3.3 Integral: International Gamma-Ray Astrophysics Laboratory

Introduction

The International Gamma-Ray Astrophysics Laboratory (Integral) is dedicated to the fine spectroscopy (E/DE=500) and fine imaging (angular resolution: 12 arcmin Full Width at Half Maximum) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV. Integral was selected by the ESA Science Programme Committee in 1993 as the next ESA medium-size scientific mission (M2) to be launched in 2001.

The mission is conceived as an observatory led by ESA with contributions from Russia (Proton launcher) and NASA (Deep Space Network ground stations). The Integral observatory will provide to the science community at large an unprecedented combination of imaging and spectroscopy over a wide range of X-ray and gamma-ray energies, including optical monitoring. The scientific instruments and the Integral Science Data Centre (ISDC) will be provided by large collaborations encompassing many scientific institutes in ESA member states, USA, Russia and Poland, nationally funded and led by Principal Investigators (PIs).

Scientific objectives

Overview

Gamma-ray astronomy explores the most energetic phenomena occurring in nature and addresses some of the most fundamental problems in physics and astrophysics. It embraces a great variety of processes: nuclear excitation, radioactivity, positron annihilation, Compton scattering, and an even greater diversity of astrophysical objects and phenomena: nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic ray interactions and sources, neutron stars, black holes, gamma-ray bursts, active galactic nuclei and the cosmic gamma-ray background. Not only do gamma-rays allow us to see deeper into these objects, but the bulk of the power radiated by them is often at gamma-ray energies.

Integral’s scientific goals address the fine spectroscopy with imaging and accurate positioning of celestial sources of gamma-ray emission. The fine spectroscopy over the entire energy range will permit spectral features to be uniquely identified and line profiles to be determined for physical studies of the source region. The fine imaging capability within a large field of view will permit the accurate locating and hence identification of the gamma-ray emitting objects with counterparts at other wavelengths, enable extended regions to be distinguished from point sources and provide considerable serendipitous science – very important for an observatory-class mission.

In the 15 keV - 10 MeV region, line-forming processes such as nuclear excitation, radioactivity, positron annihilation, cyclotron emission and absorption become important, and when used as astrophysical tools are almost certain to lead to fundamental new discoveries. Unique astrophysical information is contained in the spectral shift, line width and line profiles. Detailed studies of these processes require the resolving power (E/DE=500) of a Germanium spectrometer such as that employed on Integral. Lower-resolution spectrometers (e.g. SIGMA, OSSE, COMPTEL) do not have sufficient energy resolution to study the parameters of these lines. The last high spectral resolution space instrument, on HEAO-3 in 1979-80, was 100 times less sensitive than Integral’s. Solid observational and theoretical grounds already exist for predicting detectable emission from such varied celestial objects as the Galactic Centre region, the interstellar medium, compact objects, novae and supernovae and a variety of active galactic nuclei.

Diffuse emission

Our Galaxy contains diffuse sources of gamma-ray line and continuum radiation. The 511 keV electron-positron annihilation line and 1.809 MeV line from radioactive Al^{26} are tracers of sites of nucleosynthesis in the past 10^6 years and diagnostics of the

For further information on Integral, see http://astro.estec.esa.nl/SA-general/Projects/Integral/integral.html

