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The Infrared Space Observatory (ISO) Mission *

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Abstract. ESA's Infrared Space Observatory (ISO) is an astronomical satellite, operating at wavelengths from 2.5–240μm. Essentially, ISO consists of a large cryostat which contained at launch about 2300 litres of superfluid helium to maintain the Ritchey-Chrétien telescope, the scientific instruments and the optical baffles at temperatures of 2–8K. The telescope has a 60-cm diameter primary mirror. A three-axis-stabilisation system provides a pointing accuracy of a few arc seconds. ISO's instrument complement, built by international consortia of scientific institutes and industries, consists of an imaging photo-polarimeter (ISOPHOT), a camera (ISOCAM), a short wavelength spectrometer (SWS) and a long wavelength spectrometer (LWS). ISO was placed into a highly-elliptical orbit in November 1995 by an Ariane 4 launcher. All systems are performing very well and ISO is expected to have an in-orbit lifetime of around 24 months. In keeping with its rôle as an observatory, the majority of ISO's observing time is being made available to the astronomical community in ESA member states, Japan and the USA via "Calls for Observing Proposals".

Key words: Artificial satellites, space probes — Instrumentation: miscellaneous — Infrared: general

1. Introduction

The part of the infrared spectrum covered by the Infrared Space Observatory (ISO), namely 2.5–240μm, is of great scientific interest not only because it is here that cool objects radiate the bulk of their energy but also because of its rich variety of atomic, ionic, molecular and solid-state spectral features. However despite its scientific promise, the majority of this wavelength range has remained under explored due to the damaging effects of the Earth's atmosphere and of thermal emission from the telescopes and instruments. Putting a cooled telescope into space overcomes these problems. The first major step in this direction was IRAS (Neugebauer et al. 1984). Compared to IRAS, ISO has wider wavelength coverage, better spatial resolution, greater sensitivity, more sophisticated instrumentation especially for spectroscopy and a longer lifetime. As an observatory, ISO is open to Guest Observers.

ISO results from a proposal made to ESA in 1979. Following various studies, ISO was selected in 1983 as the next new start in the ESA Scientific Programme. After the issue of a "Call for Experiment Proposals" and evaluation of the responses, ISO's four scientific instruments were chosen in 1985. The satellite design and main development phases started in 1986 and 1988, respectively. ISO was launched by an Ariane 4 rocket on the night of 16–17 November 1995.

2. Satellite design

The ISO satellite consists of a payload module, the upper cylindrical part in Fig. 1 and a service module, which provides the basic spacecraft functions. The payload module carries the conical sun shade and the two star trackers. Overall, ISO is 5.3 m high, 2.3 m wide with a mass of approximately 2500 kg at launch.

The service module includes the load path to the launcher, the array of solar cells mounted on the sun shield, and subsystems for thermal control, data handling, power conditioning, telemetry and telecommand, and attitude and orbit control. The last item provides the three-

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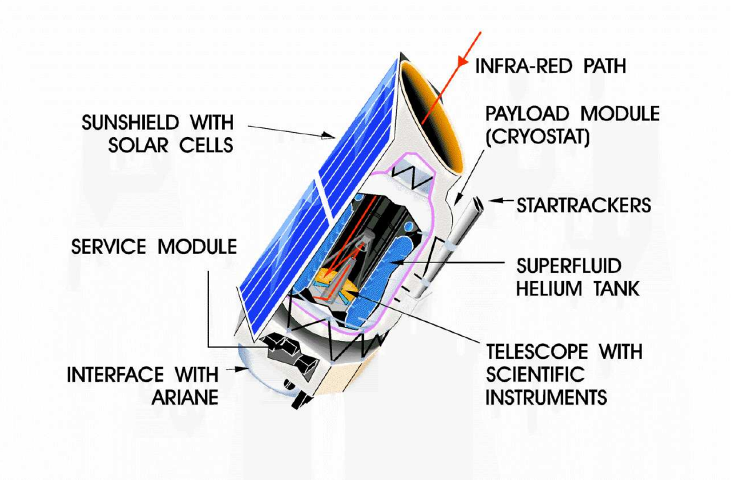

Fig. 1. A cut-away schematic of the ISO satellite

axis stabilisation to an accuracy of a few arc seconds, and also the raster pointing facilities needed for the mission. It consists of sun and earth sensors, star trackers, a quadrant star sensor on the telescope axis, gyros and reaction wheels, and uses a hydrazine reaction-control system. The downlink bit rate is 32 kbit/s, of which about 24 kbit/s are dedicated to the scientific instruments.

