 12 h) onto CD-ROMs, which are to be provided to the ISDC for scientific processing. Telemetry access to the archive is to be provided, for diagnostic purposes, to authorised external users (the ISOC and the satellite manufacturer) via the Internet.

A key element for the operation of the IMCS is the Operational Data Base (ODB). For modern satellites, with sophisticated on-board functionalities and increased on-board autonomy, the ODB becomes very large, and that for Integral contains more than 200 000 records. Powerful database editors are required to handle such massive amounts of data efficiently. These have been developed by the Integral Operations Team, based on commercially available software (Microsoft Access) and have been adopted for several future ESA missions (see article in ESA Bulletin No. 103). The IMCS is based on the SCOS 2000 infrastructure, the latest ESA development in the domain of mission-control systems.

The Integral Flight Dynamics System (FDS) is based on the ESOC ORATOS infrastructure and provides the functionality required for satellite orbit and attitude determination and control, and for mission planning. On the orbit and attitude side, the system inputs are respectively range and range-rate (Doppler) measurement data received from the ground stations and the spacecraft telemetry from selected onboard subsystems (AOCS, RCS, star-trackers, fine star sensors, reaction wheels) received on-line from the IMCS. This telemetry is processed within the FDS on the basis of the FDDB (Flight Dynamics Data Base), which consists of a subset of the ODB enhanced with specific parameters characterising the satellite from a mechanical and dynamical point of view (distribution of masses, alignments, thruster specific impulse, etc.) provided by the satellite manufacturer and re-calibrated in flight. The attitude profile for the satellite throughout its orbit is determined at the mission-planning stage and is corrected in real time, as necessary, based on the telemetry being received. The FDS is also available in real time to the operator to provide any AOCS commanding information needed to handle contingencies.

On the mission-planning side, the FDS generates a Planning Skeleton File for each orbit, defining the windows for spacecraft operations and scientific observation. Once the file has been populated by the ISOC with the science observations to be conducted during the orbit, the FDS performs a final validation of the resulting product and converts it into a format suitable for the IMCS to derive the Command Schedule for that particular orbit.

The Simulator is an essential tool for system testing of the MOC components, including the interfaces to the other elements of the ground segment, for validation of the flight-operations procedures, and for pre-launch simulations and the training of the staff responsible for mission operations. It provides a realistic simulation of the ground stations and of the satellite's in-orbit functionality through accurate software modelling based on the Satellite Data Base provided by the satellite manufacturer. Figure 3 is a schematic of the MOC computer installation.

The OGS Communication System provides connectivity between the MOC and the ground station, and between the MOC and Science Ground Segment (ISOC and ISDC). It is based on leased lines interconnecting the various Integral ground-segment elements and