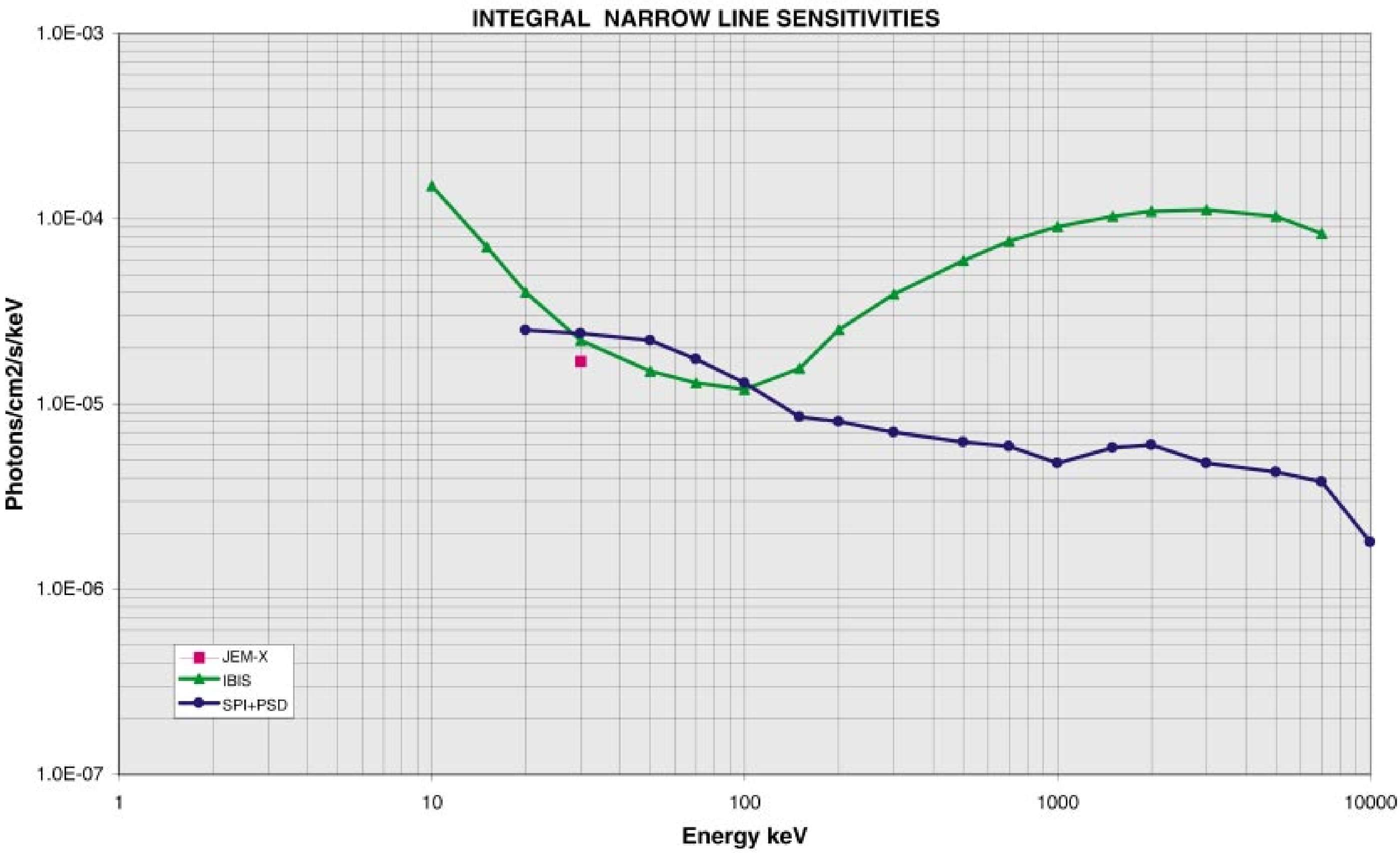


Figure 3.3.1. Narrow-line sensitivity (3σ, 10^6 s) for Integral's SPI (including pulse shape discrimination, PSD), IBIS and JEM-X instruments.

conditions in the interstellar medium. In the MeV range, the gamma-ray continuum may be used to study the low-energy cosmic ray electrons. These fluxes are now being studied by the instruments aboard NASA's Compton Gamma-Ray Observatory, but Integral's complementary combination of high spectral and angular resolution is necessary for their full exploitation. The gamma-ray emission from the Galactic plane will be mapped on a wide range of angular scales, from arc minutes to degrees, in both discrete nucleosynthesis lines, e.g. 1.809 MeV from Al^{26} and 511 keV, as well as the wideband continuum. At the same time, source positioning at the arcmin level within a wide field of view, of both continuum and discrete line emissions, is required to allow an extensive range of astrophysical investigations to be performed on a wide variety of sources, both targeted and serendipitous, with a good chance of identification at other wavelengths.