The payload module is essentially a large cryostat. Inside the vacuum vessel is a toroidal tank, which at launch was filled with over 2300 litres of superfluid helium. Some of the infrared detectors are directly coupled to the helium tank and are held at a temperature of around 2 K. All other units are cooled by means of the cold boil-off gas from the liquid helium. This is first routed through the optical support structure, where it cools the telescope and the scientific instruments to temperatures of around 3 K. It is then passed along the baffles and radiation shields, before being vented to space. Above the main helium tank is a small auxiliary tank (of volume about 60 litres); this contained normal liquid helium and met all of ISO's cooling needs for the period immediately prior to launch. Mounted on the outside of the vacuum vessel is a sunshade, which prevents direct sunlight from entering the cryostat.

Suspended in the middle of the tank is the telescope, which is a Ritchey-Chrétien configuration with an effective aperture of 60 cm. The optical quality of its mirrors is adequate for diffraction-limited performance at a wavelength of 5μm. Stringent control over straylight, particularly that from bright infrared sources outside the telescope's field of view, is necessary to ensure that the system's sensitivity is not degraded. This is accomplished by means of the sunshade, the Cassegrain and main baffles, and a light-tight shield around the instruments. Additional straylight control is provided by constraining ISO from observing too close to the Sun, Earth and Moon.

The scientific instruments are mounted on an optical support structure (which carries the primary mirror on its opposite side). Each one occupies an 80° segment of the cylindrical volume available. The 20$'$ total unvignetted field of view of the telescope is distributed radially to the four instruments by a pyramid mirror. Each experiment receives a 3$'$ unvignetted field, centered on an axis at an angle of 8.5$'$ to the main optical axis, i.e. the instruments view separate areas of the sky.

3. Instrument payload

The ISO scientific payload consists of four instruments: a camera, ISOCAM (Cesarsky et al. 1996); an imaging photopolarimeter, ISOPHOT (Lemke et al. 1996); a long wavelength spectrometer, LWS (Clegg et al. 1996); and a short wavelength spectrometer, SWS (de Graauw et al. 1996). Each instrument was built by an international consortium of scientific institutes and industry, headed by a Principal Investigator (PI), using national funding. Although developed separately, the four instruments were designed to form a complete, complementary and versatile common-user package.

Only one instrument is operational in prime mode at a time. However, when the camera is not the main instrument, it is used in parallel mode (Siebenmorgen et al 1996) to acquire extra astronomical data. Whenever possible, the long-wavelength channel of the photometer is used during satellite slews. This serendipity mode (Bogun et al 1996) is leading to a partial sky survey at wavelengths around 200μm, a spectral region not covered by the IRAS survey. Additionally, since launch, a parallel mode has also

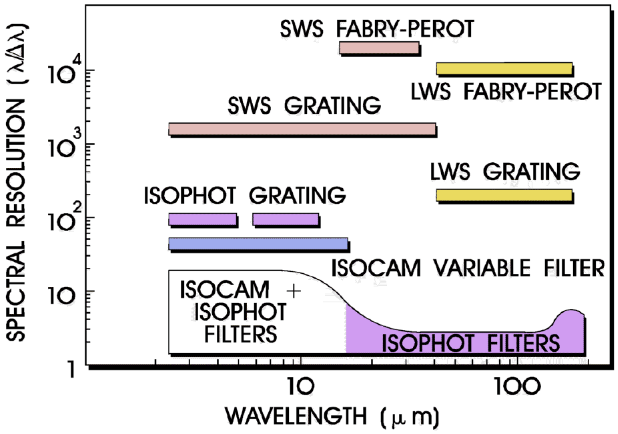

Fig. 2. Photometric and spectroscopic capabilities of ISO.

