THE INFRARED SPACE OBSERVATORY

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Abstract. The Infrared Space Observatory (ISO), a fully approved and funded project of the European Space Agency (ESA), is an astronomical satellite, which will operate at wavelengths from 3–200μm. ISO will provide astronomers with a unique facility of unprecedented sensitivity for a detailed exploration of the universe ranging from objects in the solar system right out to distant extragalactic sources. The satellite essentially consists of a large cryostat containing at launch about 2300 litres of superfluid helium to maintain the Ritchey-Chrétien telescope, the scientific instruments and the optical baffles at temperatures between 2K and 8K. The telescope has a 60-cm diameter primary mirror and is diffraction-limited at a wavelength of 5μm. A pointing accuracy of a few arc seconds is provided by a three-axis-stabilisation system consisting of reaction wheels, gyros and optical sensors. ISO's instrument complement consists of four instruments, namely: a photo-polarimeter (3–200μm), a camera (3–17μm), a short wavelength spectrometer (3–45μm) and a long wavelength spectrometer (45–180μm). These instruments are being built by international consortia of scientific institutes and will be delivered to ESA for in-orbit operations. ISO will be launched in 1993 by an Ariane 4 into an elliptical orbit (apogee 70000km and perigee 1000km) and will be operational for at least 18 months. In keeping with ISO's role as an observatory, two-thirds of its observing time will be made available to the european and american astronomical community.

1. Introduction

The Infrared Space Observatory (ISO) is a fully approved mission, currently under development by the European Space Agency. ISO was selected in 1983, just as the first data sent by the IRAS satellite was reaching the earth. IRAS has demonstrated the great advantage of space cryogenic missions for infrared astronomy: by getting rid of the absorption and emission of the earth atmosphere, and by limiting the emission from the telescope and the instruments, cooled down to superfluid helium temperature, it becomes possible to explore the infrared universe in unprecedented ways. Throughout its 10 months lifetime, IRAS has surveyed the whole sky in four wide bands around 12, 25, 60 and 100 μm. IRAS has revealed the richness of the infrared sky, and shown the relevance of infrared observations for the study of virtually all branches of astrophysics, from comets and interplanetary phenomena to galaxies and cosmology. Many unexpected discoveries were made : cometary trails, dust disks around main sequence stars, large number of bright IR stars in the galactic bulge, diffuse emission of the interstellar medium at 12 and 25 μm, ultrabright

Y. Kondo (ed.), Observatories in Earth Orbit and Beyond, 205–214.

infrared galaxies... Exciting as they are, the IRAS results suffer from many limitations , which most often make it difficult to interpret them unambiguously through physical models. We are left wondering about the emissivities of IRAS sources in the wavelength ranges outside the IRAS bands ; we would like to know in more detail the spatial and spectral distribution of the radiation, in some cases its degree of polarization ; and of course we would welcome an increment in sensitivity to be able to detect remote bright sources , such as far away starburst galaxies, and to explore better the realm of intrinsically faint sources, such as brown dwarfs.