Galactic centre

The centre of our Galaxy is known from observations in the radio and infrared windows to be the site of violent activity. Observations made so far indicate that at gamma-ray energies the behaviour of the region is no less extreme. It houses some of the most energetic gamma-ray objects in the Galaxy and is host to sources of transient emission, including variable line emission from the annihilation of positrons. Integral will provide the tools for using gamma-rays as a sensitive probe of the astrophysical processes going on within a few hundred parsecs of the nucleus of our Galaxy.

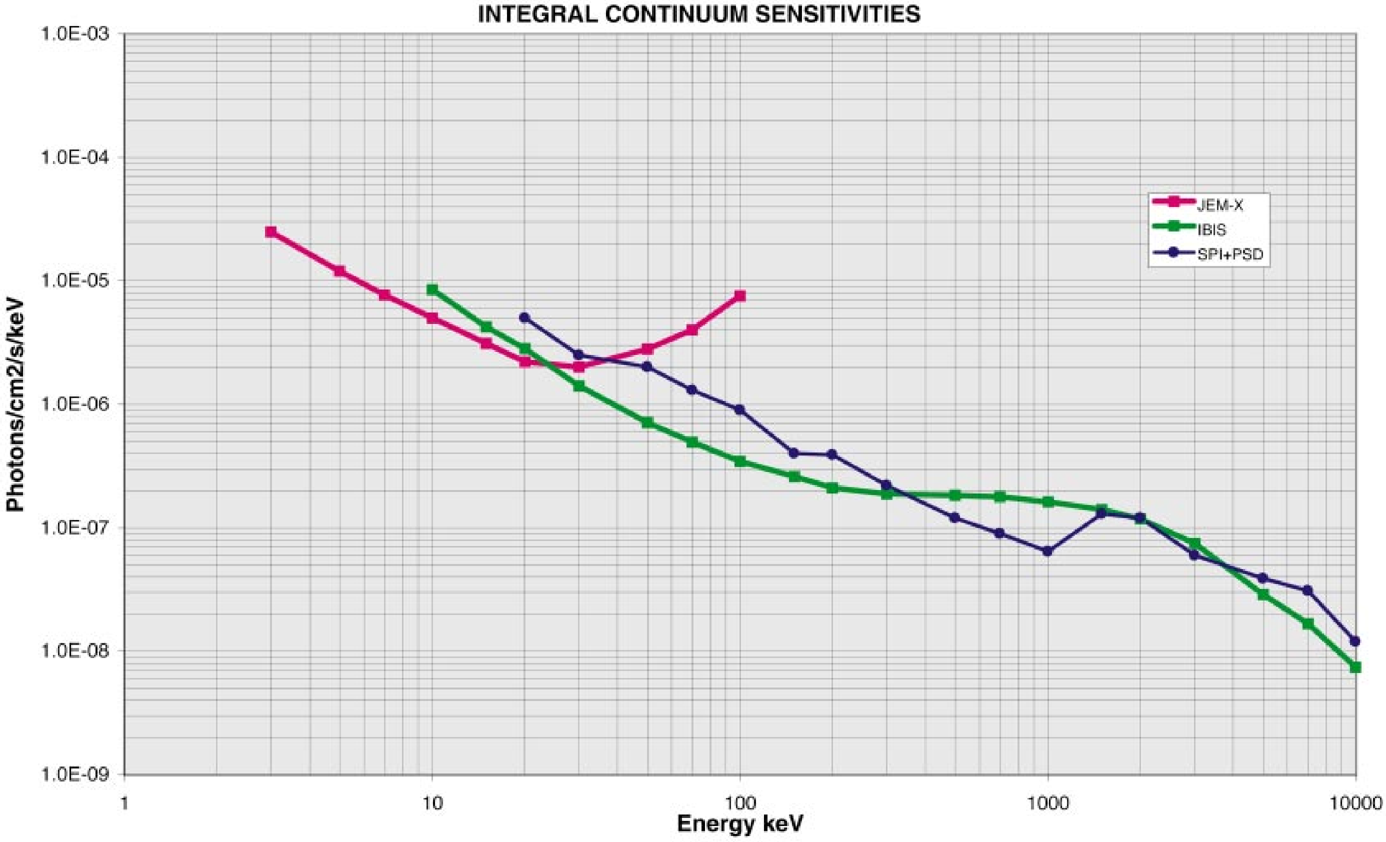


Figure 3.3.2. Continuum sensitivity (3σ, 10^6 s) for Integral's SPI (including pulse shape discrimination, PSD), IBIS and JEM-X instruments.

Compact objects
One of the most important scientific objectives of Integral is to study compact objects, e.g. neutron stars and black holes. Virtually all types of compact objects are significant sources of high-energy emission. Integral will image these objects in unprecedented detail at high energies and the spectroscopic capabilities of the mission will provide the first detailed physical diagnostics of these systems at gamma-ray energies.

Explosive nucleosynthesis
Observations of gamma-ray lines from nuclear transitions in the decay of radionuclei and the annihilation of positrons produced in various explosive nucleosynthetic processes (supernovae and novae, including historic events) provide the most direct method of studying current sites, rates and models of nucleosynthesis. Measurements with Integral of the shapes of the gamma-ray line profiles from supernovae will provide information about the expansion velocity and density distribution inside the envelope, while the relative intensities of the lines provide direct insight into the physical environment at the time of production.

