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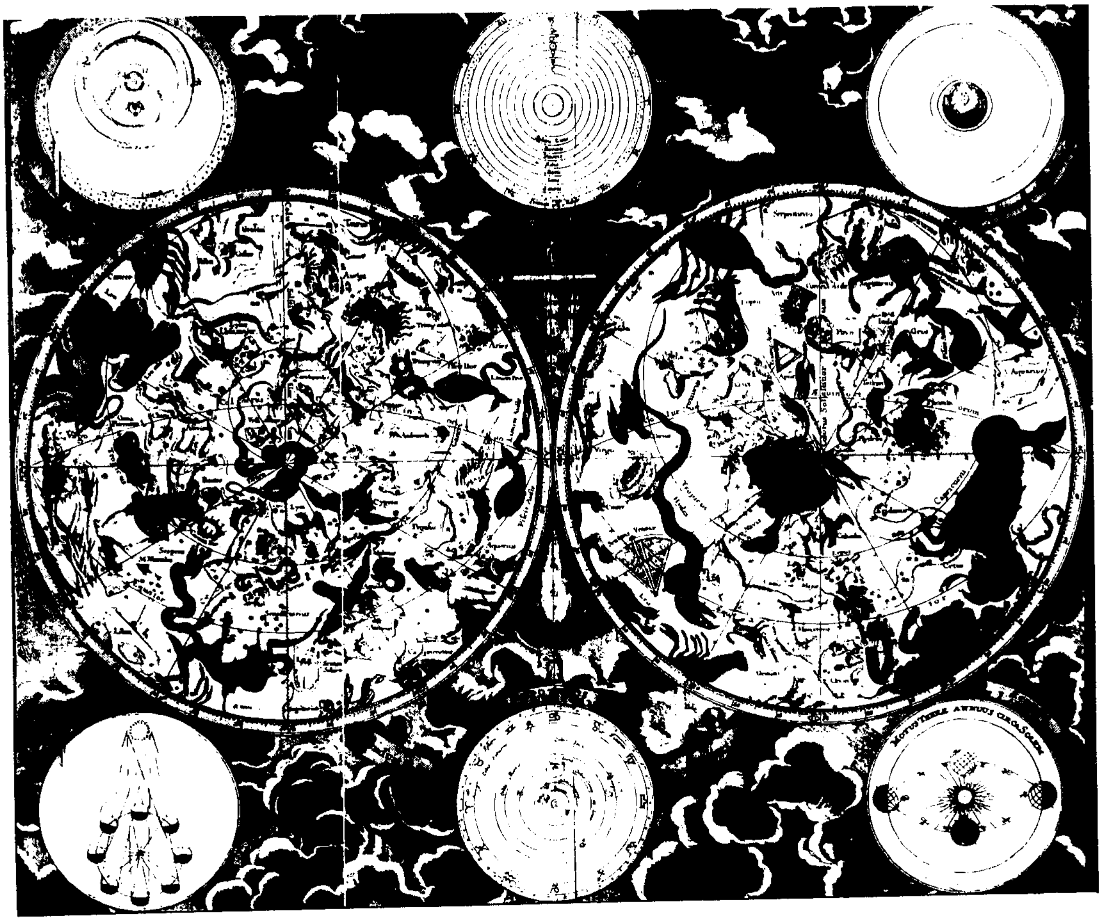
INFRARED SPACE OBSERVATORY

(ISO)

ASSESSMENT STUDY



FOREWORD

A proposal for an Infrared Space Observatory (ISO) was submitted to ESA in response to an announcement of a new planning cycle issued in November 1978.

The original proposal, made by van Duinen (NL), Courtin (F), Fitton (ESA), de Graauw (ESA), Harries (UK), Jennings (UK), Joseph (UK), Künzi (CH), Magun (CH), Moorwood (ESO), Salinari (I) and Wrixon (Eire), called for a 1 m cryogenically cooled telescope containing focal plane instruments for infrared and sub-millimeter heterodyne astronomy and possibly atmospheric research.

After evaluation of all the proposals received in response to the above-mentioned announcement, the Astronomy Working Group (AWG) recommended this proposal for an assessment study. This recommendation was subsequently endorsed by the Science Advisory Committee (SAC).

The present document is the result of this assessment study which was carried out by a science team, in close collaboration with engineers from the Future Projects Studies Office and coordinated by the AWG Secretary.

The members of the science team were:

R.J. van Duinen	Department of Space Research, Groningen (NL)
R.D. Joseph	Imperial College, London (UK)
G. Klipping	Fritz-Haber-Institut, Berlin (D)
A. Moorwood	European Southern Observatory, Geneva (CH)
F. Sybille	Observatoire de Lyon (F).

In addition, J. Beckman (UK), M. Grewing (D), R. Hoffmann (D), R.E. Jennings (UK), P. Léna (F) and P. Salinari (I), participated in various meetings and studies.

ESA personnel involved in this study included:

B. Fitton	Space Science Department
R.A. Lainé	Future Projects Studies Office
H. Olthof	AWG Secretary
M. Penston	IUE Observatory Controller.

The original concept of ISO as an observatory open to proposals from the science community for infrared observations has been retained. However, two important changes have had to be made as a result of a critical assessment of systems engineering requirements in this Phase. First the telescope diameter has had to be reduced to 60 cms in order to ensure that the mass of the spacecraft lies well within the Ariane capability and that the associated cost of the spacecraft is kept within the bounds of feasibility for ESA. This action immediately threw open to question the wisdom of attempting to accommodate a submillimetreheterodyne receiver as originally proposed. It was finally decided to abandon this idea since the angular resolution at submillimetre wavelengths was now so low as to be of very limited value whilst at the same time the heterodyne system was placing large demands on the power requirements together with an appreciable mass and some design complexity.

The second important change in this Phase has been the decision to abandon any attempt to include atmospheric studies in the infrared with ISO. This possibility of carrying out atmospheric studies with ISO was originally intended to be a secondary but attractive possibility for consideration.

However, an analysis of the thermal, instrumental and orbital requirements have showed that an IR astronomy and IR atmospheric science mission are incompatible. Attempting to combine the two simply leads to greatly increased complexity in the telescope and instrumentation, and hence in the mission cost. It will also lead to a very much shorter mission duration due to the very large thermal loading from the earth's atmosphere.

ISO is now dedicated to infrared astronomy and designed with the intention that it shall be used in the main as a guest observer facility. The changes that have been made in this Assessment Phase have simplified the concepts and give confidence that a Phase A definition could be embarked upon in 1980. However, ISO does differ from most spacecraft. The difference lies in the fact that it is the heat input from the scientific instrumentation which can constitute a significant part of the total heat input to the superfluid helium. This in turn determines the total quantity of cryogen required for a given mission lifetime and hence the sizing of the cryogen tank and the outer pressure vessel which together are the major mass elements in the total spacecraft. For this reason, it is considered essential that a detailed study of the scientific instrumentation together with some additional cryostat design activity, precede the Phase A definition of the total spacecraft system starting in 1980.

Requests for further information or for additional copies of this report should be addressed to:

Dr. H. Olthof
Scientific Programme Directorate
European Space Agency
8-10, rue Mario Nikis
75738 Paris Cedex 15
France

INFRARED SPACE OBSERVATORY

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1. EXECUTIVE SUMMARY

The rapid advances made in infrared astronomy in recent years have provided major contributions to studies of a diverse range of astrophysical objects. These include observations ranging from extragalactic systems, large scale galactic structure, molecular clouds and star formation regions, HII regions and evolved stars, through to planetary atmospheres and cometary studies. These contributions have been made despite the severe limitations imposed on observations by atmospheric effects and thermal emission from uncooled optical systems. In order to reduce these limitations, IR telescopes have been used on board aircraft and balloons, but these measures have served only to relieve the immediate problem. Improvements in IR detectors for $\lambda < 150\ \mu$ lead now to a situation where only by cooling a telescope, to around 20 K and placing it outside the Earth's atmosphere can the technological advantages be fully exploited to provide an increase in IR astronomy sensitivity of several orders of magnitude.

The 1980's will see infrared astronomy step across this atmospheric barrier with the introduction of IR space missions, and the impact of that transition will doubtless be of the same order as was made when UV and X-ray astronomy took that same step. First IRAS will carry out a survey of the IR sky in four wavelength bands; then GIRL will be used to perform initial spectroscopic studies from Spacelab. ISO is proposed now, to closely follow-up and exploit these earlier missions. It will provide high resolution spectroscopic studies, for which IRAS is not equipped, and photometric measurements at sensitivity levels, approaching the natural limit set by the zodiacal light background and with an angular resolution somewhat better than that of GIRL and IRAS. The planned ISO mission lifetime of $1\frac{1}{2}$ years will enable it to be used for the study of a whole range of astrophysical objects at an unequalled sensitivity.

ISO comprises a cooled 60 cms diameter telescope in a 3-axis stabilized spacecraft which can be pointed within a 6 arcsec accuracy. The telescope and scientific instruments are cooled by helium gas from a cryostat containing initially $\sim$ 135 kg of superfluid helium. A number of instruments can be accommodated, consistent with the concept of an IR astronomy observatory. A model payload has been considered, which consists of a near IR imaging camera ($1-5\mu$), a dual range single drive Michelson interferometer of high resolution ($\lambda/\Delta\lambda \leq 10^5$, $2 - 25\ \mu$), and a four band photometer/polarimeter system (10 to 150 μ).

The choice of a cryogenic telescope ($T \sim 20^{\circ}K$), in preference to an uncooled telescope, and the decision to concentrate on the wavelength range below 150μ arises by considering three main factors. (i) The scientific interest in this wavelength regime, which is particularly rich in molecular, atomic, ionic and solid state transitions, a study of which provides insights into a whole range of astrophysical phenomena. (ii) The recognition that, in the ST era, extragalactic studies are likely to have particular prominence, (iii) The recent developments in IR photoconductor detector technology which have led to an improvement of at least two orders of magnitude in detector performance for $\lambda < 150\ \mu$ compared to the bolometer detectors which are used for $\lambda > 150\ \mu$. The situation now is that a space infrared telescope cooled to $T \sim 20^{\circ}K$ and coupled to modern photoconductor detectors will give a sensitivity which is approaching the limit set by the zodiacal light background. This would, for example, mean that for the photometry of normal galaxies, having no IR excess, the photometric sensitivity would be comparable to that of existing optical photographic sky surveys. This enormous gain in sensitivity has occurred at the same time as the technology has provided two dimensional detector arrays which will allow imaging in the near infrared ($1 - 5\ \mu$) at the same high sensitivity.

ISO is planned as an observatory, operating as far as possible in real-time, and is intended to be used in a similar way to IUE by astronomers whose observing proposals have been accepted by an ESA Selection Committee. It will differ from IUE in two respects. First, the scientific payload will be designed and built by national groups. Consequently, an initial phase lasting about 3 months will be required not only for commissioning the spacecraft and instruments but also to provide an immediate return to those groups who have contributed to this hardware development. Some P.I. group involvement in operations will also be essential during the remainder of the mission lifetime in order to ensure efficient operation of the instrument and will require a concomitant assignment of observing time. The second difference from IUE results from the use of a 12 hour orbit, requiring two ground stations, a prime and a slave station.

It follows from the observatory concept for ISO that proposals from the scientific community for its use can be expected to cover a very wide range of scientific subject areas. IUE has clearly illustrated the benefits which accrue from such a concept. Of the many possible scientific areas where ISO will have an important impact, the field of extragalactic astronomy is expected to be one of particular importance. Conservative estimates of the number of galaxies to be detected by IRAS suggest a figure of at least 40,000. The fact that ISO will be able to integrate on weak sources for extended periods if necessary, means that it will in practice achieve sensitivity, and hence distance, limits well beyond those of IRAS. This will be particularly valuable to such extragalactic observations. The classification, total luminosity and continuum energy distribution measurements, together with mapping of galaxies, will be basic ISO photometric measurements, as will studies of time variations in active galacies. Mapping of recombination and fine structure lines at high spectral resolution will be used to observe the gas motion on a galactic scale and to carry out detailed studies of star formation regions in nearby spiral galaxies. Near infrared spectroscopy will provide information on interstellar grain distributions and composition variations, whilst H_2 emission line studies in the near IR can delineate shock fronts in the regions of star formation and their role as a triggering mechanism for molecular cloud collapse. In the same spectral region, observations of the CO and H_2O bands can give information on stellar populations in elliptical galaxies and provide indications of possible evolutionary effects as a function of redshift. Line excitation and broadening effects, together with observations of transient phenomena, will be particularly valuable tools in studying the energetic process in active galaxies. Apart from these basic observations more speculative studies are likely, such as an attempt to detect the stellar molecular features of H_2O and CO in QSO's and the possible associations of cool low mass stars with haloes around spiral galaxies.

ISO also has the potential to make significant contributions to cosmology due to its very high sensitivity, which will allow deep surveys in the near infrared for primaeval galaxies ($Z \sim 1 - 10$). Integration times of a few minutes would suffice for such work. Using ISO photometry data, together with observations at other wavelengths, it may be possible to define classes of standard IR galaxies and to study evolutionary effects through observations at various redshifts. Such data could also be used to perform classical cosmological tests, for example source counts or red-shift-magnitude measurements.

In galactic astronomy, one major interest is likely to be in star formation processes, requiring photometric and spectroscopic studies of regions in and about molecular clouds. Spectroscopic studies of more evolved objects such as HII regions, cocoon stars and planetary nebulae are certain to be of importance, together with photometric studies to try to indentify planetary system formation in young stellar objects. Clearly, observations with ISO can be expected to make a substantial impact in most fields of astrophysics.

ISO has no directly equivalent mission competitor. IRAS, to be launched 1981/82, is designed as a survey system and will spend roughly 70% of its expected $1\frac{1}{4}$ year lifetime completing a thorough survey of the IR sky. The remainder of the time may be assigned to a pointing mode for detailed photometric work and very low resolution (∿20) spectroscopy.

A comparable sized IR cryogenic telescope system of 85 cm diameter, designated SIRT-F, is under active study by NASA and a smaller (45 cm) cooled telescope (GIRL) for astrophysics and aeronomy is being developed in Germany. But both of these are very short duration missions, intended for Spacelab flights. GIRL in particular, because of its early flight date, will be an important precursor to a spacecraft observatory, carrying out initial exploratory studies.

As already pointed out by the ESA scientific advisory groups, in the 1980's the future of European astronomy must depend mainly on large observatory class satellites if it is to remain competitive. ISO is in this class. The science that can be accomplished with such an observatory is outstanding and its development in Europe will further ensure that Europe remains in the forefront of future astrophysics research.

2. INTRODUCTION TO ISO

The atmosphere of the earth is opaque through most of the ten octaves of the infrared electromagnetic spectrum from 1μ to 1 mm wavelength. There are several narrow 'windows' of varying degrees of transparency at the shorter wavelengths, but in general atmospheric absorption and emission place very severe constraints on both the wavelength range and the sensitivity of ground based infrared astronomy measurements. At airplane and balloon altitudes the atmospheric transmission is improved, allowing a greater wavelength coverage. Observations are however still limited by the remnant atmosphere, since the dominant noise source arises from the large fluctuations in its thermal emission. In consequence, it is not possible to take full advantage of the new generation of very high sensitivity IR photoconductor detectors which are becoming available for wavelengths less than ∿ 150μ.