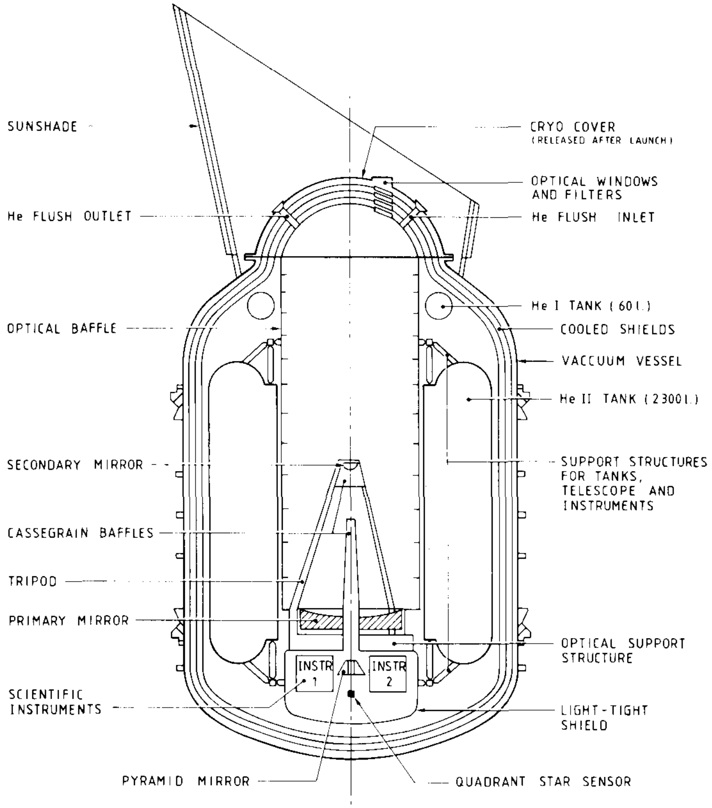
Hence the necessity of a versatile mission such as the Infrared Space Observatory, with a wider wavelength coverage (2.5 to 200 μm), improved angular resolution (by a factor of about 10), and enhanced sensitivity (by 2 to 3 orders of magnitude), a variety of spectral resolutions and polarimetric capabilities. With ISO, it will be possible for the first time to image the infrared sky from space with array detectors at various spatial resolutions, and to draw medium ($\Delta\lambda/\lambda \sim 200$ to 1000) and high resolution ($\Delta\lambda/\lambda \sim 10^4$ to 3.10^4) spectra over the entire range 3 μm to 180 μm. ISO will help to elucidate many of the problems revealed by IRAS, and the potential for discovery is clearly high as well.

2. Satellite and mission design

The satellite, consisting of a payload module and a service module, is 5.3 m high, 2.3 m wide and will weigh around 2400 kg at launch. The basic spacecraft functions are provided by the service module. These include the structure and the load path to the launcher, the solar array mounted on the sunshield, and sub-systems for thermal control, data handling, power conditioning, telemetry and telecommand (using two antennas), and attitude and orbit control. The last provides the three-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, reaction wheels and uses a hydrazine reaction control system. The nominal down-link bit rate is 33 kbps of which about 24 kbps are dedicated to the scientific instruments.

The payload module (Figure 1) is essentially a large cryostat. Inside the vacuum vessel is a toroidal tank filled with about 2300 litres of superfluid helium, which will provide an in-orbit lifetime of at least 18 months. Some of the infrared detectors are directly coupled to this helium tank and are at a temperature of around 2 K. Apart from these, all other units are cooled using the cold boil-off gas from the liquid helium. This gas is first routed through the optical support structure, where it cools the telescope and the scientific instruments to temperatures of 3–4 K. It is then passed along the baffles and radiation shields before being vented to space. A small auxiliary tank, containing about 60 litres of normal liquid helium, fulfills all of ISO's cooling needs for the last 72 hours before launch. Mounted on the outside of the vacuum vessel is a sunshield, which prevents the sun from shining directly on the cryostat. The solar cells are carried by this sunshield.

Suspended in the middle of the main helium tank is the telescope, which has a Ritchey-Chrétien configuration with an effective aperture of 60 cm and an overall f/ratio of 15. A weight-relieved fused-silica primary mirror and a solid fused-silica



Schematic Diagram of Payload Module.

Fig. 1.

secondary mirror have been selected as the telescope optics. The optical quality of these mirrors is adequate for diffraction-limited performance at a wavelength of 5 μm. Stringent control of stray light, particularly from bright infrared sources outside the telescope's field of view, is necessary in order to ensure that the system sensitivity is not degraded. This control is accomplished by imposition of viewing constraints and by means of the sunshade, the cassegrain and main baffles, and an additional light-tight shield around the instruments.