High-energy transients
Transient sources in the gamma-ray region display unprecedented variability in both the temporal and spectral domains. Integral will monitor the Galactic plane regularly

Table 3.3.1. Key parameters of the Integral scientific payload.

	SPI	IBIS	JEM-X	OMC
Energy range	20 keV - 8 MeV	15 keV - 10 MeV	3 keV - 35 keV	500 nm - 850 nm
Detector/characteristics	19 Ge detectors (ea ch 6 x 7 cm), cooled @ 85K	16384 CdTe dets (ea 4 x 4 x 2 mm), 4096 CsI dets (ea 9 x 9 x 30 mm)	Microstrip Xe-gas detector (5 bar)	CCD + V-filter
Detector area (cm^2)	500	2600 (CdTe) 3100 (CsI)	2 x 500	2048 x 1024 pixel
Spectral resolution	2 keV @ 1.3 MeV	7 keV @ 100 keV	1.5 keV @ 10 keV	--
Field of view (fully coded)	16°	9° x 9°	4.8°	5° x 5°
Angular resolution (FWHM)	2°	12'	3'	17.6"/pixel
10σ source location	20'	< 1'	< 20"	< 8"
Continuum sensitivity*	7×10^{-8} @ 1 MeV	4×10^{-7} @ 100 keV	9×10^{-6} @ 6 keV	19.2 ^{m} (10^3 s)
Line sensitivity*	5×10^{-6} @ 1 MeV	1×10^{-5} @ 100 keV	2×10^{-5} @ 6 keV	--
Timing accuracy (3σ)	0.1 ms	0.1 ms - 1000 s	0.1 ms	var. in units of 1 s
Mass (kg)	1309	628	65	17
Power (W)	250	220	52	12
Data rate (kbps)	20	57	7	2

Sensitivities are 3σ in 10^6 s, units: ph/(cm^2 s keV) [cont.] and ph/(cm^2 s) [line]

in order to detect transient sources, determine their duty cycle and their luminosity function. Gamma-ray bursts will be studied using the very broad energy range provided by the two main instruments and the two X-ray and optical monitors.