With ISO, photometry is possible in broad and narrow spectral bands across its entire wavelength range of 2.5 to around 240μm. A variety of apertures, ranging from 5 to 180 arc seconds, is selectable out to 120μm. For spectroscopy, resolving powers ranging from 50 to 30,000 are available in the wavelength range from 2.5 to nearly 200μm. An overview of ISO's photometric and spectroscopic capabilities is given in Fig 2. ISO is capable of direct imaging in broad and narrow spectral bands across the complete wavelength range at spatial resolutions ranging from 1.5 arc seconds (at the shortest wavelengths) to 90 arc seconds (at the longer wavelengths). In addition, mapping may be carried out using sequences of pointings.

4. Orbit and operations

ISO's operational orbit has a period of just under 24 hours, an apogee height of 70600 km and a perigee height of 1000 km. In this orbit two ground stations are needed to provide visibility of the satellite from the ground for the entire scientifically-useful part of the orbit — over 16 hours per day. ESA provides one ground station, located at Villafranca, Spain. The second ground station —located at Goldstone, California— and associated resources are contributed by the National Aeronautics and Space Administration (NASA), USA; and the Institute of Space and Astronautical Science (ISAS), Japan.

Operations of ISO are conducted from ESA's Villafranca Satellite Tracking Station (VilSpa), located near Madrid in Spain. Two ISO teams are co-located here; one is responsible for the operations of the spacecraft and the other is responsible for all aspects of the scientific operations ranging from the issue of the "Calls for Observing Proposals", through the scheduling and use of the scientific instruments, to the pipeline data processing.

The limited lifetime of ISO, the severe sky coverage constraints, the complexity of the scientific instruments, along with the necessity to make many short observations all dictate that a pre-scheduled operation must be carried out in order to maximise the time spent acquiring useful astronomical data. Thus, ISO is operated in a service observing mode with each day's observations being planned in detail and finalised up to 3 weeks in advance. This operational concept has driven the design of the ground segment.

Figure 3 gives a simplified overview of the ground segment, focusing on the activities of the Science Operations Centre (SOC), as seen from the Observer's point of view. The pre-planned operations mean that full details of every observation have to be available in advance. Thus, proposers make "Phase 1" proposals, which contain the scientific case for the proposal and an observation list. These proposals are subject to peer review; successful proposers go on to "Phase 2" of the data entry process. Here, they use the Proposal Generation Aids (PGA) software to enter full and complete details of all their observations into the SOC's data bases. Once the validity of the input parameters has been checked by PGA and the observing time needed for that observation has been calculated and approved by the observer, the observation is entered into the "Mission Database". Prior to launch, this data base contained over 32000 observations. Observers can, and do, update their observing parameters to optimize their programmes. The observing timelines are constructed on a daily basis, up to three weeks in advance, by the mission planning software selecting observations from this data base. Once a timeline has been built, a separate file, containing all the necessary instrument commands and the times (to an accuracy of a second) at which they must be sent to the spacecraft, is prepared and passed across to the Spacecraft Control Centre (SCC).

The SCC checks the timeline, e.g. for compliance with the various pointing constraints, and then adds in all the necessary commands to the spacecraft. All these commands are uplinked to the satellite, via either the Villafranca or Goldstone antenna, in real time. There is no on-board data storage, thus, all data are downlinked immediately and monitored in real time at the ground segment. Off-line, the data are processed by the "pipeline" to various levels and stored in the product archive. Observers are sent CD-ROMs containing data products from their observation(s) plus associated calibration files. The Principal Investigator has exclusive rights to the data for a period of one year starting from the time at which an adequate calibration and processing is available.

5. Project organisation

Overall responsibility for the management of the development, launch and in-orbit commissioning of the satellite rested with the ESA Project Team, located at ESTEC and part of the ESA Directorate of the Scientific Programme. This responsibility included the interfaces to the industrial team led by Aerospatiale, to the instrument teams for the