The scientific instruments are mounted on the opposite side of the optical support structure to the primary mirror, each one occupying an 80° segment of the cylindrical volume available. The 20 arc minute total unvignetted field of view of the telescope is split up between the four instruments by a pyramidal mirror. Thus, each instrument simultaneously receives a 3 arc minute unvignetted field centred on an axis at an angle of 8.5 arc minutes to the telescope optical axis. To view the same target with different instruments, the satellite has to be repointed.

An Ariane-4 vehicle will launch ISO into a transfer orbit with a perigee height of around 200 km and an apogee height of around 70000 km. ISO's hydrazine reaction control system will then be used to raise the perigee to attain the operational orbit (24-hour period, perigee 1000 km and apogee 70000 km). The inclination to the equator will be between 5° and 20° (to be finalised later). ESA plans to supply only one ground station, enabling ISO to make astronomical observations during the best 14 hours of each orbit. The mission's scientific return, however, could be greatly increased by the addition of a second ground station, which would permit ISO to be operated for the entire time that it spends outside the main part of the Earth's radiation belts. An international collaboration is being sought by ESA to provide this second ground station.

3. Scientific instruments

The ISO scientific payload consists of four instruments which, although being developed separately, have been designed as a package to offer complementary facilities to the observers. Each instrument is being built by a consortium of scientific institutes using national non-ESA funding and will be delivered to ESA for in-orbit operation. Details of the individual instruments and of their capabilities are given in Table I. The four instruments view different adjacent patches of the sky, but, in principle, only one will be operational at a time. However, when the camera is not the prime instrument, it can be operated in a so-called parallel mode, either to gather additional astronomical data or to assist another instrument in acquiring and tracking its target. In order to maximise the scientific return of the mission, the ISOPHOT instrument will be operated during as many satellite slews as possible so as to make a partial sky survey at a wavelength of 200 μm, a region not explored by IRAS.

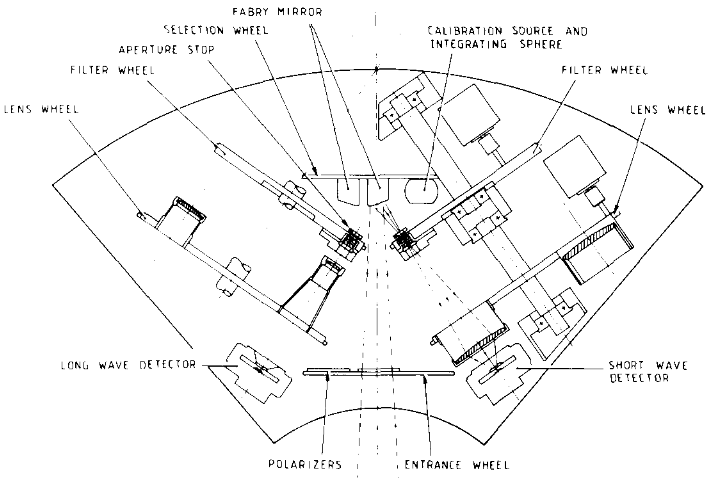
The ISOCAM (Figure 2) instrument[1] consists of two optical channels, each with a 32×32 element detector array, operating in the wavelength ranges 2.5–5.5 μm and 4–17 μm. The short wavelength array uses an InSb detector with a CID readout and the long wavelength detector is made of Si:Ga with a direct read out (DRO). Each channel contains a wheel for selecting various filters (including circular variable filters, CVF with a resolution of 45) and a second wheel for choosing a pixel field of view of 1.5, 3, 6, or 12 arc secs. Polarisers are mounted on an entrance wheel common to both channels. A sixth wheel carries mirrors for selecting between the channels, of which only one is operational at a time.