Active galaxies

The study of active galaxies in both fine and broadband spectroscopy will yield unprecedented knowledge of the particle interactions taking place in the region where the central engine's energy meets the Galaxy's matter. Because of the greatly improved sensitivity of Integral, sub-degree resolution imaging is absolutely essential to avoid source confusion from the large population of Active Galactic Nuclei (AGN) and to associate gamma-ray sources unambiguously with their optical, infrared and radio counterparts.

Scientific payload

The Integral payload consists of two main gamma-ray instruments: Spectrometer SPI and Imager IBIS. Each has high spectral and angular resolution, but they are differently optimised to be complementary and to achieve overall excellent performance. Recent observations show that line emissions occur with a wide range of angular and spectral extent, i.e. broader lines seem to be emitted from point-like sources and narrower lines from extended sources. These instruments are supported by two monitor instruments that will provide complementary observations at X-ray and optical energy bands.

The spectrometer, imager and X-ray monitor share a common principle of operation: they are all coded aperture mask telescopes. The coded mask technique is the key that allows imaging, which is all-important in separating and locating sources. It also provides near-perfect background subtraction because for any particular source direction the detector pixels can be considered to be split into two intermingled subsets: those capable of viewing the source and those for which the flux is blocked by opaque mask elements. Effectively, the latter subset provides an exactly contemporaneous background measurement for the former, made under identical conditions.

Spectrometer SPI

The Spectrometer SPI (Table 3.3.1) will perform spectral analysis of gamma-ray point sources and extended regions with an unprecedented energy resolution of 2 keV (Full Width at Half Maximum, FWHM) at 1 MeV. This will be accomplished using an array of 19 hexagonal high-purity Germanium detectors cooled by active Stirling coolers to an operating temperature of about 85 K. A hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16°) with an angular resolution of 2°. In order to reduce background radiation, the detector assembly is shielded by an active scintillator veto system that extends around the bottom and side of the detector almost completely up to the coded mask. The aperture (and hence contribution by cosmic diffuse radiation) is limited to 25°. The SPI collaboration is led by the Co-PIs G. Vedrenne (CESR, Toulouse/France) and V. Schoenfelder (MPE, Garching/Germany).

Imager IBIS

The Imager IBIS (Table 3.3.1) provides powerful diagnostic capabilities of fine imaging (12 arcmin FWHM), source identification and spectral sensitivity to both continuum and broad lines over a broad (15 keV - 10 MeV) energy range. A tungsten coded-aperture mask (3.2 m above the detection plane) is optimised for high angular resolution. As diffraction is negligible at gamma-ray wavelengths, the angular resolution obtainable with a coded mask telescope is limited by the spatial resolution of the detector array. The Imager design takes advantage of this by using a detector with a large number of spatially-resolved pixels, implemented as physically distinct elements.

The detector uses two planes, a front layer of CdTe pixels, each 4· 4· 2 mm (w· d· h), and a second one of CsI pixels, each 9· 9· 30 mm. The detector provides the wide energy range and high sensitivity continuum spectroscopy required for Integral. The division into two layers allows the paths of the photons to be tracked in 3D, as they scatter and interact with more than one element. The aperture is restricted by a lead tube system and shielded in all other directions by an active scintillator veto system. The Imager collaboration is led by the PI P. Ubertini (IAS, Frascati/Italy).