The crucial step into space, which removes the restrictions imposed by the atmosphere, will be taken first by IRAS, which will be launched into orbit in 1981/82. This mission will provide a 4 channel survey of the IR sky at a sensitivity level comparable to that obtained in the radio regime. This improvement by several orders of magnitude in sensitivity over present IR observations depends first on removing the effects of the atmosphere but it also requires the cooling of the telescope and the instruments to liquid helium temperatures. Cooling reduces the thermal emission from the optics system, which is the other main noise source, thereby allowing observations to be carried out under essentially detector noise limited conditions with the high sensitivity detectors. ISO is proposed to follow IRAS in exploiting the space environment and it too will utilize a helium cooled telescope. It will be able to provide spectroscopic studies and detailed photometric measurements of both presently known sources and those detected by IRAS, with the same or better sensitivity than IRAS.

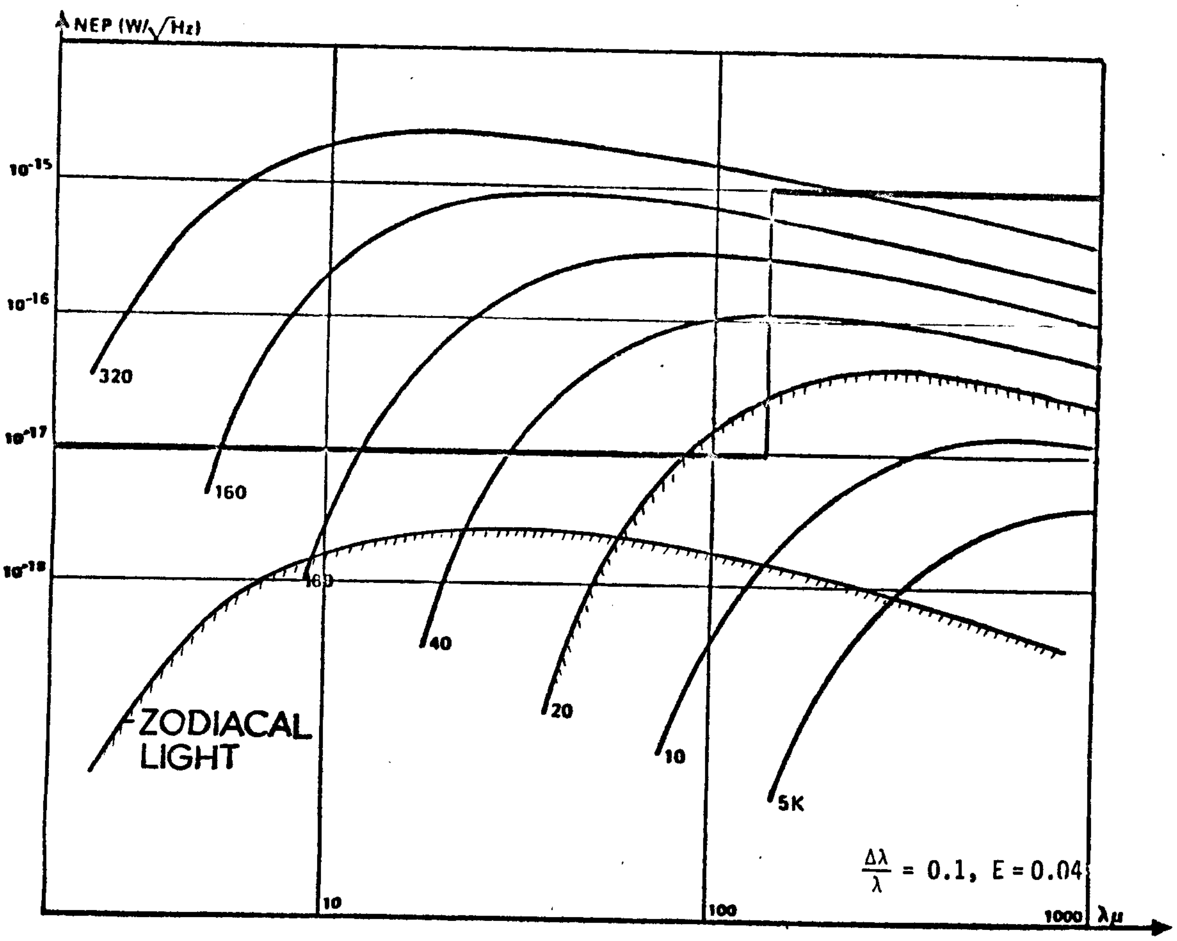


FIGURE 1. Background noise equivalent power of a diffraction limited telescope as a function of the mirror temperature.

Figure 1 gives an indication of the sort of improvement in sensitivity to be gained by the removal of atmospheric effects and cooling a telescope. For this illustration a 10% spectral bandwidth is considered and a 4% emissivity assumed for the telescope. It is clear that the noise due to thermal emission from a telescope at ∿300K, as is used presently on the ground or at airplane altitudes, is consistent with the detectors commonly used which operate with NEP's of ∿ 10^{-15}W/$\sqrt{\text{Hz}}$. This equivalent noise level is of course further degraded by the atmospheric noise. Removing the atmospheric effects and cooling the telescope to 20°K permits the exploitation of existing advanced detectors which operate with NEP's of the order of 10^{-17}W/$\sqrt{\text{Hz}}$ for wavelengths below 150μ. This improvement in usable sensitivity, of at least two orders of magnitude, is the root of the developments which will follow as IR astronomy enters its space era.

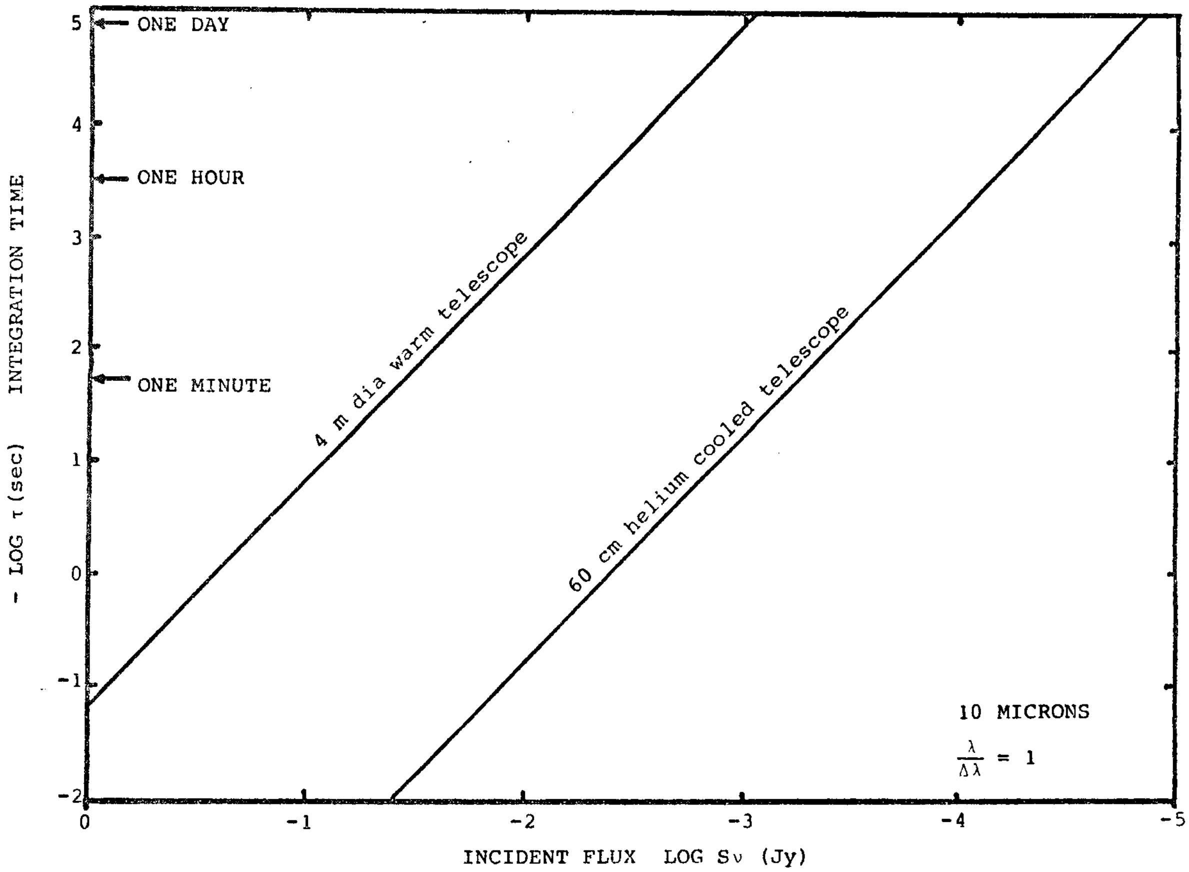


FIGURE 2

Another way of looking at this gain in sensitivity is in terms of observation times, as illustrated in Figure 2. The integration times required to reach a signal-to-noise ratio of 5 on a source of a given flux density, for photometry at 10μ, are compared for a 4 m ground-based (warm) telescope, which is background limited, and a 60 cm cooled telescope in space with the advanced detectors as proposed for ISO. We see that it would require a day to detect a weak source of 1 mJy using a large ground-based telescope (if integration times of this duration were possible), but that a small cooled space telescope can achieve this in a few seconds. A similar advantage is to be gained for spectroscopy as well as for photometry. The photon noise from a warm telescope decreases at best only as the square root of the infrared bandwidth, and so it is only when the spectral bandwidth $\Delta\lambda/\lambda$ is reduced to the order of 10^{-5} that the spectroscopic sensitivity of a warm telescope can approach that of a cooled ISO type system. But the Michelson interferometer systems of ISO, whilst having a spectral *resolution* of $\sim 10^{-5}$, have a very large spectral *bandwidth*. This large bandwidth of the ISO Michelson allows for the extraction and encoding of spectral information from all resolution elements simultaneously, thereby providing the enormous time advantage over the narrow bandwidth-warm telescope approach.

Clearly, the ISO mission provides the basis for a major advance for infrared astronomical spectroscopy and photometry, not only by eliminating the restrictions caused by the earth's atmosphere, but also through the vast gain in sensitivity/bandwidth that a cooled telescope makes possible.

While this breakthrough in sensitivity demonstrates the technical advantages of an infrared space observatory, the timeliness of such a mission is also very important. Infrared astronomy is still in its infancy, but it has already developed, both scientifically and technically, to the point that a dedicated space mission can now be fully justified. Scientifically, it is clear that infrared observations will play a critical role in studies of active galaxies, and of star-formation regions in our own galaxy. In the scientific objectives outlined below are presented a selection of some types of observations and astrophysics likely to be accomplished with ISO. Technically infrared astronomy has also reached a level of development that warrants investment in such a mission. As discussed earlier, IR detector sensitivity has recently improved by more than two orders of magnitude, so that for ISO the system noise would be very nearly equal to the fundamental limit set by the photon shot noise in the thermal emission of zodiacal dust particles, as indicated in Figure 1. Similarly, infrared spectroscopic techniques, of which Fourier transform spectroscopy is probably the most important, are now well understood and in routine and widespread use.

The timing of an infrared space observatory mission in the mid-1980's is also ideal in the context of space astronomy in general. With the launch of IRAS providing the first high sensitivity infrared all-sky survey, the next infrared space mission needed will be one to follow up with a detailed study of the host of new objects discovered. Clearly it should have a sensitivity and angular resolution, at least equal to IRAS and it must also be provided with a complement of instrumentation designed for these more refined studies. ISO meets these requirements. Two other space infrared projects are in the planning (SIRT-F) or development (GIRL) phase. Both of these use a cryogenic telescope of a size similar to that of ISO but they will be flown on Spacelab and are limited to flight durations of 7 to 30 days. The 1½ year mission of ISO has the enormous advantage that it will allow adquate time to fully utilize the gains that the space environment offers to observations in this wavelength range. The timing of the proposed ISO mission, its duration, its instrumentation complement and the observatory concept have each been considered with due cognizance of the Space Telescope era. The ST observations will undoubtedly have a significant bias toward extra-galactic objects and this fact is reflected in the wavelength range of ISO, where spectroscopy of highly red-shifted lines in the short wavelength range and photometry at high sensitivity in the 100μ region are foreseen as important complementary measurements to the ST observations.

3. SCIENTIFIC OBJECTIVES

3.1 Introduction

The freedom from atmospheric absorption and emission, the high sensitivity and unrestricted spectral range available to a cooled spaceborne infrared telescope, all provide capabilities for tackling a wide variety of astrophysical problems on well-known classes of celestial objects which are impossible to do without such a facility. However, this same capability also permits serious investigations of a more speculative type, such as looking for primeval galaxies. Because of the high sensitivity of ISO, measurements yielding results which are negative or upper limits will be of value. In the scientific objectives outlined below we have included some examples of various types of observations, in order to indicate not only how ISO may contribute to current astrophysics, but also how the inventory of astronomical objects and events may be altered by ISO observations.

It is difficult (and perhaps foolish) to attempt to forecast what types of observations will be most rewarding five years hence, but it seems very probable that extra-galactic observations will be the major focus of ISO. Thus we have chosen the ISO photometric bands to cover the spectrum well into the far-infrared (wavelengths out to 150μ), where much of the emission of galaxies appears. The spectroscopic instruments are designed to operate with high detection efficiency and spectral resolution in the 2-25 μ wavelength range, which is particularly rich in atomic, molecular, and solid-state features, as Figure 3 shows. However, these complementary instruments are also well suited for observations of star-formation regions in our galaxy - the luminosity lies in the far-infrared while most of the spectral information lies in the near- and middle-infrared. Thus the ISO instrument complement, comprising a photometer and a spectrometer, provides a capability for undertaking a very large range of possible infrared observations. In this sense it is truly an infrared observatory.

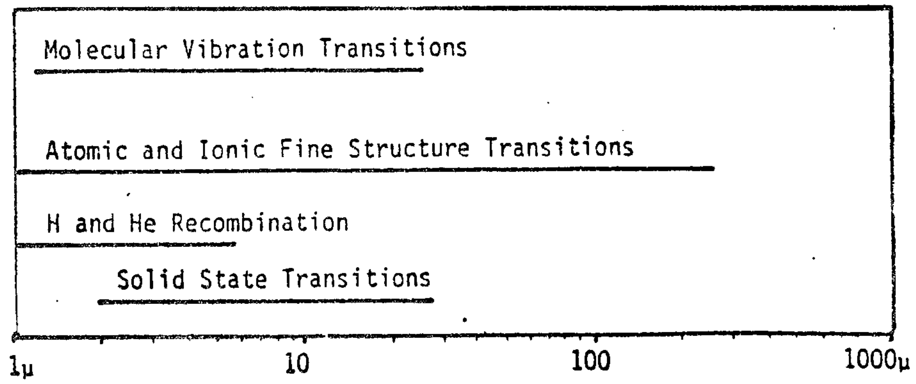


FIGURE 3 (a). Spectral regions where various transitions of astronomical interest are to be found.

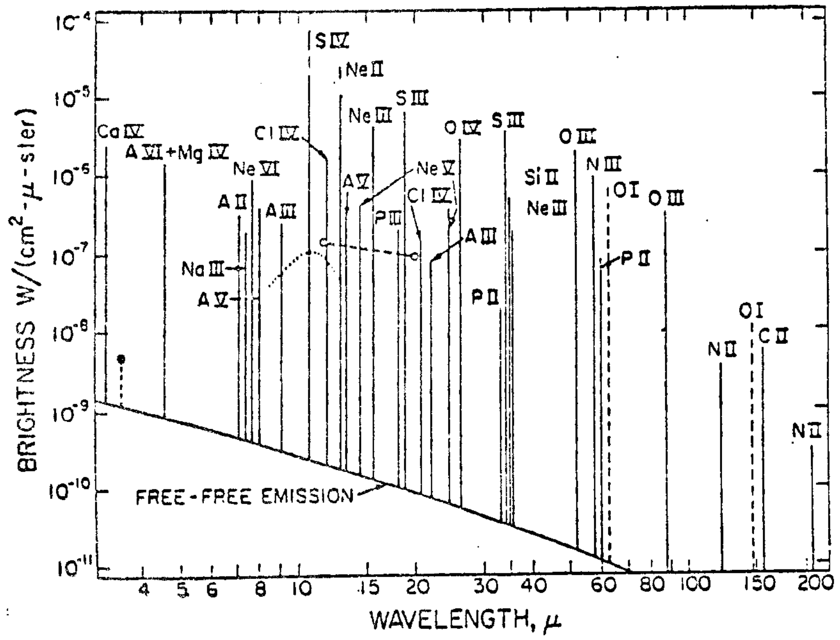


FIGURE 3 (b). Examples of the wide range of atomic and ionic fine-structure lines lying in the infrared. Those at wavelengths less than 30μ will be accessible to ISO. (After Petrosian, Ap. J. 159, 833 (1970)).