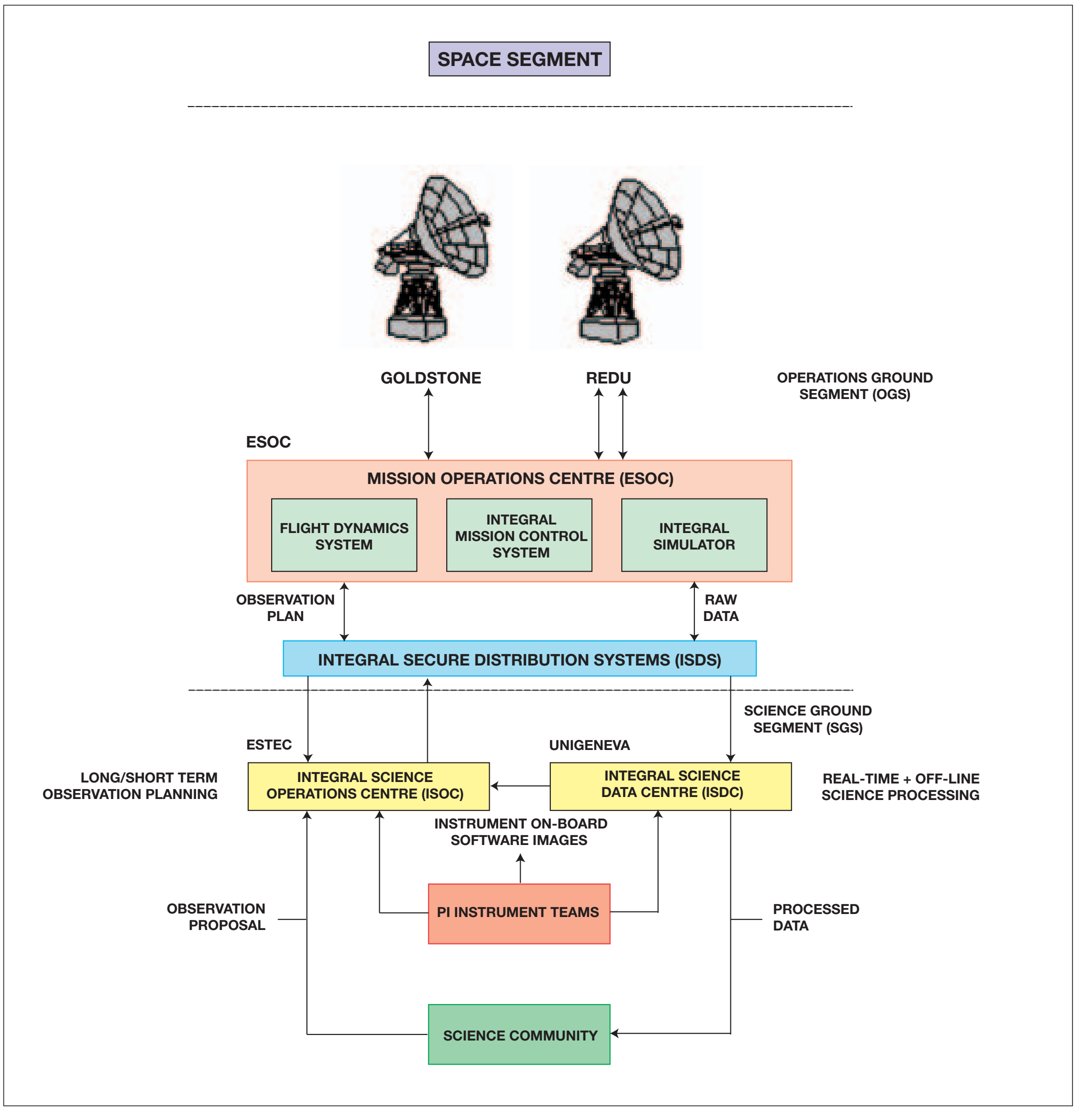

Figure 2. The Integral Ground Segment architecture

providing sufficient bandwidth to support the required operational traffic. Two protocols are used for communications within the Integral ground segment: the traditional protocol based on ISO X25 Recommendations for the operational communications between the MOC and the ESA ground stations, and the more modern TCP/IP protocol suite (as per RFCs) for the communications between the MOC and the Goldstone ground station and between the MOC and the Science Ground Segment.

State of the art elements in the Integral OGS

State of the art design has constantly been promoted within ESA in the Operational Ground Segments of ESOC-supported missions, and Integral is no exception. On the contrary, it is serving as the pilot mission for several new ground-segment infrastructure elements developed in parallel with the implementation of the Integral OGS. The pioneering work of the Integral OGS team in the extensive operational validation of these latest developments will be of significant advantage for future missions adopting similar infrastructures in their ground-segment designs. Three of the newly developed infrastructure elements used in the Integral OGS are described in more detail below.

The SCOS 2000-based Integral Mission Control System

SCOS 2000 is the latest ESA development in the field of Spacecraft Control Systems (SCOS) and Integral is the first science mission to exploit its full functionality and performance for its mission-control system. The IMCS has been build around the SCOS 2000 infrastructure, which comprises a telemetry chain for processing the satellite telemetry received through the ground stations, a generic telecommand chain, and an on-board software-maintenance subsystem for handling on-board memory images. This infrastructure has been complemented by additional software developments required to accommodate Integral-specific satellite design elements, both in the areas of telemetry and telecommand and ground-segment interfaces, and specifically those between the OGS and SGS.