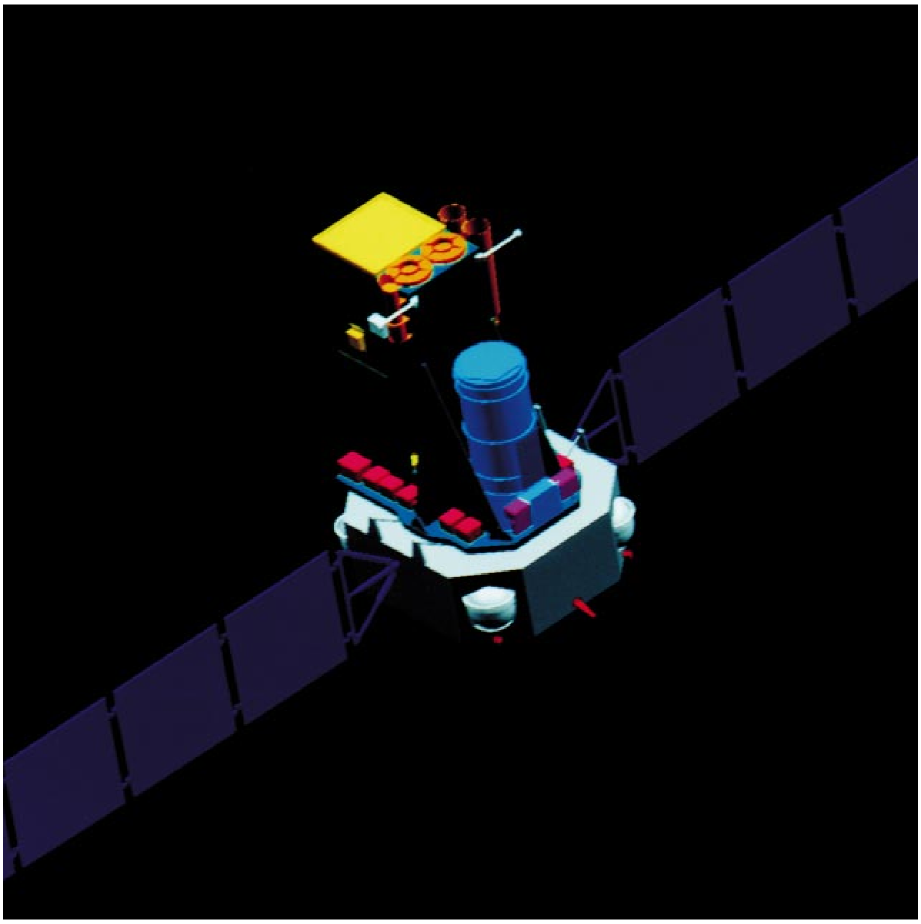
X-Ray Monitor JEM

The Joint European X-Ray Monitor JEM-X (Table 3.3.1) supplements the main Integral instruments (Spectrometer and Imager) and plays a crucial role in the detection and identification of the gamma-ray sources and in the analysis and scientific interpretation of Integral gamma-ray data. JEM-X will make observations simultaneously with the main gamma-ray instruments and provides images with 3 arcmin angular resolution in the 3-35 keV prime energy band (extension up to 100 keV possible). The baseline photon detection system consists of two identical high-pressure imaging microstrip gas chambers (Xenon at 5 bar) each viewing the sky through a coded aperture mask located at a distance of 3.2 m above the detection plane. The JEM-X collaboration is led by the PI N. Lund (DSRI, Copenhagen/Denmark).

Optical Monitoring Camera OMC

The Optical Monitoring Camera OMC (Table 3.3.1) consists of a passively cooled CCD in the focal plane of a 50 mm lens. The CCD (1024· 2048 pixels) uses one

Figure 3.3.3. The Integral spacecraft (solar arrays stowed). The overall dimensions are 6×4 m (h×w), the total dry mass is 3600 kg (with 2019 kg for the payload). The coded masks for the Imager (IBIS) and X-ray monitor (JEM-X) are positioned 3.2 m above the detector planes.