3.2 Extragalactic Objects

Perhaps the single most important result to emerge from infrared astronomy to date is the discovery that many different types of galaxies are powerful infrared sources. Strong infrared excesses, above the stellar continuum, seem to be the rule for most spiral galaxies. For a substantial fraction of them, such as our own galactic centre, the infrared luminosity is large and dominant. Interacting galaxies, such as M51, appear to be especially luminous in the infrared. Continuum spectra of several "normal" spiral galaxies are shown in Figure 4. For those galaxies detected in the far-infrared, the total luminosity is 10-50 times the 10μ luminosity.

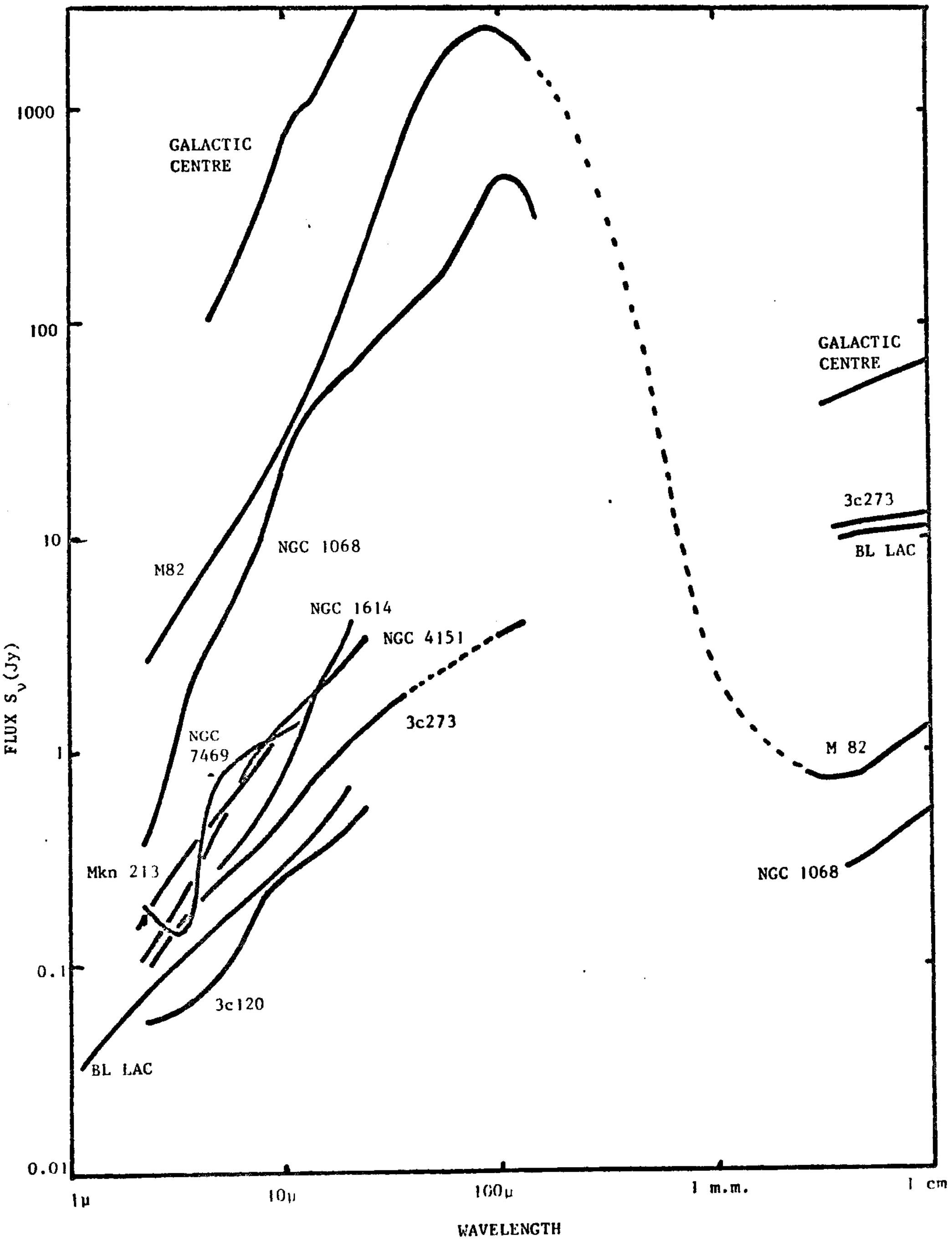


FIGURE 4. Representative spectra of various classes of extragalactic objects.

For most of these galaxies, stars are apparently the fundamental energy source, and the IR luminosity is due to re-radiated thermal emission from dust. However, the details of these processes are not at all clear, and the solutions of some problems posed by this tiny sample of observations raises fundamental questions. For example, quantitative and qualitative differences are found between extragalactic sources and galactic HII regions, despite the similarity of spectra. The mass/luminosity ratios of the nuclei detected in the far-IR range from 0.002 to 2. At the low end of this range it is difficult to reconcile the required stellar luminosity function with that thought to characterize star-formation processes. Models involving recent bursts of star formation have been invoked, but these in turn imply very substantial heavy element enrichment in the nuclei or else large mass outflows and replenishment with fresh un-processed material. Thus it is evident that a great deal of our understanding of the content and evolution of the nuclei of galaxies, interstellar chemical abundances, and the interaction between galaxies and inter-galactic gas, is dependent on much more extensive and detailed information on the infrared emission from nuclei of galaxies.

ISO presents some outstanding capabilities for infrared spectroscopy and photometry, which for 'active' galaxies can make a fundamental contribution towards understanding the enormous diversity of astrophysical phenomena operating in the giant radio galaxies, Seyfert galaxies, BL-Lac objects and QSO's. Although evolutionary or physical relationships between these groups of galaxies are still uncertain, there are suggestive similarities. Figure 4 suggests at least one common feature, that much of the enormous energy released in these objects appears via unknown emission processes in the middle or far-infrared.

Perhaps the potential scientific impact of ISO for extra-galactic astronomy can best be illustrated by listing examples of some observing programmes for bot normal and active galaxies that will be carried out using ISO.

3.2.1 Multi-colour photometry from 1μ - 150μ. Multi-colour photometry observations will probably be used:

a) to discover and to classify new infrared galaxies, by observations of known optical, x-ray, or radio objects, by obtaining improved positions for IRAS sources, and by sensitive deep sky surveys in limited areas. For a given source brightness, the distance limit of ISO will be about 30 times that of present far-infared systems,

b) to measure the total infrared luminosity, which will in turn have strong implications for the energy generation and emission processes,

c) to find the continuum energy distribution, which will constrain models of emission mechanisms,

d) to map the infrared dust emission in nearby galaxies to locate star formation regions along spiral arms, and study their relation to galactic evolution,

e) to search for time variations in the fluxes of active galaxies in order to distinguish thermal and non-thermal emission processes.

3.2.2 Spectroscopic observations are foreseen for the following types of observations:

a) to map recombination and fine-structure line emission at resolutions $\sim 10^4$ to measure gas motions, free of extinction effects, for determining rotation curves and central nuclear masses,

b) to probe the environment of active galactic nuclei by searching for molecular emission or absorption lines,

c) to look for solid-state features at $R \sim 10^2 - 10^3$ (e.g. 10μ "silicate" or 3μ "ice" features) which bear strongly on the relative contribution of thermal and non-thermal emission processes,

d) to study the stellar populations of elliptical galaxies by observing at $R \sim 10^2$ the 2.3μ and 4.6μ CO and 2μ H_2O bands, and perhaps to use the results to search for evolutionary effects as a function of redshift.

e) to carry out recombination line and fine-structure line observations at $R \sim 10^3$ of star formation regions in nearby spiral galaxies (cf. 1) (d)), and to search for near-infrared H_2 emission as a tracer indicating shock fronts which may have triggered the star formation process,

f) to measure the excitation and broadening of fine-structure lines in Seyferts (with the advantage over optical observations that no extinction corrections need be made),

g) to look for time variations in active galaxy spectra, and

h) to study the apparently anomalous recombination line ratios of Lα relative to Hα and Hβ in QSO's, where the Balmer lines are red-shifted into the near-infrared, at $R \sim 10^2$, free of the red-shift restrictions imposed by the atmosphere in ground-based observations.

3.2.3 Multi-colour polarimetry will also provide a major new information channel on infrared emission mechanisms in both "normal" and active galaxies. Virtually no polarimetric measurements in the infrared exist beyond 10μ wavelength, due principally to the high sensitivity required (measurement of 1% polarisation requires photometric signal-to-noise ratio > 100). Only a cooled telescope like ISO provides such a capability.

3.2.4 There is another class of observing programmes distinct from 1), 2) and 3) above. While the latter groups of observations represent major advances on present studies within the context of current astrophysical understanding, there are also more speculative observing programmes at the limit of ISO sensitivity which might lead to important new discoveries. Among these are:

a) obtaining direct evidence that QSO's are galactic nuclei by detection of stellar molecular features such as the H_2O and CO bands,

b) direct confirmation of the existence of massive haloes around spiral galaxies, if such haloes are composed of low-mass, cool stars, and

c) discovery of new types of extra-galactic objects - for example by measuring recombination-line red-shifts of unidentified high-latitude IRAS sources.

In summary, the thousand-fold gain in sensitivity which ISO offers over conventional infrared telescopes permits photometry, polarimetry and spectroscopy which could revolutionize understanding of the fundamental astrophysical problems associated with the energy sources and emission mechanisms in both normal and active galaxies.

3.3 Cosmology

Although ISO is not designed for making observations on the cosmic background radiation, its unexcelled high sensitivity at wavelengths greater than 2μ for a deep survey will permit several fundamental cosmological studies to be undertaken.

3.3.1 Searches for young galaxies

The epoch of galaxy formation is variously estimated at $Z \approx 1 - 10$, and so the spectral region to search for these intrinsically very luminous objects is in the near-infrared - unless there is substantial dust present, in which case all the energy will be in the far-infrared. Sensitivity sufficient to test current models should be achieved with ISO integration times of a few minutes. Such searches from ISO will undoubtedly complement similar studies using the ST.

3.3.2 Evolution of infrared galaxies

Using ISO photometry and observations at other wavelengths, it may be possible to define one or more classes of standard infrared galaxies. By looking at the properties of these galaxies at various red-shifts, infrared luminosity evolution or evolution of other properties should emerge, if it exists. Such studies could help to determine whether infrared (or active) galaxies are intrinsically so, or represent one or more phases of normal galaxy evolution.

3.3.3 Classical cosmology using infrared galaxies

Armed with the results from 2) above , the data from a deep survey would permit repeating some of the classical cosmological tests using infrared objects - e.g. source counts or red-shift-magnitude. In particular the Fisher-Tully method may be the most dependable way to measure extra-galactic distances. The high sensitivity of ISO would permit using it to extend the Hubble Law to larger red-shifts.

3.4 Star Formation and Stellar Evolution

Although star formation has been a subject of considerable theoretical interest for many years, it has only been since the relatively recent advent of radio and infrared astronomies that a substantial body of observations could be assembled to confront theoretical ideas. As a result, a host of new and fundamental questions has appeared, and concurrently, we have also become aware of a variety of fascinating new astronomical objects, such as molecular clouds, maser sources, cocoon stars, and infrared nebulae. Infrared observations have already proved to be extremely powerful in the study of these dense complexes of dust and gas, and observations using ISO can play a central role in enlarging our understanding of the many facets of astrophysics associated with star-formation regions.

Star formation is intrinsically a large-scale phenomenon, since it may be triggered by compression of interstellar gas clouds by spiral density waves, shock fronts from expanding HII regions or supernova explosions. Therefore, to find regions of active star formation, and to study the relative importance of various processes that may induce it, large-scale mapping is needed. This requires rapid -- and therefore very sensitive -- source detection so that large areas may be mapped reasonably quickly with diffraction-limited angular resolution. This requirement makes it essential to use a cooled telescope in space, such as ISO. And since IRAS data on these regions will almost certainly be confusion-limited -- the survey angular resolution ranges from 1 to 4 arcmin -- ISO will be well-suited to follow up the IRAS results in detailed studies of star-formation regions.

At the other end of a star's life, post-main-sequence evolution seems to feature phases in which a substantail amount of mass is returned to the interstellar medium by processes ranging from rather gentle winds, through more vigorous puffs, to the cataclysmic events making up a supernova explosion. These phases of mass loss are generally accompanied by condensation of molecules and dust grains, and in the latter case direct observation of the star itself, in these late evolutionary stages, is possible only at infrared wavelengths.

Illustrative examples of observational programmes on star formation and stellar evolution which might be undertaken using ISO include:

1) Large-scale mapping, probably based on IRAS results and infrared "photographs" of small regions with the ISO array camera, to find the distribution of those infrared sources indicative of stellar or pre-stellar objects.

2) Multi-colour photometry of these sources to measure luminosity and temperature, combined with spectroscopic studies for line emission, will help identify proto-stellar candidates, which can then be compared with theoretical tracks of pre-main-sequence evolution.

3) Using similar photometric data, supplemented by molecular spectroscopy at $R \sim 10^3$, the existence of cool, low-mass ("brown dwarf") stars can be investigated, thereby extending knowledge of fragmentation processes and the luminosity function.

4) Recombination line observations at $R \sim 10^4$ of the HII regions in star-formation areas can be used to measure extinction and radial velocities, from which distances can be obtained.

5) Molecular cloud dynamics can be investigated by measurements at $R \gtrsim 10^4$ of the near-infrared CO absorption bands against embedded infrared sources, such studies give unambiguous velocity information and would be a useful complement to mm-wave observations.

6) The near-infrared emission lines of H_2 observed at $R \sim 10^3 - 10^4$ should provide tracers for shock fronts which may be responsible for initiating cloud collapse.

7) It may also be possible to observe directly the formation of planetary systems in some of these young stellar objects. Recent work on the emission line stars Lk Hα 101 and MWC349 indicates that dust discs are forming around these young stars, and they are in fact proto-planetary systems.

8) The observations of stellar populations in both spiral and elliptical galaxies, discussed earlier, may provide a better view of large-scale star formation processes than observations of the Milky Way. Comparisons will certainly lead to a more comprehensive understanding of star formation and evolution.

9) Infrared photometry and spectroscopy, which penetrate the dust clouds enshrouding stars in later stages of evolution, will provide direct observational data on evolutionary tracks for comparison with theory.