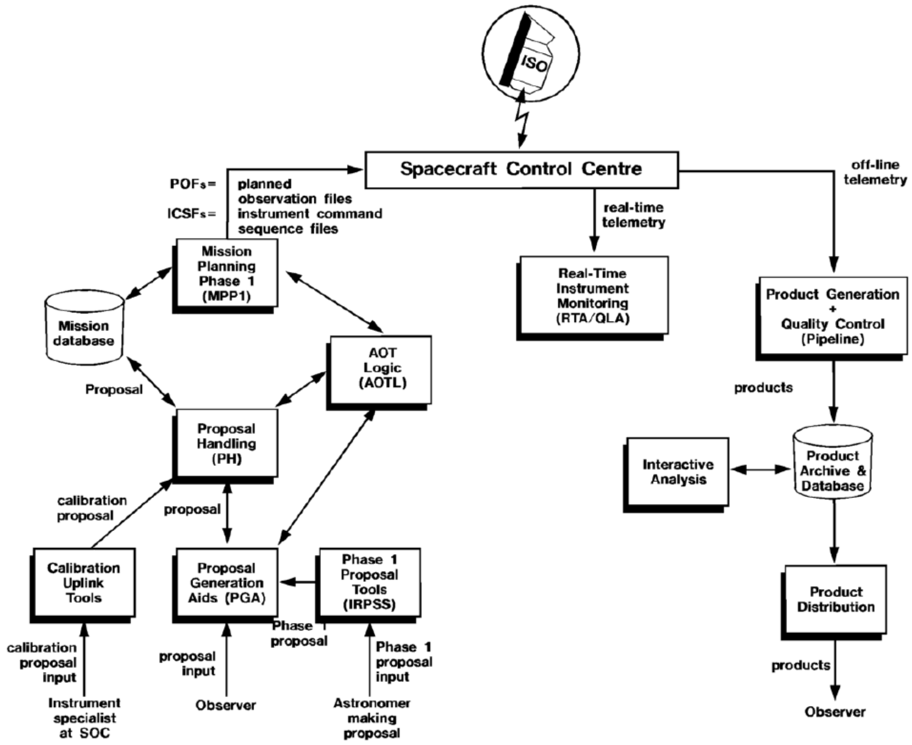

Fig. 3. Simplified view of ground segment operations, focusing on activities of the Science Operations Centre.

development of the scientific payload and to Arianespace for all launch services. From the start of the routine operational phase, overall responsibility for ISO passed to ESA's Space Science Department, Astrophysics Division.

The ISO Science Team —composed of the four instrument Principal Investigators, five Mission Scientists, a representative from each of NASA and ISAS, and ESA staff including the Project Scientist as Chairman— provided advise to ESA throughout the development phase; this rôle is continuing during the operations phase.

The satellite prime contractor, Aerospatiale (F), was responsible for the design and development of the satellite and for the integration and testing of the scientific instruments with the satellite. The industrial team numbered 32 companies (Steinz and Linssen 1995), including Daimler-Benz Aerospace (D) (formerly MBB) responsible for the payload module, Linde (D) for the helium subsystem, Aerospatiale (F) for the telescope, CASA (E) for the service module, and Fokker (NL) for the attitude and orbit control.

The Science Operations Centre (SOC) was developed under the responsibility of ESA's Astrophysics Division at ESTEC, Noordwijk, with extensive contributions from the instrument teams. During the last year before launch, the SOC moved to Villafranca, Spain. ESA's space operations centre, ESOC, in Darmstadt, Germany is responsible for the overall ground segment, including developing and operating the Spacecraft Control Centre (SCC) and the interfaces to NASA-JPL for Goldstone and to ISAS, Japan for flight operations support. The satellite was controlled from Darmstadt for the first 4 days after launch; thereafter, control passed to Villafranca.

6. Observing time

The majority of ISO's observing time —allocated on a "per observation" basis— is being made available to the astronomical community by the traditional route of "Calls for Observing Proposals", followed by peer review. These Calls are, in principle, open only to proposers in ESA member states, Japan and the USA. A pre-launch Call was issued in April 1994 and a post-launch "Supplemental Call" was issued in August 1996.

One thousand proposals were received in response to the pre-launch Call. After their assessment, the ISO Observing Time Allocation Committee recommended about 3000 hours of observations in two priority bands for ISO to carry out. They also designated an additional approximately 3000 hours of observations as third priority, to be carried out whenever no suitable higher priority observation is available. The main use of the post-launch supplemental call is to modify and/or extend and/or redirect existing programmes.