The LWS (Figure 3) instrument[2] consists of a reflection diffraction grating used in 1st and 2nd order with an array of 10 discrete detectors to provide a spectral resolving power of $\sim$200 over the wavelength range from 45 μmto 180 μm. The detectors are made of Ge:Be (to be confirmed) and Ge:Ga (stressed and unstressed) material. Two Fabry-Pérot interferometers are mounted in a wheel and either can be rotated into the beam to increase the resolving power to $\sim10^4$ across the entire wavelength range.

The SWS (Figure 4) instrument[3] provides a resolving power of between 1000 and 2000 across the wavelength range from 2.4 μmto 45 μmby means of two reflec-

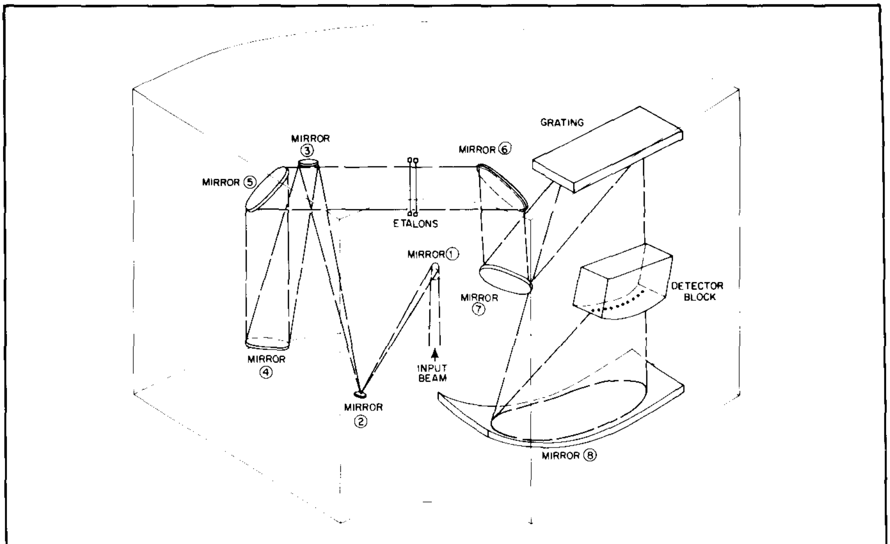
TABLE I
Characteristics of the Instruments

Instrument and Principal Investigator	Main Function	Wavelength (Microns)	Spectral Resolution	Spatial Resolution	Outline Description
ISOCAM (C. Cesarsky, CEN-Saclay, F)	Camera and Polarimetry	3 - 17	Broad-band, Narrow-band, and Circular Variable Filters	Pixel f.o.v.'s of 1.5, 3, 6 and 12 arc seconds	Two channels each with a 32x32 element detector array
ISOPHOT (D. Lemke, MPI für Astronomie, Heidelberg, D)	Imaging Photo-polarimeter	3 - 200	Broad-band and Narrow-band Filters. Near IR Grating Spectrometer with R=100	Variable from diffraction - limited to wide beam	· sub-systems: i) Multi-band, Multi-aperture photo-polarimeter (3-110 μm) ii) Far-Infrared Camera (30-200 μm) iii) Spectrophotometer (2.5-12 μm)
SWS (Th. de Graauw, Lab. for Space Research, Groningen, NL	Short-wavelength Spectrometer	3 - 45	1000 across wavelength range and $3x10^4$ from 15 - 30 μm	7.5x20 and 12x30 arc seconds	Two gratings and two Fabry-Pérot Interferometers
LWS (P. Clegg, Queen Mary College, London, GB)	Long-wavelength Spectrometer	45-180	200 and 10^4 across wave-length range	1.65 arc minutes	Grating and two Fabry-Pérot Interferometers