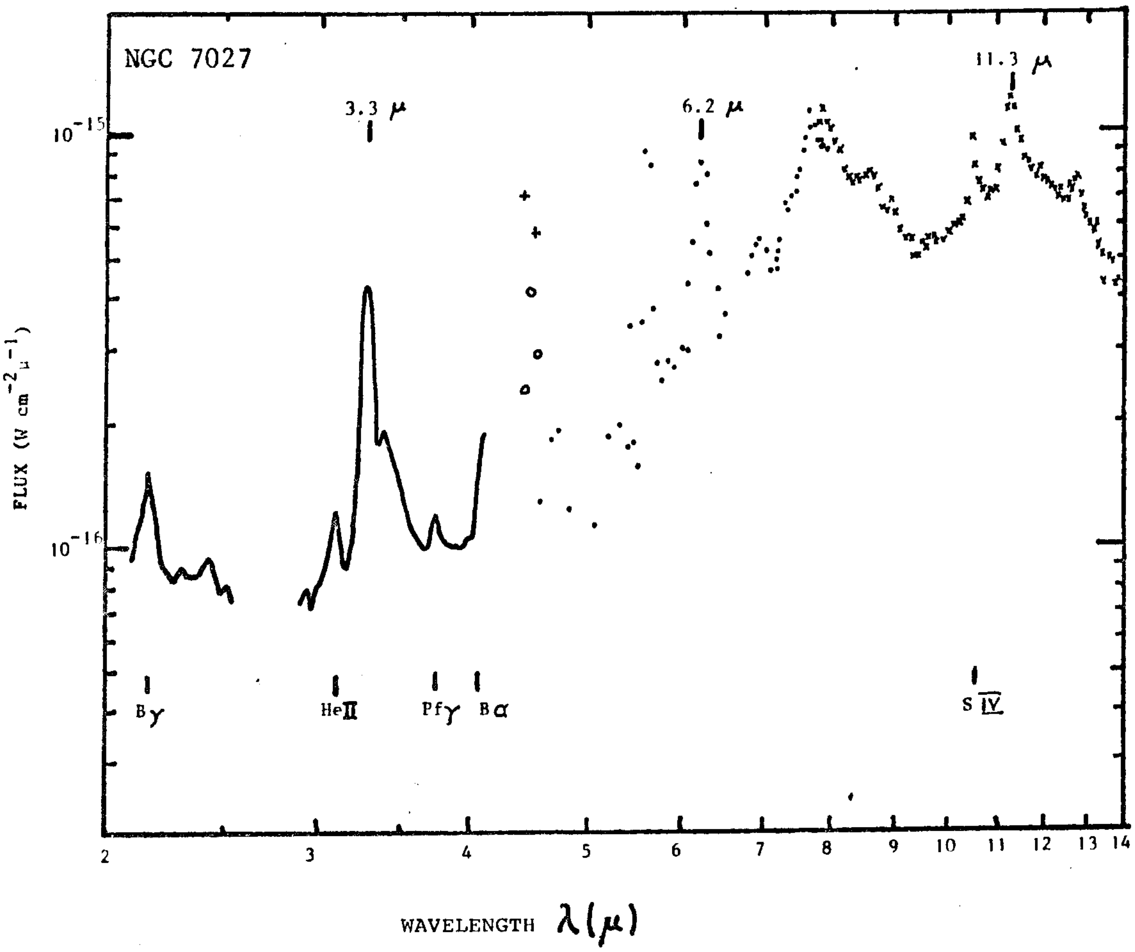


FIGURE 5. Spectrum of NGC 7027 compiled by Russell et al., Ap. J. 217 L149 (1977) from both ground-based and airborne observations. This one spectrum demonstrates dramatically (a) the spectral complexity one finds, (b) the need for resolution greater than 100, which was used in these measurements and (c) the inadequacy of groundbased measurements alone: all the features in the 4-8μ region were obtained from aircraft-borne telescopes.

10) Planetary nebulae are one specific class of stars in late stages of evolution for which infrared photometry and spectroscopy at $R \sim 10^2 - 10^4$ can provide essential diagnostic data. Figure 5 shows the spectral complexity of one planetary, N7027, and demonstrates both the limitations of ground- and airplane-based observations and the need to reach spectral resolution exceeding $R \sim 100$. Recombination line and forbidden line intensities may be used to determine physical conditions, ionization structure, and abundance ratios, and the study of various solid state spectral features of the dust emission is required to understand the apparently anomalous and complicated nature of the dust.

This list of observational possibilities, while perhaps eclectic and idiosyncratic, demonstrates the power of near- and middle-infrared spectroscopy, when carried out with high sensitivity and spectral coverage unlimited by the atmosphere, for elucidating the astrophysics of star formation and evolution.

3.5 The Interstellar Medium

Very little is known about the interstellar dust with any certainty. Formation and destruction mechanisms are largely the subject of speculation, and the size, shape, and composition are guessed at as well. And yet the dust is of major astrophysical importance, not only as an interstellar constituent itself, but because of the central role it plays in many other processes. Aligned, asymmetrical dust grains are evidently present, but the alignment mechanisms which have been proposed do not seem adequate.

The widespread HI interstellar gas, as well as the gas in HII regions existing around hot O-B type stars are another interstellar constituent accessible to infrared observations through the fine-structure and recombination lines it emits. While a few of these lines are detectable by airplane or balloon-borne telescope systems for the brightest objects, the freedom from all atmospheric interference and particularly, the high sensitivity of a cooled space telescope will permit efficient detection of all lines in the spectral range covered by the interferometer in a very large number of objects, so that it is possible to study a sufficiently large number of HI and HII regions to make statistically valid generalisations.

Representative studies of the interstellar medium might include:

1) A rigorous attack on the dust composition problem by detailed spectroscopy of solid-state features which extend over most of the 2-25μ region, including observations at $R \sim 10^4$ to investigate whether some of the features have any high resolution spectral structure.

2) Photometric maps, using absolute chopping, to get the large-scale dust distribution (an observation which is impossible with a warm telescope). Such maps can be compared with mm-wave maps to measure the dust temperature and density distributions.

3) To determine the total luminosities of the early-type star clusters powering HII regions requires far-infrared photometry, and ISO observations will be useful to clarify confusion-limited IRAS data on many of these sources.

4) Polarimetry, to the high sensitivity required, can only be done with a cooled telescope. Polarimetric observations of dust emission yield critical information on the scale and spatial structure of the grain alignment mechanism.

5) Excitations, chemical abundances, and possibly the ionisation structure of both HI and HII regions can all be directly measured using those atomic and ionic fine-structure lines which occur in the near and middle-infrared. A variety of astrophysical investigations can be made with such data, but an important one is to study abundance gradients and the implications for chemical evolution of the galaxy.

6) Matter is continually interchanged between stars and the interstellar medium. IR spectroscopic studies of mass loss in evolving stars will have an important impact on theories of stellar evolution.

3.6 IRAS Follow-up

In 1981/82 the Infrared Astronomical Satellite (IRAS), which has a 60 cm diameter helium gas cooled telescope, will conduct an all sky survey in four wavelength bands between 8μm and 120μm (see table I for details). The sensitivity limit for all channels is around 10^{-19}W cm^{-2}. The IRAS mission design includes a high level of redundancy in sky coverage to achieve high reliability for detection of infrared sources.

The spacecraft is expected to operate in the survey mode for roughly 70% of its planned mission lifetime of ∿ 15 months. Outside of this period the spacecraft can be used in a pointed mode. One objective in this period will be to measure the spectra of some of the brighter sources found in the survey mode using a low resolution (R ∿ 20) spectrograph operating between 6.5μ and 24μ. In addition to this instrument, a diffraction limited *two*-channel chopped photometer (45-120μ) will be used in the pointing and the raster scanning modes of the spacecraft for studies of specific objects.

The high sensitivity of the IRAS instrument together with the all sky coverage will undoubtedly lead to the discovery of many new sources. Present estimates indicate about a million IR sources will be detected. In the domain of Galactic astronomy an appreciable fraction of the IRAS sources will be hot spots in molecular clouds, presumably protostars. In extragalactic astronomy the few IR extragalactic objects presently known will be increased into the tens of thousands. In both fields therefore there will be an enormous amount of detailed work to be done by a mission such as ISO in carrying out in-depth studies of the most interesting of this mass of objects.

The IRAS survey will produce data in four broadband channels up to 120μm at an angular resolution ranging from 1 to 4 arcminutes. To study further the IRAS sources one desires an expansion of the wavelength range above 120μ and also to shorter wavelength (below 10μm). In addition, better angular resolution is a distinct advantage in order to resolve the marginally or unresolved IRAS sources. A modest extension of wavelength range and angular resolution can be provided by the proposed instrumentation in ISO. To achieve effective follow-up, the sensitivity of the proposed system should be at least as good as IRAS and this will indeed be the case with ISO.

TABLE I - IRAS CHARACTERISTICS

Survey

DETECTORS

μm	Type	f.o.v. (arcmin)	NEF (W/cm^2)	NEF D Jy
8.5 - 15.0	Si : As	0.75 x 4.5	$3.6\ 10^{-19}$	0.024
19.2 - 30.2	Si : Sb	0.75 x 4.5	$3.2\ 10^{-19}$	0.056
40 - 80	Ge : Ga	1.5 x 4.7	$1.6\ 10^{-19}$	0.042
83 - 119	Ge : Ga	3.0 x 5.0	$0.7\ 10^{-19}$	0.064

Spectrometer

μm	Resolution ($\lambda/\Delta\lambda$)	Detector	f.o.v.
6.5 - 13.0	20	Si : Ga	5 x 6 arcmin
11.5 - 24.5	20	Si : As	7.5 x 6 arcmin

Photometer

μm	f.o.v. (arcmin)	Detector
45 - 63	1.2	Ge : Ga
81 - 116	1.2	Ge : Ga
5 - 8	0.25	Si : As

4. THE TELESCOPE AND EXPERIMENT SYSTEM DESIGN

4.1 Introduction

The fundamental parameters in the total design of an infrared observatory are the diameter of the telescope primary mirror and the operating temperatures of it and the other optical components. Everything else in the design hinges on these two factors. From the science aspects, sensitivity and angular resolution demand as large a primary mirror as possible operated at a temperature which is consistent with the limits set by detector performance and the zodiacal background light. From the preceeding discussions and Figure 1 it is evident that with typical detector NEP's of 10^{-17}W/$\sqrt{Hz}$ at wavelengths less than 100μ, a mirror temperature of roughly 20°K is necessary. Taken together with the requirement for certain detectors to operate below 2°K, this leads directly to the selection of superfluid helium as the cryogen. Apart from these considerations, superfluid helium has the advantage as a space cryogen of having been tested extensively for such purposes. It also has the important property, for zero-g conditions, of forming an extremely high thermal conductivity superfluid film over all exposed surfaces.

The optimum size of the primary mirror is probably the most difficult problem in the design. Other studies (e.g. SIRTF) indicate that the mass of the total telescope assembly increases rather faster than the square of the telescope diameter, up to d $\sim$ 150 cms, where a transition from a beryllium primary to Cervit becomes necessary. An increase in cryogen mass follows of course as the thermal loading increases with diameter, primarily by an increase in the parasitic inputs due to enlarging the strut supports to take the higher suspended mass and the additional surface area. Engineering and thermal design complexity will also rapidly increase with the size.

In the original proposal a primary mirror diameter of 100 cms was selected. Detailed studies during this Assessment Phase have clearly shown that a telescope of that diameter would probably lead to a spacecraft mass in excess of the Ariane capability for a 12 hour orbit, and it would possibly also exceed the guidelines for acceptable spacecraft cost. Although various telescope dimensions were subsequently considered, it was decided that 60 cms diameter represented an acceptable compromise between final spacecraft mass/cost and ultimate system sensitivity and angular resolution. To reduce the diameter to substantially less than 60 cms would certainly lead to difficulties in fully utilizing sources from the IRAS catalogues. A 60 cms diameter primary will provide sufficient sensitivity and angular resolution to allow the possibility for the scientific objectives discussed earlier to be reached on the basis of a 1½ year mission duration. At the same time it leads to an all-up spacecraft mass which is consistent with an Ariane launch into a 12 hour orbit.

In order to explore the potential of an infrared observatory of this type, a *model* experiment payload was established. This comprised of three basic elements. First, an indium antimonide 1000 pixel array camera with a 1 arc minute FOV operating in the 1 to 5 micron region. In addition to band pass imaging, this would also be used to calibrate and periodically to check on the infrared optical axis and the pointing system.

For high resolution spectroscopy in the important 2 to 25 μ region a dual channel fast scan Michelson interferometer system of resolution 10^4 was studied. The virtue of a Michelson in this application is that it allows full advantage to be taken of the lack of thermal background induced noise from the cooled optics by obtaining spectral information simultaneously across the whole wavelength range provided by the chosen detectors. It does this with a resolution which can be varied up to a maximum depending on the total optical path difference and optical tolerances. This spectral multiplex advantage is of paramount importance in the present situation where the mission duration is limited to 1½ years and observational efficiency must be maximized. The disadvantage of the Michelson is that the drive system represents the single major source of heat from the experiment to the cryogen and it is also the point where a failure would be catastrophic. The advantages were considered to far outweigh the disadvantages, but the further work on the model payload will include a detailed study of failure modes and the provision of adequate redundancy.

The third instrument studied for the model payload was a photometer unit which would operate from 10μ out to 150μ. The design of this unit has to balance the desire for good spatial resolution and moderate channel bandwidth against the increasing heat load resulting from increases in the number of wires to each detector element. The configuration selected represents a compromise between a substantial improvement on the IRAS pointed mode system and the necessity to limit the thermal loading.

It is strongly emphasized that this was a *model* payload. The resulting payload is certainly adequate to the task of carrying out the observations suggested in the scientific objectives and the resource demands lie within the capabilities of the total spacecraft/cryogen system. However there are alternative routes to satisfy most of these same observational requirements. This in itself is a healthy situation at this stage and frees the mission from being restricted to a single instrument design situation.

4.2 Telescope Design

The table below presents a summary of the main features of the telescope system.

ISO - TELESCOPE OPTICAL CHARACTERISTICS

TELESCOPE - CASSEGRAIN f/10 FIXED SECONDARY
PRIMARY DIAMETER, 60 cms, SECONDARY DIAMETER, 11 cms
FOCAL RATIO : 1.55 PRIMARY, 1.9 SECONDARY
AREA OBSCURATION 9%, WITH SECONDARY SHIELD 18 cms dia.
TOTAL FIELD OF VIEW, 10 ARC MINUTES
PLATE SCALE : 30 ARC SEC/mm
QUALITY : DIFFRACTION LIMITED AT 5 MICRON
GEOMETRICAL ABERRATIONS : < 1 ARC SEC IN CENTRE OF FIELD
BAFFLING : OUTER, REJECTION FOR > 56° OFF-AXIS
INNER, NO PRIMARY ILLUMINATION FOR 28° OFF-AXIS

The decision to use a fixed secondary and a 10 arc minute field of view with the Cassegrain system simplifies considerably the mechanical, optical and thermal design of the telescope, although the fixed secondary does add some complexity to the design of the photometer. The cheapest route is to use a classical Cassegrain (parabola-hyperbola) for the optics but the limitation in performance due to coma indicates that to meet the requirement on aberrations, it may be necessary to use the Ritchey-Chretien form.

The requirement for as small a central obscuration as possible and hence the absence of a secondary shield, has to be weighed against the demand to keep the telescope as short as possible, thereby limiting the possible extent of the main baffle and hence the degree of off-axis rejection. In the schematic of the optical system, shown in Figure 6, a shield with a diameter of 18 cm is incorporated in order to reduce radiation scattered from illuminated baffles of the main tube onto the secondary. A third baffle, within the obscured area of the primary, is incorporated to reduce scattering and diffraction into the beam exit direction. This baffle will be cooled to a temperature close to that of the experiment chamber.