section (1024· 1024 pixels) for imaging, the other for frame transfer before readout. The OMC will observe the optical emission from the prime targets of the Integral main gamma-ray instruments with the support of the X-Ray Monitor JEM-X. OMC offers the first opportunity to make long observations in the optical band simultaneously with those at X-rays and gamma-rays. Variability patterns ranging from 10s of seconds, hours, up to months and years will be monitored. The limiting magnitude will be 19.2 visual magnitudes (3s, 10^3 s), which corresponds to ~40 photons $cm^{-2}s^{-1}keV^{-1}$ (at 2.2 eV) in the V-band. Multi-wavelength observations are particularly important in high-energy astrophysics, where variability is typically rapid. The wide-band observing opportunity offered by Integral is of unique importance in providing for the first time simultaneous observations over seven orders of magnitude in photon energy for some of the most energetic objects in the Universe. The OMC collaboration is led by PI A. Gimenez (INTA, Madrid/Spain).

Mission scenario

The Integral spacecraft (Figure 3.3.3) consists of a service module (identical to the module of the ESA XMM mission) containing all spacecraft subsystems and a payload module carrying the scientific instruments. The simplicity of the interface between service and payload module is a major design driver. The modular approach has been conceived to allow for a parallel development, assembly, integration and test of service and payload module, respectively.

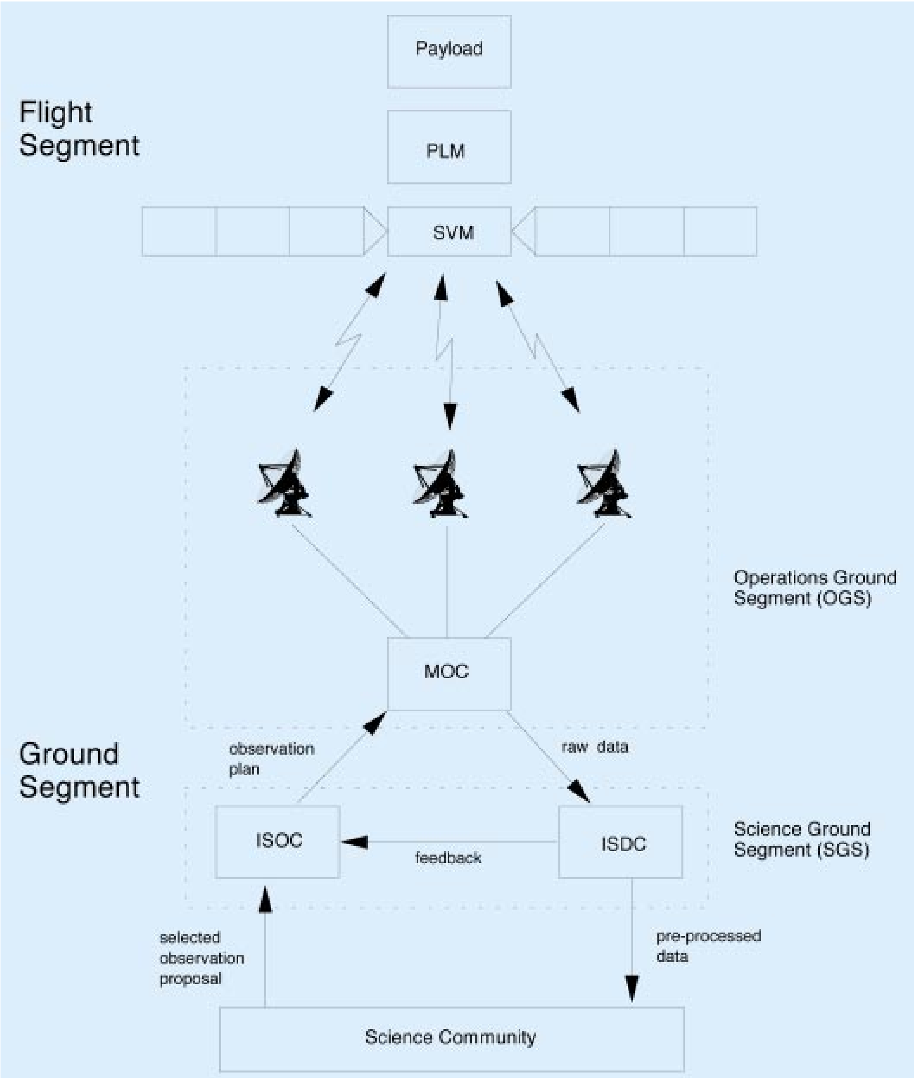


Figure 3.3.4. The Integral ground segment.