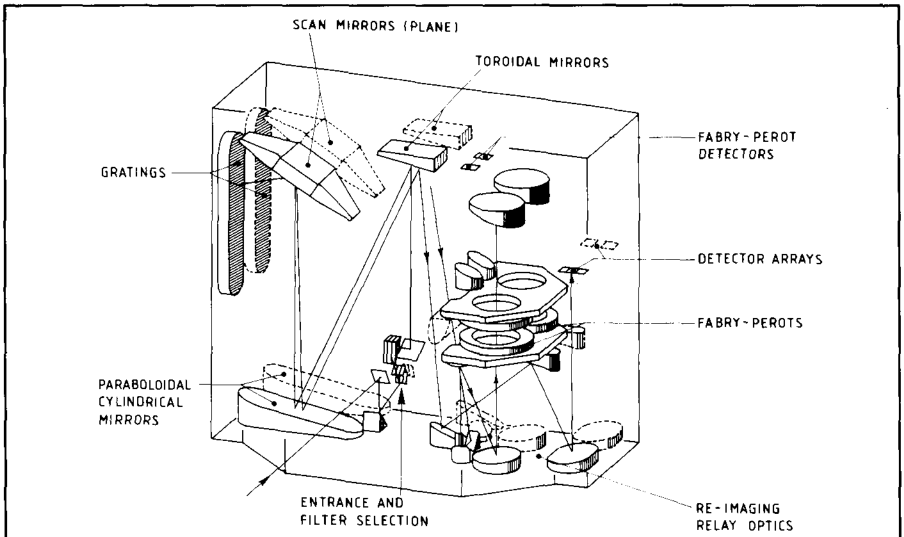
Schematic View of ISOCAM.

Fig. 2.



Schematic View of LWS.

Fig. 3.



Schematic View of SWS.

Fig. 4.

https://doi.org/10.1017/S0252921100077046 Published online by Cambridge University Press

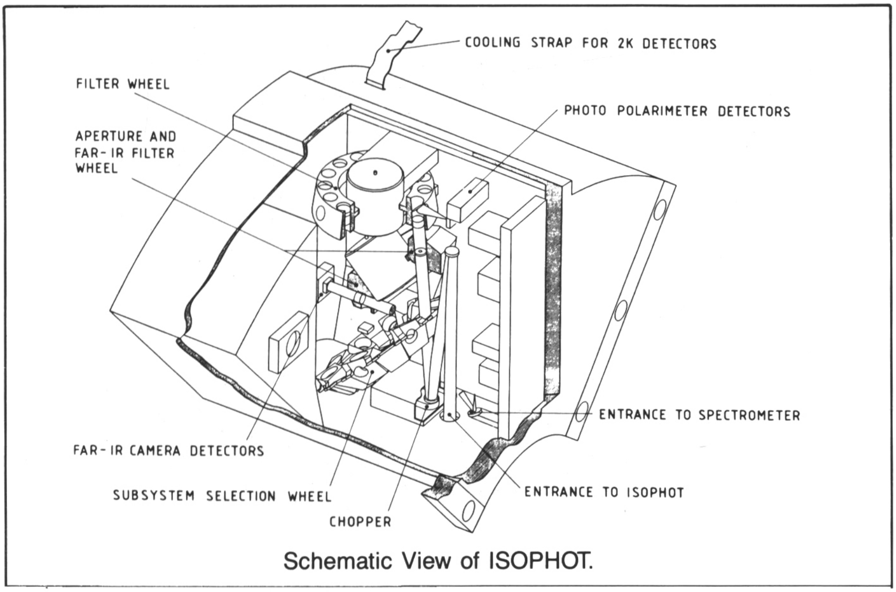


Fig. 5.

tion diffraction gratings used in 1st, 2nd and 3rd orders. Filters for order-sorting are placed at the instrument's various entrance apertures. Detectors made from InSb, Si:Ga, Si:P and Ge:Ga material are used. Over a part (14–30 μm) of the SWS's operating range, the resolution can be increased to $\sim$2 x 10^4 by directing the incident radiation through either of two Fabry-Pérot interferometers.