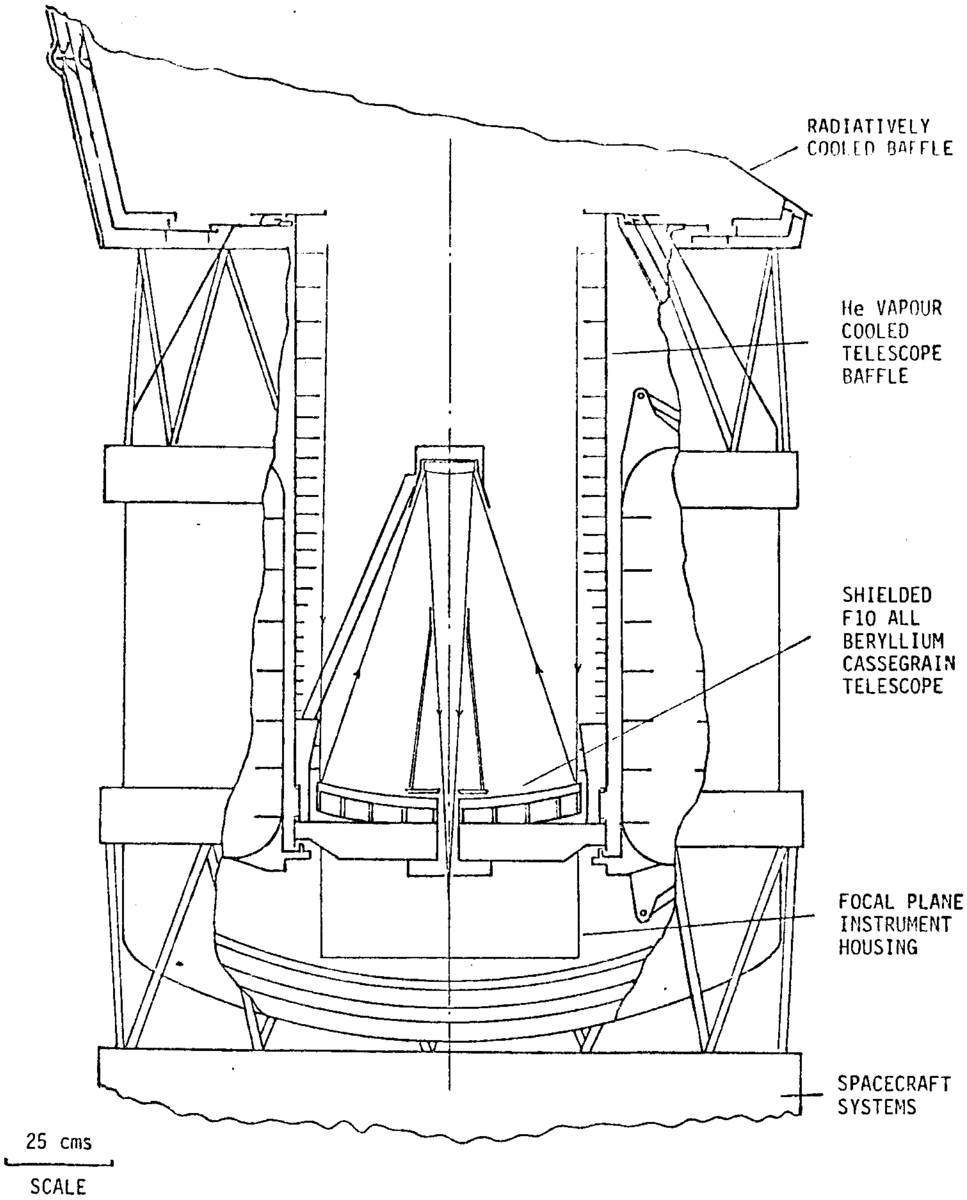


FIGURE 6. ISO Telescope and Focal Plane Instruments Accommodation.

The primary and secondary mirrors should be manufactured from beryllium, which provides a lightweight mirror with good mechanical and thermal properties and which can take a surface polish down to about 0.01 μ in stress relieved material. In order to minimize the problems of stress and distortion on cooling the optical system, it is foreseen that the secondary mirror unit will be attached to the beryllium primary support by Be struts. The final baffle will also be fastened to the Be primary mirror support plate. Similarly, the strut supports for the experiment chamber should also be of beryllium and attached directly to the beryllium support plate.

Thermal control of this optics assembly is by gas cooling coils around the primary mirror support, the baffle/strut system, and the experiment chamber. Attachment of the optics assembly to the aluminium support ring is by three flexing joints whose lines of action intersect at the optical axis. In addition, local support to the mirror will use three universal joints to take up rotational motion resulting from misalignment or fabrication errors.

The main baffle tube is fabricated from a honeycomb aluminium structure and attached to the strong ring. At the lower end, the strong ring is fastened to the cryogen tank, which is in turn supported by a glass fibre strut system.

Apart from minimizing distortion on cooling, the aim of this telescope design is to allow the fabrication and test of the complete optics unit independent of the rest of the spacecraft and the cryostat (see Section 7).

4.3 2-25 μm Michelson Interferometer

4.3.1 Rationale and concept

A Michelson interferometer offers an excellent combination of performance and flexibility for fulfilling the ISO spectroscopic aims. It is possible to achieve, with a relatively compact instrument, variable resolving powers (well over 10^4 at the shorter wavelengths) while exploiting the multiplex, throughput and wavelength coverage advantages due to the fact that the telescope and instrument are cooled. The concept proposed is a single, rapid scanning interferometer which has, however, separate optical paths for the wavelengths regions 2-5 μm and 5-25 μm, thus allowing optimisation of beam-splitter coatings and detectors in these two ranges. Each channel has one input beam and two output beams to maximise the interferometer efficiency, and there will thus be two detectors associated with each channel, which will probably be InSb (2-5 μm) and Si : As (5-25 μm).

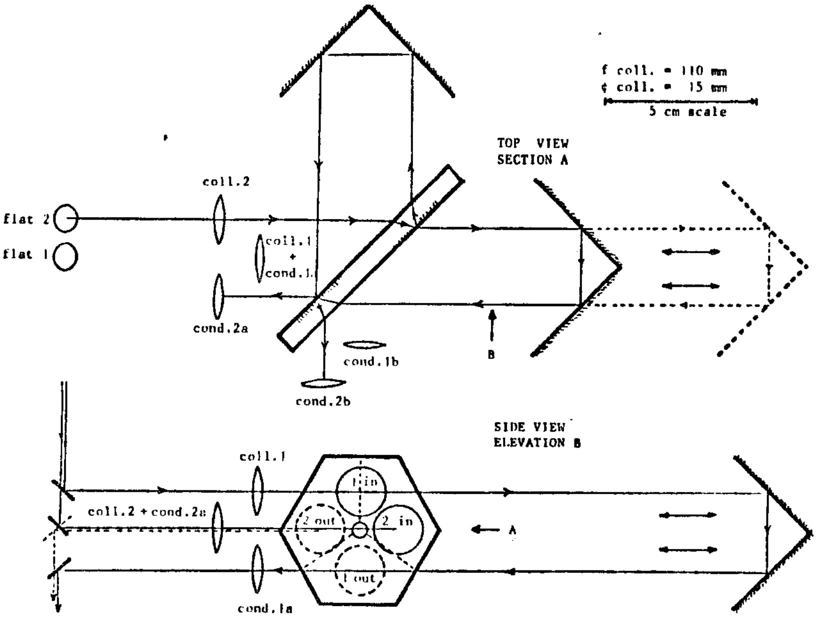


FIGURE 7. Optical layout of the Michelson interferometer showing beam division and recombination in one plane. The optical path for the second wavelength channel is identical but in an orthogonal plane as indicated in the side view which shows the coated regions of the beam-splitter.

4.3.2 Optical design

The two wavelength channels are separated in orthogonal planes by making use of the properties of corner cube reflectors and applying different coatings to the appropriate sections of the beam divider. Fig. 7 shows the optical layout for one of the orthogonal planes together with a sketch showing how the two channels are divided at the beam splitter. This is self compensating and is provided with an additional coated region optimised for the laser reference used to control the moving mirror and data sampling. The corner cube reflectors assure alignment stability in addition to allowing this wavelength division.

The two input flat mirrors view an off-axis region of the focal plane (∿15') away from the field reserved for the on-axis camera. Light is fed to two collimators (f ∿ 10 cm) which have been represented here as lenses but in practice will probably be off-axis mirrors which can be readily incorporated with the flexibility offered by the input flats. Similarly, the output condensers may also in practice be mirrors. A filter wheel is also provided to allow for narrow band observations, if required, on bright sources which may otherwise be source photon noise limited. The beam diameters through the instrument will be less than 2 cm for fields ≲ 1' and R ∿ 10^4 at 10 μm. The overall size and accommodation of this instrument is shown on Fig. 8.

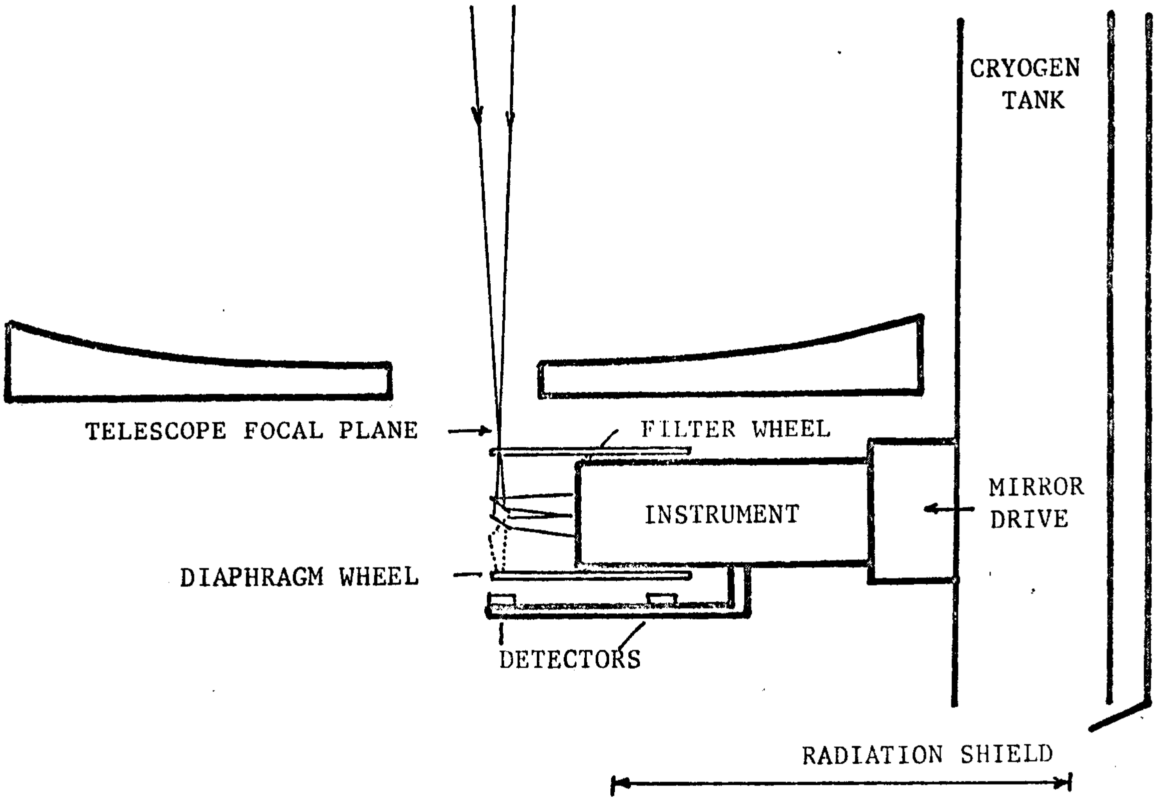


FIGURE 8. Accommodation of the Michelson interferometer in the ISO focal plane. The two mirrors just below the focal plane are the flats 1 and 2 shown in Fig. 7.

4.3.3 Interferometer Drive

A physical movement of 2.5 cm is required for one of the corner cube reflectors to provide for an unapodised resolution of 0.1 cm^{-1} (R = 10^4 at 10 μm). Translation speeds will be in the range 0.5 - 5 mm/s. It is proposed to achieve this motion with a solenoid drive along the lines now adopted and under development in cryogenic laboratories both in Europe and the US. Particular design care must be paid to minimise the heat input, to keep it below 10 mW. A choice has also to be made of the most suitable reference control line. This could be provided by a conventional or solid state laser located outside the cryostat, which utilises a fibre optics connection to minimise the heat dissipation within the cryostat.

4.3.4 Data and control link

Each of the detector outputs will be sampled at a rate of about 300 samples/sec and with 12 bit accuracy. Allowing for the addition of up to 4 status bits/data word and the fact that only two detectors will be in use at any time, the overall signal data rate will be about 10 k bit/s. Monitoring of housekeeping data including amplifier gains, filter and diaphragm settings etc. should require less than 1 kbit/s.

A number of command words are required for setting (i) short or long wavelength channel (ii) scanning length (iii) scanning speed (iv) sampling interval (v) AC gain (vi) filter position (vii) diaphragm position. Each of these can be accommodated within an 8 bit word.

4.3.5 Performance and operation

The instrument is designed for operation between 2 μm and 25 μm at any resolution up to 0.1 cm^{-1} (R = 1 x 10^4 at 2 μm and 5 x 10^3 at 20 μm) and with apertures of ≤ 1' ; an advantage of the Michelson is that at short wavelengths, one is not constrained to use the full spectral resolution. With helium cooling (≤ 20°K) the telescope and instrument contribute negligible photon noise in both wavelength bands. A filter wheel has been incorporated in the design, for use when only narrow band regions are of interest.

Data from the spectrometer will be telemetered to ground for recording and for on-line Fourier transformation to produce spectra of sufficient quality to monitor the progress of the observation. On weak sources, spectra obtained over a period of up to 30 min. will be averaged to build up the final s/n ratio.

Michelson Interferometer - Summary Table

RESOURCES	MASS	10 kg
	SIZE	25 x 20 x 15 cm
	POWER	20 W
	HEAT LOAD (AVE)	10 mW
	DATA RATE	10 K bits/s
	COMMAND LINK	10 8 bit words
DESIGN FEATURES	MODE	RAPID SCAN, DOUBLE OUTPUT
	OPTICS	CORNER CUBES AND SEPARATED SHORT AND LONG WAVELENGTH CHANNELS
	DETECTORS	2 x InSb, 2 x Si : As
PERFORMANCE	WAVELENGTH RANGE	2 - 5 μm, 5 - 25 μm
	MAX RESOLUTION	0.1 cm^{-1} (R = 10^4 at 10 μm)
	SENSITIVITY (3δ in 30 min)	$2 \cdot 10^{-21}$ $W \cdot cm^{-2} (sp \cdot el)^{-1}$ (assuming NEP = $10^{-17} W \cdot Hz^{-\frac{1}{2}}$)
	FIELD OF VIEW	≤ 1'

4.4 The Photometer System

A multi-band photometer is an important element in the ISO science instrument complement. The science objectives discussed earlier suggest that a photometer would be required to carry out the following types of observations:

1) Long integrations to detect faint objects -- especially extra-galactic sources. IRAS, being primarily a survey instrument, is not designed to carry out such long exposures to reach faint limits on particular sources of special interest.

2) Determination of improved positions for IRAS objects, or those from other sources, e.g. x-ray or radio. The IRAS survey angular resolution ranges from 1 to 4 arcmin, and so many of its source detections will be confused. The ISO photometer should provide roughly a factor of two improvements in spatial resolution.

3) Location of specific infrared objects for which spectroscopy using the ISO Michelson interferometers is desired.

4) Polarimetry, especially since it is impossible to reach astrophysically-interesting levels of sensitivity in infrared polarimetry without the benefit of a cooled telescope.

5) Absolute photometry of extended objects, which is not possible with the conventional sky chopping used in most infared observations and in the IRAS survey.