Other SCOS 2000-provided functionalities have been adapted to best fit the satellite's operational requirements, as indicated in Table 2.

The highly distributed architecture of the IMCS-SCOS 2000 is based on the innovative SCOS 2000 concept of sharing the processing load within a family of servers. Specifically, the IMCS includes a main server where all of the kernel telemetry and telecommand functionality are provided, and a secondary server hosting the long-term archive, mission archive, archive consolidator and telemetry distribution to external users (SGS). IMCS-SCOS 2000 also has a modern and intuitive man/machine interface.

On the telemetry side, the main server performs the essential general-purpose processing (packet extraction and inclusion of headers with additional information); the telemetry is then distributed to the peripheral client work stations where the (configurable) part of the telemetry required by the specific application is processed. The main advantage of such a design is optimal usage of processing resources, and consequently increased system performance.

With Integral being the first SCOS 2000 client mission, during the IMCS's development and extensive testing, including operational validation, intense dialogue between the IMCS and the SCOS 2000 development teams has taken place, aimed at optimising the further releases of both systems. Significant effort has been devoted by the IMCS development team to system integration and configuration aspects, including failure and recovery analysis. This pioneering work will hopefully benefit future missions making use of the SCOS 2000 infrastructure for their ground segments.

Table 2. SCOS-2000 / IMCS functional mapping

Operational Data Base	**IMCS specific**
Telemetry Handling	
Telemetry reception (Packetiser)	IMCS specific
Telemetry processing	SCOS 2000
On-board events handling	IMCS specific
Telemetry displays	SCOS 2000
Variable packet display	SCOS 2000
Time correlation and stamping	IMCS specific
Telecommand Handling	
Command sender (Releaser)	SCOS 2000
Manual stack	SCOS 2000 enhanced with IMCS specific
Auto stack	SCOS 2000 enhanced with IMCS specific
Command verification	SCOS 2000 enhanced with IMCS specific
On-board queue management	SCOS 2000 enhanced with IMCS specific
On-board queue model display	IMCS specific
Infrastructure Services	
Short-term archive	SCOS 2000
Long-term archive	SCOS 2000 enhanced with IMCS specific
Time correlation	IMCS specific
Events and actions	SCOS 2000
Events logging	SCOS 2000
Task launcher	SCOS 2000
User-access management	SCOS 2000
OBSM Functionality	SCOS 2000 enhanced with IMCS specific
MPS Functionality	IMCS specific
External User Access	IMCS specific
File Transfer Service	IMCS specific
Data Distribution	SCOS 2000 enhanced with IMCS specific
Performance Analysis	SCOS 2000 enhanced with IMCS specific
Mission Archive	IMCS specific
Archive Completeness Checker	IMCS specific
CD-ROM Production	IMCS specific

The Intermediate Frequency Modem System (IFMS)

At the beginning of its main development phase (Phase-C/D), the Integral mission was the subject of several trade-offs. These were targeted on the one side at optimisation of the satellite's orbit, taking into account both the Proton launcher's performance and the scientific mission requirements, and on the other at maximising the telemetry allocation to the various on-board instruments for scientific-return purposes. Ultimately, this has resulted in a high bit rate (92 kbps) being transmitted over a large distance (orbital apogee: 153 000 km) via the radio-frequency link, keeping the on-board modulation scheme and the transmitter output power unchanged in terms of its inheritance from the XMM mission design. This results in the modulation characteristics of the received signal (in terms of carrier suppression) being at the limit of the performance specified for the standard receivers and demodulators in the current ESA ground-station network. The decision was therefore taken to adopt for the main Integral support ground station (Redu), the IFMS, at that time under development, which had a performance specification compatible with Integral's requirements.