The ISOPHOT (Figure 5) instrument[5] consists of three sub-systems:

– ISOPHOT-C: a photopolarimeter which also provides imaging capability at close to the diffraction limit in the wavelength range from 40 μmto 200 μm.

– ISOPHOT-P: a multi-band, multi-aperture photopolarimeter for the wavelength range from 30 μmto 110 μm.

– ISOPHOT-S: a dual grating spectrophotometer which provides a resolving power of $\sim$90 in two wavelength bands simultaneously (2.5–5 μmand 6–12 μm)

A focal plane chopper with a beam throw of up to 3′ is also included in ISOPHOT. Selection between the different modes of the various sub-systems is achieved with appropriate setting of three ratchet wheels. ISOPHOT contains several types of infrared detectors made of Si:Ga and Ge:Ga (stressed and unstressed). These detectors are read out by specially designed cryogenic electronics, which exists in both multiplexed and 'un-multiplexed' versions.

4. Observing time

The two thirds of ISO's observing time will be available to the scientific community via the submission and selection (by peer review) of proposals. In addition to this *Open Time*, there will also be *Guaranteed Time* for the groups who provide the instruments, for the five Mission Scientists (T.Encrenaz, H.Habing, M.Harwit,

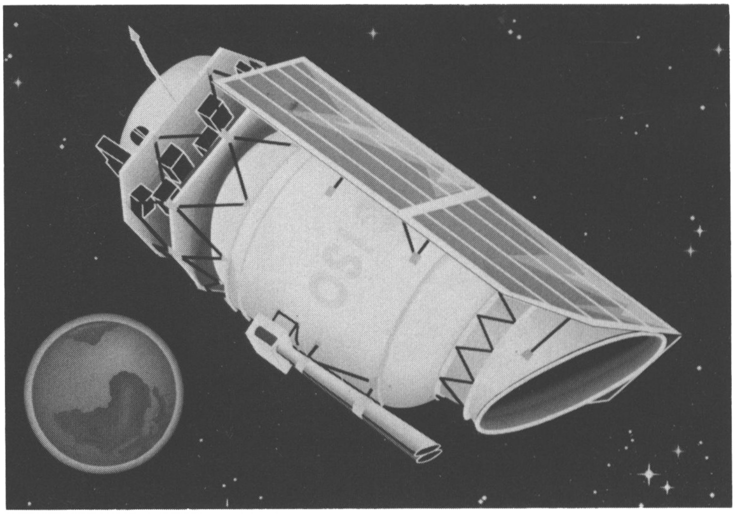


Fig. 6.

A.Moorwood, J.L.Puget) and for the Observatory Team, who will be responsible for all scientific operations. The division of time between these two categories will vary as the mission progresses. After launch, it is anticipated that there will be a period of up to 8 weeks during which the operational orbit will be attained, the spacecraft sub-systems switched on and checked out and the scientific performance of the instruments established. Following this, there will be a 1-month period, consisting of 50% *open time* and 50% *guaranteed time*, during which astronomical observations, designated by the *Observing Time Allocation Committee* as being of the highest priority, will be carried out. For the rest of the mission (at least 15 months), 65% of the time will be *open time*.

The programme to be carried on during the guaranteed time is currently being defined by the instrument groups, the mission scientists and the ESA Project Scientist (M. Kessler). It will include a number of fundamental obervations which may require long observing times, but which are indispensable outputs of a mission such as ISO. For example, complete spectra of a number of bright objects will be drawn over the whole range available to ISO ; these will allow to explore unknown wavelength domains and will be used as templates for more reduced observations of fainter sources. Low resolution spectra of the diffuse interstellar medium at wavelength below 15 μmwill be obtained with the ISOCAM CVF and/or with ISOPHOT-S; in this way, it will be possible to test the hypothesis that this emission is due to the same kind of very small grains or large molecules (possibly polyaromatic hydrocarbons) that emit bright "unidentified" lines in reflexion or planetary nebulae. Star formation regions will be mapped with various ISOCAM filters and in fine structure lines (CII and OI) with the long wavelength spectrometer, to study both star formation processes, and the structure of molecular clouds. The distribution of the main constituents of comets will be determined, and the deuterium abundance of Uranus and Neptune will be measured precisely, with the