These observational requirements define a photometer which is (a) of diffraction-limited angular resolution (b) is efficient in locating objects whose positions are not known precisely, and (c) optimized for long integrations on faint objects to achieve maximum photometric sensitivity and precision.

The ISO photometer-camera design follows naturally from these requirements. It consists of four quasi-imaging cameras and a wide-field photometer. The characteristics of each camera are listed in the following table.

ISO PHOTOMETER

Array	Waveband	Detector	Number	Field of View	Pixel Size
A	1-5 μ	InSb (CCD)	32 x 32	1 x 1 arcmin	4 arcsec
B	10-25 μ	Si : As	15	3 x 3	21
C	25-60 μ	Ge : Ga	13	5 x 6	48
D	60-150 μ	Ge : Ga	9	6 x 12	126
WIDE-BAND PHOTOMETER					
	10-150 μ in three bands		3	5 x 5	300

Detectors of the type listed above are now commercially available. The photometer has the following features:

1) Each waveband spans only a little over an octave, so that the entire region 10-150μ is completely covered, while minimizing the number of discrete detectors.

2) The central 3 x 3 array in cameras B, C, and D gives 9 diffraction-limited pixels for each waveband. Thus we have a quasi-imaging camera which will provide rapid determination of source positions and efficient acquisition of two-dimensional contours for extended sources.

3) Cameras B and C have also a linear array extended in one dimension. When the telescope is scanned perpendicular to the linear direction of this array, mapping large areas and searching for sources can be carried out with good efficiency.

4) The wide-field photometer will permit long integrations on faint objects for the maximum detection sensitivity and photometric precision on both extended and point-like sources.

5) Long integrations or absolute photometry of extended sources can be carried out by commanding on a focal plane chopper. Two choppers, both of the tuning fork (electro-mechanically resonant) type are incorporated. One chops the array cameras and one the wide-field photometer, providing a measure of redundancy with little extra complexity. Choppers of this type operate reliably at cryogenic temperatures and are now spaceflight qualified.

6) Polarimetry can be done by commanding into the beam a rotatable wire-grid analyzer.

4.5 1-5 μm Camera Array

This detector array provides the capability for two dimensional imaging and for multiband photometry in the 1-5 μm spectral range. It can also serve the very important purpose of determining the focal plane alignment relative to the spacecraft pointing system, for the purpose of positioning the other instrument apertures.

The basic design proposed here is derived from a commercially available and fully developed InSb array. Since infrared array technology is now progressing very rapidly, the actual array selected will obviously be based on the state of the art which is current when the camera design is frozen. The array finally chosen will obviously be better than that described here, hence the present discussion relates to a minimum performance specification.

Since the telescope is cooled, giving a low background level, there is no need for pupil re-imaging. Consequently, the array could be mounted directly at the focal plane near the telescope axis. However, the 2°K temperature required at this place by other detectors is probably too low for ideal InSb operation. The focal plane zone reserved for the InSb array (1 x 1 arcmin) can be reimaged by simple optics to a place where the temperature is about 20°K. The optical path can be arranged in such a way that the camera shares its filter wheel with the short wavelength channel of the Michelson interferometer.

Filtering is expected to be based on the standard S, H, K, L and M photometric bands plus the 1.9μ H_2O and 2.3 μ CO bands and a wideband 1-5μ filter. Filter manufacture for this spectral range presents no technological problems as multilayer dielectric filters are already routinely used in both groundbased and satellite instrumentation. Data outputs required are video channel (10 Kbits/s), one pixel identification channel (TTL pulse) and the filter wheel position readout. The most important instrument parameters are summarised in the table below:

Field of View	50 x 50 arcsec	Instrument Size	∿ 5 x 5 x 5 cm
Resolution	1.5 arcsec/pixel	Mass	< 1 kg
NEP	$< 10^{-16}$ W/$\sqrt{\text{Hz}}$	Power Consumption	3W
Filters	8 - 10	Data Rate	10 Kbits/s (1 image/s)
Array Area	2 mm x 2 mm	Command	1 word (4 bits)

4.6 Detector Signal Processing and Cryogen Heat Loads

The total number of discrete detectors in the model focal plane amounts to 44. Typical detector sizes will be 1 x 1 x 0.5 mm for the silicon detectors and 1 x 1 x 3 mm for the germanium ones. Integrating sphere cavities of high Z material will be used to achieve shielding of the detector against trapped particle radiation. Each detector will be connected in a transimpedance preamplifier configuration with load resistors in the 10^{10} Ω range and a mosfet or a jfet pair close to the detector. The operational amplifiers which complete the preamplifier will be located in warm electronics box outside but close to the dewar.

It is necessary to use coaxial cables in the preamplifier circuit. Both the fet dissipation and the cable harness constitute one of the main sources of dissipation in the focal plane.

IRAS experience has shown that 100 micro-Watt per dual channel fet dissipation provides a comfortable margin for fet operation. This number leads to the total heat load directly to the cryogen to 4 m Watt. As the array will operate at elevated temperature, (20°K) there is no direct dissipation of the output amplifier of the array to the cryogen.

Cabling introduces an appreciable load which can largely be carried by the enthalpy of the gas by proper heatsinking of the cable to the vapour cooled shields. Thin gauge stainless steel coaxial cables should be used. The direct heat load on the cryogen can be estimated from the IRAS experience to be 6.5 m Watt. The vibrating choppers proposed for the photometers introduce a negligible load as these are driven in a harmonic mode requiring almost no power. Such choppers are used in a variety of cryogenic systems. The IRAS choppers, as an example, dissipate less than 0.1 m Watt each at the cryogen.

The Michelson drive system, based on a superconductive solenoid drive, will have a variable dissipation dependent on the scan speed and scan range used. From development level experience which exists in Europe for similar applications, we estimate the direct heat load to be less than 10 m Watt. Possibilities exist to reduce this load even further by application of cooling through the gasphase. This solution might however, introduce some additional cryostat/experiment interface complexity.

4.7 The Cryogenic System

The requirement for a telescope primary mirror temperature of the order of 20°K and Si and Ge photoconductor detector temperatures below 2K point to the use of superfluid liquid helium as the cryogen. Apart from the thermal requirements, the choice of liquid helium has the advantage that liquid helium cryogen systems for space use have undergone test flights and will shortly be used in the IRAS space mission, the Spacelab II IR survey mission and the GIRL Spacelab mission. The cooling concept is in all cases practically the same. The superfluid helium is kept at the temperature required for the focal plane equipment while the other parts, such as the optical system, baffle and radiation shields, are kept at somewhat higher temperatures, either by heat conductance or by using the enthalpy of the cold helium gas. Thermal control is based on active control of the helium gas flow and the stored helium temperature.

In order to reach temperatures below 2°K it is necessary to reduce the pressure over the liquid helium so that it passes through the λ point (2.17K) and reaches the superfluid phase. This process can be carried out prior to launch. An important advantage of superfluid helium for space use is the fact that its thermal conductivity is very high and its viscosity almost zero. A film of superfluid helium covers the exposed walls and reduces temperature gradients to nearly zero. Separation of the He vapour/liquid phases, which of course is necessary in the zero-g environment, is achieved using a phase separator in the vent exit. The separator consists of a capillary system across which exists a temperature gradient. As a result of the temperature increase of the gas towards the vent there will exist a fountain pressure directed inwards to the storage tank which separates the superfluid from the helium gas being released to the vent line. This exploitation phenomenon has been exploited in porous plugs which are now available commercially and which have been extensively tested for space use. They will be flown on the space missions mentioned above and can confidently be specified for ISO. There is now also a more advanced system, under active development in Germany, which can serve both as a passive phase separator, and as an active one when required to respond to relatively large changes in power dissipation.

Although the latent heat of evaporation of liquid helium is comparatively small, the fact that the enthalpy of the gas is large means that with suitable design the total helium cryogenic system can be efficient.

Cryostat Sizing

The design specifications for the ISO telescope system and science instruments lead to a predicted 57 m Watt maximum load directly to the superfluid helium, a value consistent with a ∿ 50% extrapolation from the IRAS performance. The design cryogen lifetime is 1½ years. Work on other space cryogen system e.g. IRAS, has confirmed that a design with three helium vapour cooled shields leads to a total system efficiency which is consistent with 1½ year cryogen lifetime. In order to maintain the bath at a temperature around 1.6 K, with a total effective heat lead of 57 mW, some 117 kg of superfluid helium, say 800 litres are necessary. Taking into account a 15% margin, which is necessary at this stage of the project, the required volume of superfluid helium will be 920 litres, (i.e.) 135 kg. The corresponding mass of the alumium storage tank is estimated to be 113 kg for a volume of 1012 litres (10% ullage).

Based on a total internal suspended mass of 440 kg, the cross-section of the mechanical supports which are required can be estimated and this leads to an estimate of the associated heat leaks. Taking into account also the overall dimensions of the cryostat, the total heat load on the helium bath is given in the table below. A 15 mW experiment heat dissipation is considered in a first approach. A substantial improvement in the margins for the heat loads acceptable can be anticipated if retractable supports are adopted for the prime support of the 440 kgs of suspended mass, prior to and during the launch. Location of the suspended mass whilst in orbit would utilise very thin retainers. By this means it should be possible to realize a reduction of about 12 mW in the heat leak via the supports, which can be used, in the first place, as a further substantial project margin, leading to over 30% in total. If that margin is not fully utilized, and every effort should be made to ensure this, then the mission lifetime will be proportionally increased towards 2 years.

SUSPENDED MASSES	
Helium	135 kg
Reservoir	113
V.C. Shields	63
Valves & Plumbing	20
Superinsulation (internal)	15
Optical System & Baffles	74
Experiment	21
TOTAL	441 kg

HEAT LOADS ON He BATH	
Experiment Dissipation	15 mW
Supports	29
Superinsulation	5
Fill Line	1
Electrical Leads	6.5
Baffles (+ aperture load)	1
TOTAL	57.5 mW

Analysis of the Feasibility

The feasibility of large cryostats has been demonstrated by the studies and developments carried out on the various projects which are now in progress in USA and within Europe. The IRAS cryostat, built by Ball Brothers, is designed for 1¼ year lifetime and contains 540 litres superfluid helium. The IR telescope for Spacelab II (9 days mission) is a small telescope cooled by the vapour from a separated and conventional dewar. Another experiment for Spacelab II (SHFE) uses a 100 litre He II reservoir and is intended to study the properties of superfluid helium under zero-g. Finally, the German Infra Red Laboratory has a 45 cm telescope built for a variety of instruments for astronomy and aeronomy research on Spacelab . In this project, a 300 l cryostat will be used for a 30-days lifetime.

Within ESA, the CRHESUS project is intended to provide for a 70 litre superfluid helium cryostat. It is designed as a Spacelab facility to accommodate small experiment payloads or telescopes requiring cryogenic cooling for a mission up to 30 days. The projects GIRL and CRHESUS are designed for Spacelab short duration missions but together they contribute within Europe to the development of a technology directly applicable to ISO. Consequently, it can be considered that the basic technology of materials, supports, superinsulation at low temperatures, valves and helium management devices are now proven or will be proven between now and 1981/92.

The satisfactory operation of porous plug in a zero-g environment has been verified within a NASA aircraft and rocket test programmes. Similar tests will be made with active phase separators in the near future. Various other critical elements for a helium space cryostat, like cryogenic valves, struts, etc. are currently under development. The performance of the valves tested during the phase 1 and 2 of the CRHESUS programme are satisfactory and these valves are now under qualification.

The feasibility of the ISO project is mainly related to the mass of cryogen which is required for the required lifetime. The table below gives the mass budget for the cooled telescope, which is derived from the cryogenic requirements. The proposed mission appears to be feasible from a thermal design viewpoint within the constraints discussed above. The provision of retractable supports will increase further the margins and should lead finally to additional mission lifetime beyond 1½ years.

Developments

The following points are considered as technological items which would be desirable to initiate soon for development in Europe.

(i) Retractable support system.

Such supports, with pyrotechnic initiation, were planned at the very beginning for IRAS. Good operation and reliability of such systems has not been demonstrated. This development is considered beneficial to the ISO mission, but not essential. Mechanical, thermal and alignment requirements shall be considered together for the design of such system. In particular each support must be carefully designed, in order not to generate additional parasitic radiative heat loads. An early start on such a technological development would be desirable.

(ii) Electrical actuators for cryogenic valves. Such devices do exist within Europe but space qualification is necessary in terms of reliability. Space qualified US produced hardware could however replace these if necessary.

MASS BUDGET (kg)

CRYOSTAT	Cryostat outer vessel	310	
	Helium reservoir	113	
	Helium	135	
	V.C. shields	63	
	Cryo components (valves, plumbing)	20	
	Insulation (internal)	15	
	Supercritical He cover	40	696
EXPERIMENTS	Optical system and baffles	74	95
	Focal plane instruments	21	
SUPPORT EQUIPMENT	Superinsulation (external)	6	
	Sunshade	46	
	Experiment electronics	77	
	Interface skirt	22	151
Total Telescope			942

THE INFRARED SPACE OBSERVATORY

LAUNCH CONFIGURATION

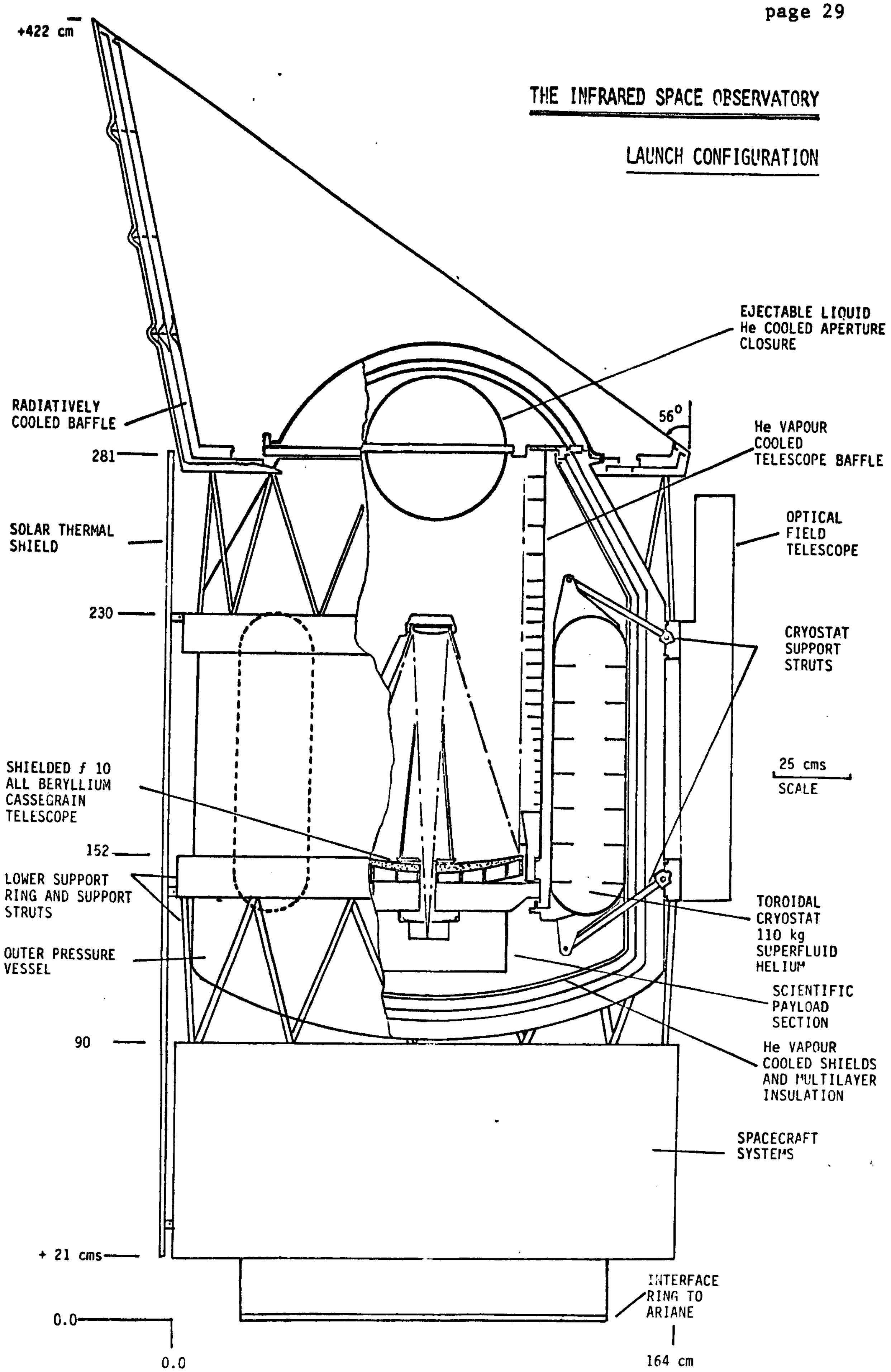


FIGURE 9

5. THE SPACECRAFT

5.1 Requirements and Constraints

5.1.1 Orbit and Launcher

A basic requirement of this mission is to maximise real time operation of the experiments. To allow continuous real time operation from one European ground station a 24 hour geosynchronous orbit would be necessary. For this orbit the present Ariane I and expected Ariane II, III capabilities would impose unacceptable margins to the derived spacecraft mass.