The IFMS integrates into a single unit the functionality of the station receiver, including diversity combination, the tracking subsystem for satellite range and range-rate measurement, the remnant-carrier and suppressed-carrier demodulator (the latter not

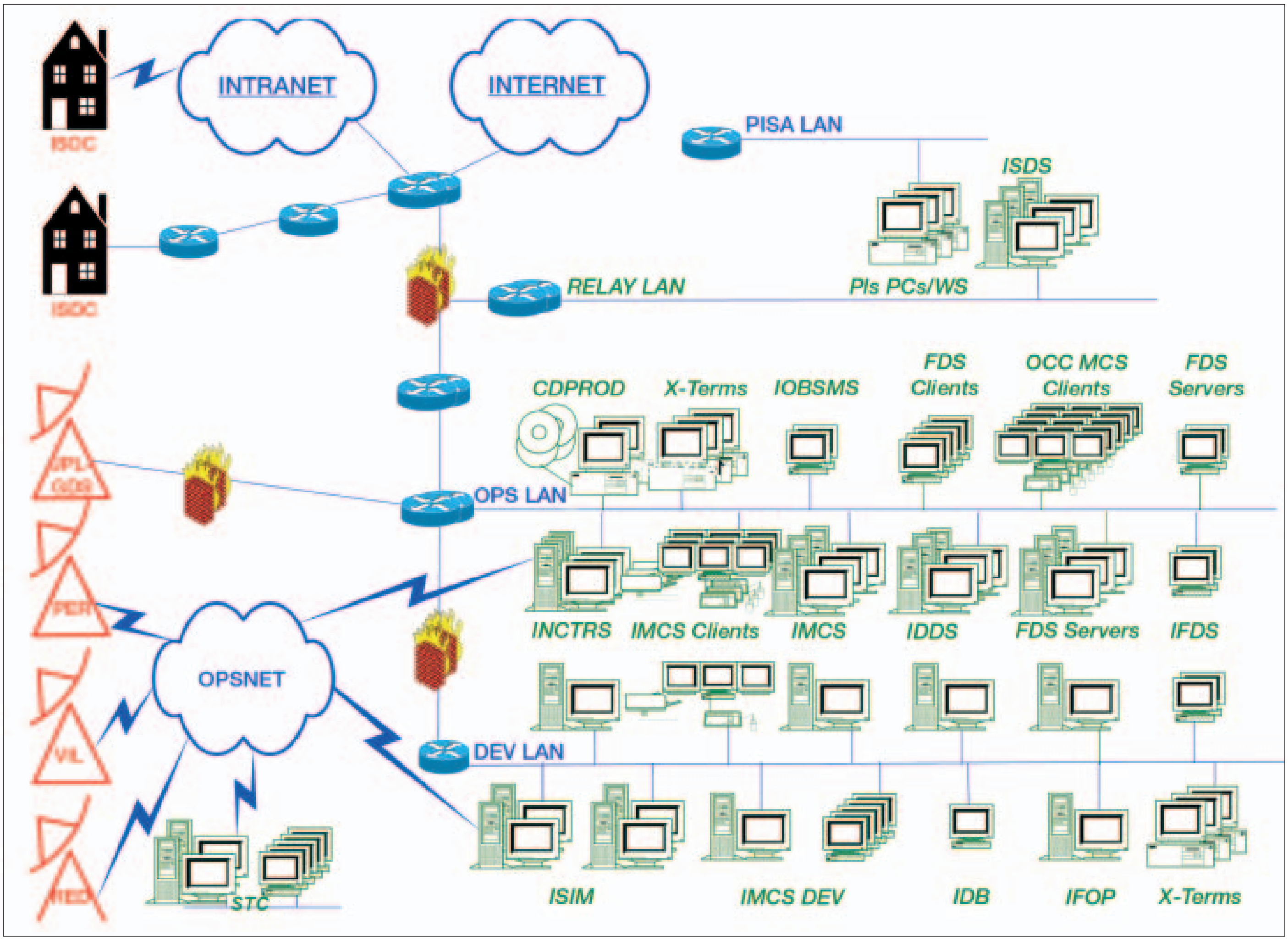

Figure 3. The Integral Mission Operations Centre computer-system configuration

applicable to Integral), and finally the uplink modulator. The system is based on three newly developed modules: a front-end module interfacing at the station intermediate downlink frequency (70 MHz) and sampling at 280 Msample/s, a number of Generic Digital Signal Processing (GDSP) modules implementing the demodulation and ranging functions, and a digital modulator module including digital-to-analogue conversion and up-conversion to the station uplink intermediate frequency (230 MHz). Subsystem control and auxiliary functions (time code reader, interface to the station monitoring and control computer, etc.) are largely based on commercial off-the-shelf products. The GSDP modules make use of Field Programmable Gate Arrays (FPGAs) which, still executing as conventional digital gates, can be programmed in software to implement the specific functionality allocated to the module. A particular feature of the IFMS is its suitability for remote operation and/or maintenance through the so-called 'Development Control Position'. This uses the Internet as the communication protocol and provides a web-browser-based interface, allowing remote control and/or maintenance of the IFMS system via the web.

The IFMS has undergone several tests in the context of the Integral Radio-Frequency Compatibility Tests and has also been validated in-flight on the Cluster and XMM missions as part of the Integral system validation process.

The Space Link Extension (SLE) services for Integral cross-support

The NASA/JPL ground station at Goldstone (Calif.) will be used to cross-support Integral for approximately 20% of its operational orbit above the Earth's radiation belts. For past missions, inter-Agency cross-support has always been dealt with in an ad-hoc manner through mission-specific arrangements involving the exchange of equipment, or mission-specific designs for gateways in order to adapt the interfaces between the ground-segment elements involved in the cross-support (ground stations and/or control centres).

The inefficiency of this way of operating was recognised some years ago by the Consultative Committee for Space Data Systems (CCSDS) which, through its Panel 3, has developed a Cross-Support Reference Model from which the recommendations for the SLE services, aimed at providing a uniform cross-support capability within the CCSDS member agencies, have been derived.