https://doi.org/10.1017/S0252921100077046 Published online by Cambridge University Press

consequent cosmogonical implications. There will be a variety of programmes on normal galaxies, studying the dust in them through their far infrared emission, the distribution and excitation of very small grains and PAH, molecules wich emit mid infrared photons, the cooling of the gas through the emission of far IR fine structure lines, the chemical abundances, the regions of star formation, the nuclei at various wavelengths... Also, ISOCAM and ISOPHOT will perform deep surveys in chosen regions of the sky, devoid of cirrus. In this way, discoveries will be made or at least meaningful limits will be established on the number of bright, perhaps interacting, galaxies in the past, and of brown dwarfs in the solar neighborhood.

The first *Call for Observing Proposals* will be issued 18 months before launch. It will contain details of expected instrument performances and the program for the guaranteed time, and will solicit proposals for observations to be carried out in the period from 3 to 10 months after launch. Due to the large number of observations expected to be proposed for ISO, the proposal-handling system will be automated as much as is feasible. Thus, proposals will be submitted electronically. Observing time on ISO will be allocated on a "per object" basis, as was the case for EXOSAT, rather than on a "per shift" basis as is done with IUE. In order that the best use can be made of ISO's limited lifetime, there will be a review of the implementation of the observing programme about 5 months after launch; if actual instrument performances differ from those predicted, the *Observing Time Allocation Committee* will recommend suitable adjustments to the programme.

5. Operations

The in-orbit operations of the spacecraft and instruments will be carried out by a team of scientists and engineers located at the ISO Control Centre in Villafranca near Madrid, Spain. This site is currently used by the IUE Observatory. During scientific use, the satellite will always be in real-time contact with the ground segment; however, ISO will be operated according to a detailed, pre-planned schedule in order to maximise the overall efficiency of the mission.

Examination of the scientific data will be carried out both on- and off-line. In close to real-time, a "quick-look" output, adequate for an initial estimate of the success or failure of an observation will be available to the Resident Astronomer and Guest Observer (if present). A final product with more detailed data reduction and calibration will be supplied later; the goal is within a few days. This product will be the one with which observers make their astronomical analyses.

6. Present status

ISO results from a mission proposal submitted to ESA in 1979. After a feasibility study (phase A) in 1981-82, it was selected in March 1983 to be the next new start in the ESA Scientific Programme. The definition study (phase B) for the ISO spacecraft was successfully completed early in 1988. The detailed design, development, integration and test phase (C/D) was started on the 15th of March 1988 by an industrial contsortium led by Aerospatiale (F).

The activities are now centered on finalizing the development of the first model of the satellite, the structural-thermal model. The Service Module STM has undergone static load tests and vibration tests; ground lifetime tests are in progress. The thermal behaviour of the Payload Module STM is under investigation, and the telescope is being tested as well. The primary mirror for the flight model has been polished already.

The scientific instruments were selected in mid-1985. Their development is well advanced with the first models, the alignment and mass/thermal dummies, having been delivered to ESA in 1989. The integration and tests of the engineering qualification models, which are very similar to the eventual flight units, is well advanced for a delivery to ESA in the summer of 1990.

The implementation of the ground segment is progressing as well. It is worth noting that ESA has recently signed a contract with Arianespace, for an ISO launch in mid 1993.

7. Conclusions

ISO is a fully-approved and funded mission, which will offer astronomers unique and unprecedented observing opportunities at infrared wavelengths from 2.5–200 μm for a period of at least 18 months. Two thirds of the observatory's time will be available to the european and american astronomical community. Both the spacecraft and its selected complement of instruments are in their main development phase and the scheduled launch date is May 1993.

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