A low earth orbit was abandoned since this would not allow real time operations. Therefore as a baseline for this assessment study a 12 hour elliptical (1000, 40.000 km) equatorial orbit has been taken, The satellite mass allowed on this orbit is 1535 kg for Ariane I and 1840 kg for Ariane II.

Note that analysis is continuing within ESA with a view to establishing the particle environment experienced by ISO when operating in such a 12 hour orbit.

To minimise the influence of the residual atmosphere (drag and contamination) the perigee height needs to be above 1000 km. Since this orbit cannot be reached by direct injection an on-board propulsion system (six ION hydrazine thrusters) is required for perigee raising and synchronising with the earth rotation. Due to luni-solar perturbations the perigee and apogee altitudes will vary in the course of the mission. From time to time orbit corrections will be needed to keep the perigee height within the acceptable limits.

5.1.2 Ground Network

To maximise real time operation from one station in Europe, Villafranca has been assumed as prime station and Carnavon (Australia) as the second station. Due to the fact that both stations are not 180° apart in longitude, rather than 100% coverage a total ground coverage of 93% of the time per day is obtained. This appears satisfactory and in view of the small data loss, on-board data storage is not justified.

5.2 System Description

5.2.1 Configuration

An outline of the proposed ISO spacecraft is illustrated in figure 10. Essentially the design can be considered as consisting of 3 main elements:

- Liquid helium cryostat
- Cooled telescope
- Support sub-system compartment

Within the Assessment Study preliminary support sub-system designs were explored to the appropriate depth and proposals are included in this report. However, concerning the design of the Cryostat/cooled telescope, it must be said that the technology associated with the

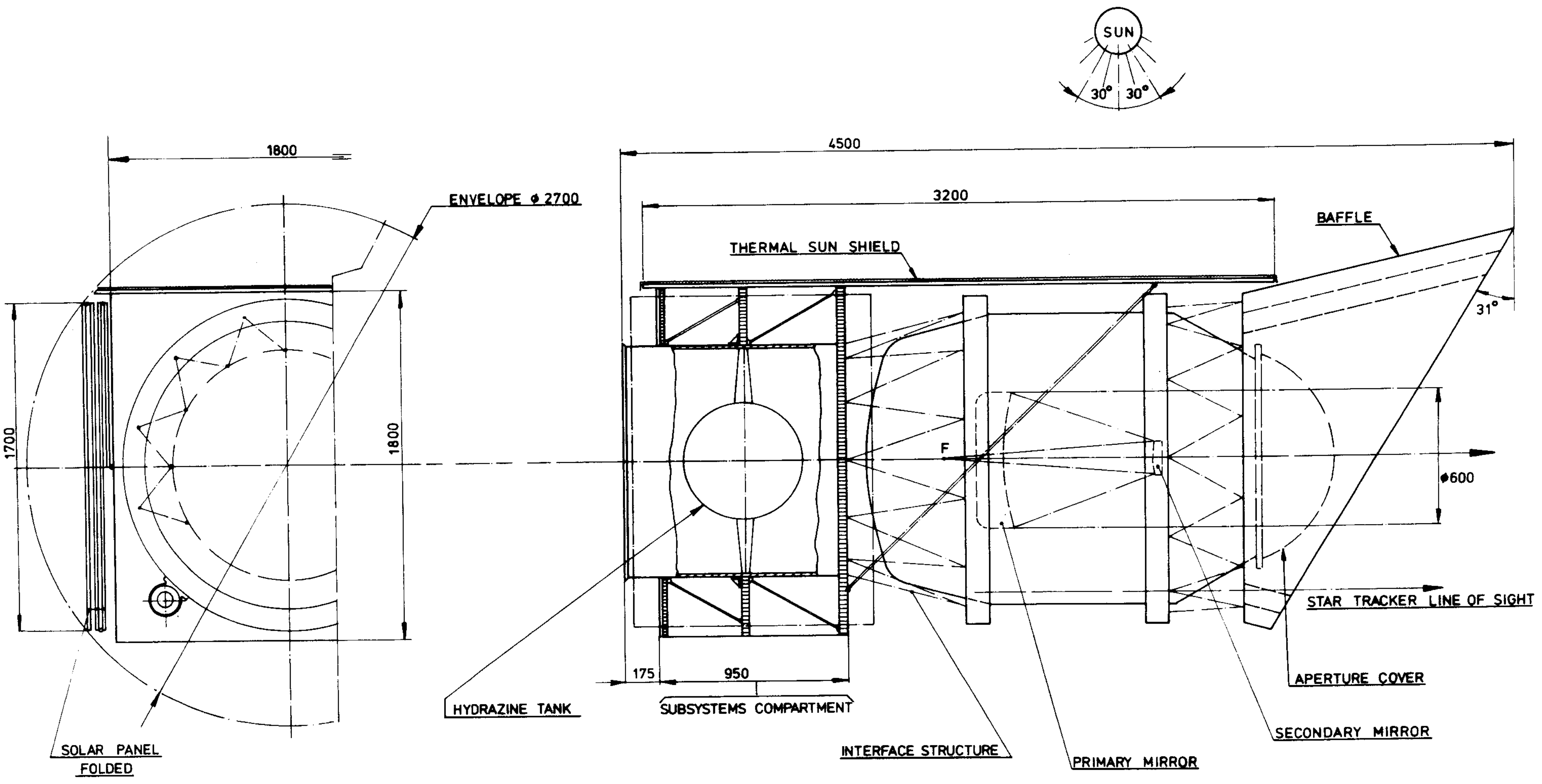


FIG. 10 - I.S.O. CONFIGURATION. 12 h.

proposed sizes demanded by ISO, is not yet accessible within Europe and consequently the assessment is tentative. Further work is obviously required in this area (see section 5.4). For the purpose of this assessment study, however, it was agreed that the IRAS cryostat design would be used as a model.

The cryostat is by far the major element of this spacecraft. From a strictly structural point of view it would be desirable to interface the cryostat directly with the launch vehicle, with the remainder of the spacecraft attached in turn to the cryostat structure. However, this configuration would present high thermal loads on the liquid helium, leading to short mission lifetime.

It is therefore proposed to decouple the cryostat from the subsystem compartment such that thermal flux radiated and conducted from the subsystems towards the cryostat is minimised. This also has the additional advantage of allowing separate design development and testing of the cryostat and of the subsystem compartment.

In order to minimise thermal coupling with the cryostat, the upper floor would be covered with superinsulation. Equipment boxes would be installed on the side wall and lower floor. The solar array and antenna booms are folded during launch and supported by the side walls.

5.2.2 Satellite Resource Budget

Preliminary mass and power budgets have been established and these are summarised in the following table.

	MASS (kg)	POWER (W)
- Telescope (incl. cryogen, experiments, interface skirt sun baffle)	942	80
- Subsystems		
AMCS	81	80
Power (incl. battery charging 95 W)	86	100
OBDH - TM/TC	27	70
Thermal	15	2
Harness	30	-
Structure	90	-
Satellite in final orbit	1271	332
Orbit Control System	171	-
Satellite at launch	1442	332

Launch capabilities		
	Ariane I	1535 kg
	Ariane II	1840 kg

If this satellite is to be launched with Ariane I a strict control of the mass will have to be exercised, since current estimates only allow 6% mass margin: at this stage of the studies 20 to 25% mass margin is considered appropriate.

The power budget reflects the worst case requirement from the solar array. Note, 95 W is included for battery charging to a level which can sustain operations during the maximum eclipse time of 2.4 hrs.

5.3 Sub-system Description

5.3.1 Attitude Measurement and Control System (AMCS)

The main pointing and control requirements of the ISO mission may be summarised as:

. The telescope optical axis can be pointed anywhere within ± 30° from the plane perpendicular to the earth/sun vector except within a few degrees of the Earth. This requirement is dictated by the need to minimise the heat load on the telescope.

. Optical axis pointing on the celestial sphere is:

- Absolute pointing accuracy	± 10 arc secs (r.s.s.)
- Pointing stability long term	± 6 arc secs (r.s.s.) for a period of 60 minutes
- Short term	± 2 arc secs (r.s.s.) for a period comparable to the AMCS gas jet limit cycle
- Attitude reconstitution (a posteriori knowledge)	preliminary requirement ± 1 arc sec (r.s.s.) but it is being investigated if this may be relaxed to ± 5 arc secs.
- Attitude roll error about the optical axis	not scientifically important, an error of 0.5 deg. is acceptable.

. No particular constraint on the time required to slew from one target to another, although the selected observation programme sequence would attempt to minimise large slew angles, in order that maximum observation time can be achieved.

Target attitude sensing reference will be provided by two star sensors which are boresighted with the telescope optical axis. The star sensors would be mechanically fixed to the telescope structure and pre-aligned with the optical axis prior-to-launch: no in-orbit alignment is foreseen. In addition to the star (boresight) sensors, sun sensors will be provided for a second reference axis; these EXOSAT type sensors control the telescope roll around the line of sight and also provide solar array pointing reference towards the sun. Note that gyros are also included to provide back-up second axis inertial reference during eclipse period and during manoeuvres; these gyros may also be similar to the EXOSAT type.

For attitude control actuation, a set of 4 reaction wheels (5 Nms) will be provided (3 orthogonal sets plus one skewed): hydrazine thrusters will provide de-saturation of the reaction wheels at the appropriate time intervals.

The proposed concept is now becoming somewhat standard for 3-axis controlled spacecraft and it is considered that the proposed requirements could be met by such a system.

5.3.2 Power Sub-systems

The power requirements (332 watts) given on page 32 will be provided by solar arrays based upon the ECS design. Two ECS panels provide 255 W. Four ECS panels would provide 510 W end of life at 30° sun aspect angle.

The requirement being 332 Watts could therefore be achieved by use of 3 ECS panels: 2 active panels on one array side and one active panel plus dummy (for balance) on the other side.

For eclipse operation two 23 Ah Ni Cd batteries are provided which are recharged from the solar array. Power distributed will be provided by a 28 V DC regulated bus.

5.3.3 On-Board Data Handling Sub-system (OBDH)

The data handling sub-system proposed for this mission is based on the standard ESA on-board data handling concept. This modular system consists of a redundant command and power distribution unit (CPDU), a redundant control terminal unit (CTU) and a number of remote terminal units (RTU) and mini RTU's. These units are connected to the CTU via a data bus, and access for experiments is via a mini RTU. Since all operations are to be performed in real time no data memory is required.

The OBDH will provide the following functions:

- accept ground commands with validation and routes routine command via CTU for execution within the appropriate unit
- acquire sample data from experiments or sub-systems as required
- formatting and routing of data and housekeeping information to telemetry transmitter
- a 250 KHz or 1 MHz clock signal together with synchronisation signals for use by the experiments

A schematic diagram of the sub-system and its interrelations with other spacecraft sub-systems and experiments is shown in figure 11.

5.3.4 Telemetry and Telecommand Sub-system

In view of the observatory nature of the mission, omnidirectional antenna coverage is necessary. This can be achieved by switching between two antennas each providing hemispherical coverage (e.g. EXOSAT): the antennas are mounted on deployed booms. In view of the number of switchings between antennas required during the life of the spacecraft and in order to minimise the data lost during the change-over time it is proposed to use PIN diodes switches rather than mechanical devices.

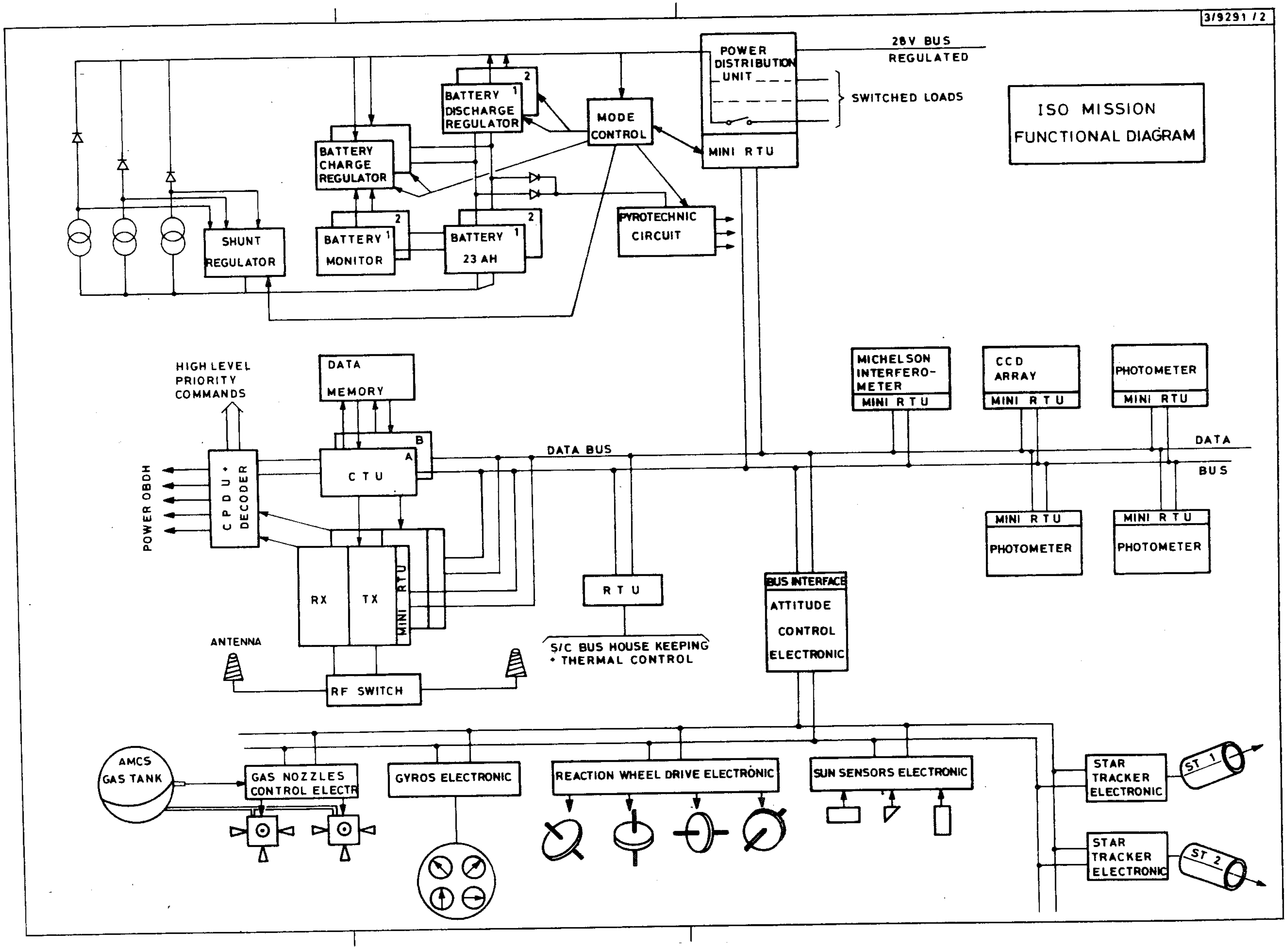


FIGURE 11. Data Handling Sub-System Schematic

Redundant standard 2.5W RF S-band transponders will be incorporated. Using Villafranca (15 m dish) insures a down-link margin of 4.3dB for a telemetry data rate of 30 Kb/s. The corresponding telecommand uplink margin would be 18dB.