The Cross-Support Reference Model was published in a CCSDS Blue Book in May 1996 (ref. CCSDS 910.4-8-1). That same year, the Integral Project and JPL agreed on an initial SLE services development for the cross-support by the Goldstone station of the Integral mission. That agreement was endorsed at agency level by ESA and NASA in 1997. The basic set required for Integral operation, i.e. Return All Frames (RAF) and Return Virtual Channel (RVC) on the Return Link (telemetry) side and Forward Space Packet (FSP) on the forward-link (command) side, was defined and the development work was started both at ESOC and JPL. At the Plenary ITCOP meeting in Paris in 1998, at which 7 CCSDS member agencies were represented, CLTU was selected for the forward-link service instead of FSP, for reasons of compatibility with legacy systems still present in some ground-station networks.

The SLE services design contains three key elements: the Transfer Service Application and Protocol specified in the CCSDS Recommendation applicable to the service concerned; the Application Programming Interface, a generic design able to accommodate a variety of communication middleware technologies, and supporting both service provider and service user functions; and finally the Service Management, which includes the exchange of trajectory-prediction, scheduling, resource-allocation and operations-control procedures. The parallel ESOC and JPL development work was completed at the beginning of 2001 and the services have subsequently undergone extensive progressive testing in the Integral context, starting from a back-to-back testing of the application for each service, and continuing through trans-Atlantic testing between the Integral MOC and JPL/Goldstone, until their recent final validation including the service-management functionality.

Conclusions

The distributed architecture of Integral Ground Segment has been presented, with the focus on the functionality of the Operational Ground Segment (OGS), in which state-of-the-art design has been applied. In particular, three new major infrastructure developments – the main design features of which have been presented here – are being used for the first time to support the operation of a demanding ESA scientific mission. The OGS has undergone an extensive testing programme to validate its functionality and interfaces to the other Integral Ground Segment elements (ISOC and ISDC), and is now ready to support the Integral mission.