Integral (with a payload mass of about 2000 kg and a total launch mass of about 4000 kg) will be launched in 2001 into a geosynchronous highly eccentric orbit with high perigee in order to provide long periods of uninterrupted observation with nearly constant background and away from trapped radiation. The baseline is to launch Integral with a Russian Proton vehicle into a high Earth orbit (orbital parameters: period 48 h, inclination 51.6°, perigee height 46 000 km). Owing to background radiation effects in the high-energy detectors, scientific observations will be carried out while the spacecraft is above an altitude of 40 000 km. This means that 100% of the time spent in the orbit provided by Proton can be used for scientific observations (realtime scientific data rate: 85 kbit/s).

Ground segment

The ground segment (Figure 3.3.4) consists of two major elements, the Operations Ground Segment (OGS) and the Science Ground Segment (SGS). The OGS, consisting of the ESA and NASA ground stations and the Mission Control Centre at the European Space Operations Centre (ESOC) in Darmstadt, Germany, will implement the observation plan within the spacecraft system constraints as an operational command sequence. In addition, the OGS will perform all classical spacecraft operations and maintenance tasks. The SGS consists of two components, the Integral Science Operations Centre (ISOC) and the Integral Science Data Centre (ISDC). The ISOC (at the European Space Research and Technology Centre, ESTEC, in Noordwijk, The Netherlands) will process the accepted observation proposals into an optimised observation plan, consisting of a timeline of target pointings plus the corresponding instrument configuration.

The ISDC, located in Geneva, Switzerland, will receive the science telemetry plus the relevant ancillary spacecraft data from the OGS. Taking into account the instrument characteristics, the ISDC will convert these raw data into physical units. Final data products will be distributed to the observer and archived for later use by the science community. ESA will also keep the (same) archive at the ISOC. ESOC and ISOC are under the responsibility of ESA, the ISDC will be provided by the scientific community led by PI T.Courvoisier, Geneva Observatory.

Science operations

Integral will be an observatory-type mission (nominal lifetime 2 years, extension up to 5 years possible). Most of the observing time (65% during year 1, 70% year 2, 75% year 2+) will be awarded to the scientific community at large as the general programme. Typical observations will last from 10s of minutes up to 2 weeks. Proposals will be selected on their scientific merit only by a single Time Allocation Committee. These selected observations are the base of the general programme. The first call for observation proposals will be issued 1 year before launch. The remaining fraction of the observing time (i.e. 35% year 1, 30% year 2, 25% year 2+) will be reserved for institutes that have developed and delivered instruments and the data centre (guaranteed PI time), for Russia and NASA for their contributions to the programme (Proton launcher and Deep Space Network ground stations), for ESA/ISOC and Mission Scientists. This fraction, the core programme, will be devoted to: (i) a Galactic Plane Survey to map its gamma-ray emission in order to detect as yet unknown persistent sources (e.g. recent Galactic supernovae) and to facilitate the study of transient sources, (ii) a deep exposure of the central radian of the Galaxy, and (iii) pointed observations yet to be determined by the members of the Integral Science Working Team (PIs, Mission Scientists et al.) The full details of the core programme will be made available at the issue of the first AO. The ISDC will serve the entire guest observer community and it is the place where the archive and derived scientific products will be built and made accessible to the wide astronomical community. Scientists will have the possibility of visiting the ISDC to familiarise themselves with Integral data. All scientific data will be made available to the scientific community 1 year after they have been released to the observer. This guarantees the use of the scientific data for different investigations beyond the aim of a single proposal.