In addition to this "Open Time", there is "Guaranteed Time" reserved for the groups involved in the preparation and operation of the ISO mission. These groups are: the four Principal Investigators and their teams, who built the ISO instruments; the five Mission Scientists; the Science Operations Team; NASA, USA; and ISAS, Japan. A co-ordinated programme of observations, to be carried out in the guaranteed time, was prepared by the holders of the guaranteed time and published to the community with the pre-launch Call for Observing Proposals.

7. In-orbit status

ISO was given a perfect launch by an Ariane 44P vehicle into its planned elliptical transfer orbit with lift-off from Kourou occurring at 02.20 CET on 17 November 1996, in the first second of the launch window.

The first 21 days after launch were devoted to the "Satellite Commissioning Phase". During this time, the operational orbit was attained, the cryo-cover closing the cryostat on the ground was ejected, all spacecraft subsystems were tested and found to be in excellent condition, first light for all instruments was achieved, engineering checks were successfully made of all the four scientific instruments and the integrated ground segment was validated.

The following 56 days (from 8 December to 3 February 1996) were devoted to the "Performance Verification Phase", during which a detailed assessment of the in-flight performance of the scientific instruments was made, their core calibrations established and most of the planned observing modes commissioned.

The execution of these critical initial phases of the mission went extremely smoothly, with schedules and timelines —that had been laid down in the months before launch— being followed very accurately.

The cryogenic system is providing all the expected temperatures and the estimated mass flow rate of the boiled-off helium seems close to predictions. Current estimates, based on indirect indications, are that ISO's in-orbit lifetime will be 24 ± 2 months, well above the requirement of 18 months. A direct measurement of the remaining liquid helium is planned for September 1996.

Regarding optical performance, images of point sources have been made with ISOCAM clearly showing up to the sixth Airy diffraction ring. Analysis of the data has shown that the ISO telescope is diffraction-limited down to a wavelength at least of 15μm; work on shorter wavelength data is underway.

All nominal modes of the Attitude and Orbit Control system have been successfully verified. The pointing performance is also substantially better than the specifications. The short term jitter (formally, the relative pointing error) is about 0.5 arc secs (2σ, half cone over a 30 second period) as compared to the specification of ≤ 2.7 arc secs. The blind pointing (formally, the absolute pointing error) is about 3.5 arc secs (2σ, half cone) as compared to the specification of ≤ 11.7 arc secs. The drift between the telescope boresight and the warm startrackers is < 0.1 arc secs per hour as compared to the specification of $\leq$ 2.8 arc sec per hour.

The scientific instruments are all operating very well (Cesarsky et al. 1996; Lemke et al. 1996; Clegg et al. 1996; de Graauw et al. 1996; and references therein). The biggest in-orbit issue has been the effects on the sensitivity of the instruments caused by impacts of high-energy cosmic ray particles on the infrared detectors; these necessitated changes in operating conditions and data processing. All instruments are returning scientific data of excellent quality; this volume contains their initial scientific results.

By the end of the performance verification phase, most of the planned main observing modes had been successfully commissioned; the exceptions being absolute photometry with ISOPHOT and the LWS Fabry-Pérot modes, which needed to be revised following in-orbit results. Since then, one of the LWS Fabry-Pérot modes has also been commissioned. Work is proceeding on commissioning the remaining modes and, also on polarisation with ISOCAM and ISOPHOT, with the goal of releasing them during the autumn of 1996.

Routine operations (i.e. carrying out the planned open and guaranteed time observations) started on 4 February 1996. The ground segment is working very smoothly; efficient observing schedules with highly-graded observations are being regularly planned and executed. Per day, roughly 16.75 hours —the time ISO spends outside the main parts of the van Allen belts of trapped particles— is available for science use; this is 45 mins longer than had been anticipated prior to launch. During these 16.75 hours, an average of about 45 observations is made, using between 90% and 95% of the available time. The remaining time is mainly used for slews and engineering activities.

Acknowledgements. During the history of ISO, now stretching back almost 20 years, countless engineers and scientists have contributed to its development, launch and operation. They are too numerous to name individually but without their expertise, enthusiasm, dedication, professionalism and sheer hard work, the success of ISO and the results discussed in this volume would not have been possible.

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