5.3.5 The Thermal Control Sub-system

The requirements of the spacecraft thermal control sub-system are:

- to provide to the sub-system equipment compartment a thermal environment which is compatible with the mission operation requirements
- to minimise the thermal exchange between the equipment compartment and the cryostat
- to maintain the temperature of the cryostat outer skin as low as possible during the entire mission.

For the sub-system compartment passive control techniques are suitable, however a few heaters will be required for temperature maintenance during long eclipses.

Temperature levels will be maintained by a combination of super insulation blankets and adequate radiators on the anti-sun face. Maximum thermal decoupling of the equipment compartment and cryostat will be a design feature.

Concerning the temperature of the cryostat outer skin preliminary analysis indicates that a value of 170 K can be maintained by completely covering the structure with a multilayer insulation blanket.

The sun facing side of the cryostat will be shielded by a thermal screen and low emissivity coatings on all spacecraft surfaces facing the cryostat will be applied. In addition the cryostat support structure must be manufactured from low conductivity material.

5.3.6 Structure

The main structure of the sub-system compartment would be a tube interfacing at one end with the cryostat interface skirt, and at the other end with the launcher. The hydrazine tank would be located inside this central cylinder. The sub-system compartment would be closed by 4 side walls and the upper and lower equipment floors.

This structure is expected to be relatively conventional.

Concerning the structure of the cryostat no comparable European development in terms of size and lifetime has yet been undertaken. In order to meet the lifetime requirements (1.5 years), within the mass constraints imposed by Ariane, careful design consideration must be given to the interrelationship between structural integrity and thermal loads. This may well lead to sophisticated adaptive structural techniques (e.g. retractable supports).

5.4 Areas for Future Work

This assessment study has shown that uncertainties exist with respect to the design and development of the cryostat. Also it has yet to be shown that the heat dissipation of the focal plane instruments can remain within acceptable limits, in order to ensure a lifetime of about 1.5 years. It is considered to be essential that these points are addressed prior to the start of the industrial phase A.

In this context it is proposed to take the following course of action:

- a detailed definition study of the model focal plane instruments is conducted with technical assistance from appropriate scientific institutes

- an optimization of the focal plane assembly

- explore the potential European industrial capabilities in the design and development of the required cryostat and establish design limits (mainly in the area of thermal heat load) for the focal plane instrument package.

- Should it turn out that the preliminary design calculation of the liquid helium cryostat show that the mass of the spacecraft is likely to exceed the launcher capability it would be necessary to explore the possibilities by the latest technology developments in thermodynamic cooling cycle machines. Alternatively a re-assessment of the mission objectives (e.g. instruments, lifetime, orbit etc.) would be necessary.

The results of these actions will provide ESA with the appropriate technical input for compilation of the phase A study specification.

6. OPERATIONS AND DATA MANAGEMENT

6.1 Introduction

The 12 hour orbit selected for ISO allows for almost continuous coverage of the spacecraft when two ground stations are used. It is proposed to link the two stations together via a high speed data link in such a way that one station is a slave to the main Operations Control Centre.

In the following, the ISO operations are presented based on the preferred concept of an observatory with all the supporting functions, such as quick look and *preliminary* science analysis, available at one site. This approach is felt to be by far the most attractive in terms of maximum observational efficiency for the scientists. Since the mission lifetime is only 1½ yrars, this observational efficiency is considered to be of prime importance. However, it is not the only possible mode of operation. Another option would be to provide quick look and data analysis facilities at the various institutes that have provided the instrumentation. This however would mean sacrificing the near real-time feed back in observations and it would also probably impair the exchange of ideas between scientists working with the different instruments.

6.2 Operations

This section presents a model of the mode and staffing of ISO operations. It assumes that ISO will be controlled from a ground station connected to a real-time data link between the ground station and the satellite (via a second data relay station for part of the day). It draws on the success of the ESA Observatory for the IUE satellite modified as necessary to provide round-the-clock operations. It also attempts to improve on this and also on the planning for the Exosat Observatory operations. Of course, there are alternative modes of operation which are possible and in the case of photometry, a preplanned observation programme could be used successfully. On the other hand, there is no doubt that spectroscopy and mapping would greatly benefit from a real time link.

To take advantage of the real time access to the satellite, observers will come to the ISO Observatory to perform the functions of, (i) identification of targets, (ii) near-real time quick look analysis, (iii) real time optimisation of observing programme, (iv) collection of final outputs within about a day observation.

Points (i), (iii) and (iv) require little discussion since they can follow the patterns used successfully by the IUE Observatory and at ground-based telescopes. However, a major improvement over the IUE model can be achieved for point (ii) if the quick-look analysis software forms a natural part of the later image-processing procedures. For example, reconstruction of the spectrum from a Fourier-transform spectrometer should take place during real time and may not need to be duplicated later. Such a software system would have to be well separated from the spacecraft control computer to avoid interference with operations and it is proposed that the control and image processing computers be connected only by a one-way link allowing data to be sent to the latter. This also has the possible advantage of permitting a "hands-on" operation of image processing computer by visiting astronomers without affecting the operations.

6.3 Data Management

It is to be expected that, while adequate image processing software should exist for each focal plane instrument at launch, the acquisition of real astronomical data will present problems - and also provide opportunities not previously foreseen. Therefore, it should be anticipated from the start that improvement and optimisation of the image processing software will be an on-going process following launch through the lifetime of the satellite. A schematic scientific data flow is illustrated in figure 12.

Image processing computers and software support will be necessary to provide:

i) quick look data in real time
ii) a final image processing system
iii) a test-bed for image processing improvement.

Some of these functions are similar to those required for instrument checkout, where possibly they could be provided as part of the scientific instrument. Mini-computers attached to array processors will probably be adequate for the tasks mentioned above. The exact specification for these computer systems would only be possible after the experiments are selected and the data processing requirements settled.

Special attention should be paid to the final scientific data reduction activity. While it is proposed that this activity be part of the tasks of the instrument teams which will be selected both for the actual hardware and for the data reduction software (both quick-look and final data processing), it is certainly worthwhile to consider the option that the final processing be actually carried out at the operations centre under the responsibility of the teams but under ESA's overall observatory management. This approach would ensure timely delivery of data products to the user community.

6.4 Observatory Staffing

Since it is preferable to concentrate all data reduction activity at the operations control centre, this approach leads to the following requirements.

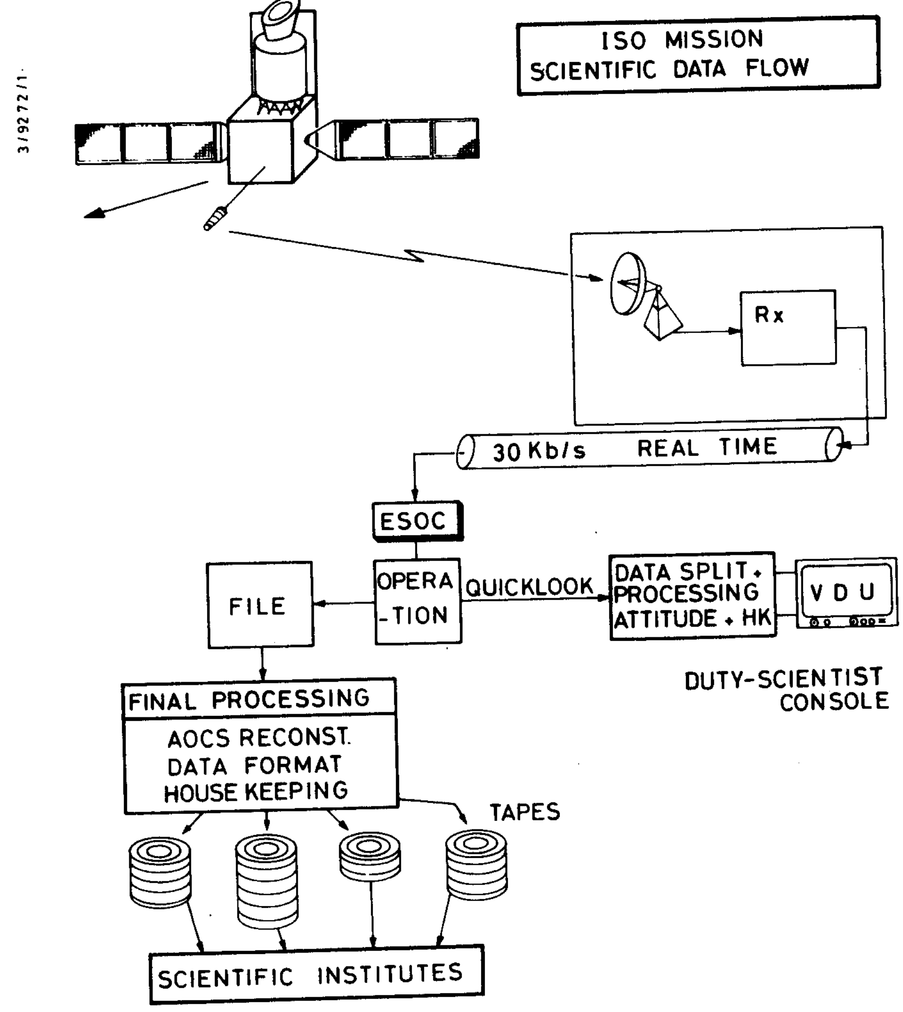
In order to interface with the users, who will not all be deeply familiar with ISO's performance and capabilities, and to support the improvement of the image processing, a scientific (observatory) group, resident at the ground station, will be necessary following the IUE model.

As a starting point to estimate the number of staff necessary to operate such an observatory, it might be assumed that the following tasks have to be carried out:

i) to support real-time operations
ii) to "train" new users
iii) to improve image processing software
iv) to support image processing

It is estimated that about 13 man years of effort are required for the basic *science* operations. Naturally, astronomers performing functions (i), (ii), and possibly (iii), will require time to carry out some

FIGURE 12.


ISO MISSION
SCIENTIFIC DATA FLOW
3/9272/1
Rx
30 Kb/s
REAL TIME
ESOC
OPERA
-TION
QUICKLOOK
FILE
DATA SPLIT +
PROCESSING
ATTITUDE + HK
V D U
DUTY-SCIENTIST
CONSOLE
FINAL PROCESSING
AOCS RECONST.
DATA FORMAT
HOUSE KEEPING
TAPES
SCIENTIFIC INSTITUTES

research work. Therefore a figure of roughly 16 man years should be taken as indicative of the level of support required. In addition, about 4 man years of support staff will be essential.

It seems unlikely that ESA alone could provide such a large group of astronomers and analysts to operate the ISO observatory. Apart from this reason however, it would also make excellent sense to place on the groups providing the focal plane instruments the obligation and the advantage of providing some astronomical and system analysis staff. This would provide an essential and natural continuity between "project" and "operations", given that the instrument groups would be responsible for the image processing software. On the other hand, ESA will need to maintain the overall management of the observations since it will still bear the major responsibility for all aspects of the operations.
A guide to the level of support that might be sought from P.I. groups may be made by considering that there are three focal plane instruments, and for each instrument the P.I. group might provide two astronomers plus possibly one image processing analyst to the ISO Observatory.

7. MANAGEMENT

The basic philosophy for the division of work is that ESA shall be responsible for the spacecraft systems, spacecraft operations and for the science operations and data handling to the extent proposed in Section 6. Within the definition of the term spacecraft systems is included the liquid helium cryostat. It excludes the telescope system and the scientific focal plane instruments. These should be designed, built and tested as a single integrated scientific instrument system. Each major part of this system would be the responsibility of a Principal Investigator who is supported by National funding.

The relationship between the scientific instrumentation for ISO and the spacecraft system as defined above is a rather unusual one in that the mass of the instruments and, in particular, their power dissipation to the cryogen determine in a major way the total amount of cryogen required and hence the size and mass of the single largest component of the spacecraft. This makes it imperative that the design of the total system is right before proceeding to an advanced stage of development. This probably requires that the design phase be longer than normal. It also means that the control of the scientific instrument development and of the cryostat must be extremely tight in a management sense. The total management scheme, inside ESA and amongst the P.I.'s must reflect this necessity. Likewise all participants in the project must, from the outset, accept that stringent controls have to be applied and will be applied.

7.1 Proposal Phase

Following approval of the mission by the Science Programme Committee, ESA will issue an announcement of opportunity for the European scientific community to participate in ISO to provide the telescope system and/or specific focal plane instruments and associated equipment. The announcement of opportunity will state the scientific requirements, the technical interfaces and the scheme for their control by ESA, the schedule, deliverable items, responsibilities of the parties, the observation programme philosophy, etc. The proposals from the scientific community must show the management structure within the collaboration and the means for ensuring that the responsibilities for the scientific, technical, operational and analysis activities will be properly discharged.

Selection of proposals will be via the normal route of recommendations by the ESA advisory groups and approval by the Science Programme Committee.

7.2 Design and Development Phase

After the selection, the participating laboratories will be responsible for the detailed design, development, procurement and calibration of the relevant experiment subsystem on a time schedule which is in accord with the spacecraft development plan (see fig. 13). To assist in this process and to provide the essential very close interaction with the spacecraft design and development process, it will be necessary to establish an ISO Instruments Working Group composed of the experiment Principal Investigators, the Project Scientist and an ISO Instruments Coordinator as nucleus, supported by co-investigators and the Project Manager, as appropriate.

At an early stage in the Phase B definition of ISO, the ESA Project Manager will draw up an ISO Project Plan. This will provide the blueprint for the future project development through to the operational phase. It will give the necessary visibility to the main elements in the project development and provide an agreed working basis for the project and for the PI's. Those sections related to the instrument development will, of course, be generated in close association with the relevant Principal Investigators. The final document will be made available to the ESA advisory and delegate bodies for information.

To minimise the number of changes in the cryostat, it is mandatory that the layout and interface of the telescope and focal plane package be defined prior to the start of the cryostat design.

For the development and production of the cryostat, it is proposed to build 3 models:

- a structural and thermal development model (STM)
- a qualification model (QM)
- a flight model (FM).

For the subsystems, a structural and thermal model (STM), an electrical engineering model (EM) and a proto flight model (PF) should be sufficient.

It is estimated that for the design and procurement phase of the cryostat ESA would need a team of 12 persons, on average. For the design and procurement phase of the subsystems and for integration and test of the spacecraft, ESA would need a team of 20 persons, on average.

7.3 Operational Phase

During the operational phase, the science instrumentation teams are charged with the responsibility for carrying out scientific instrument performance verification, and providing input for updating and fine tuning the science

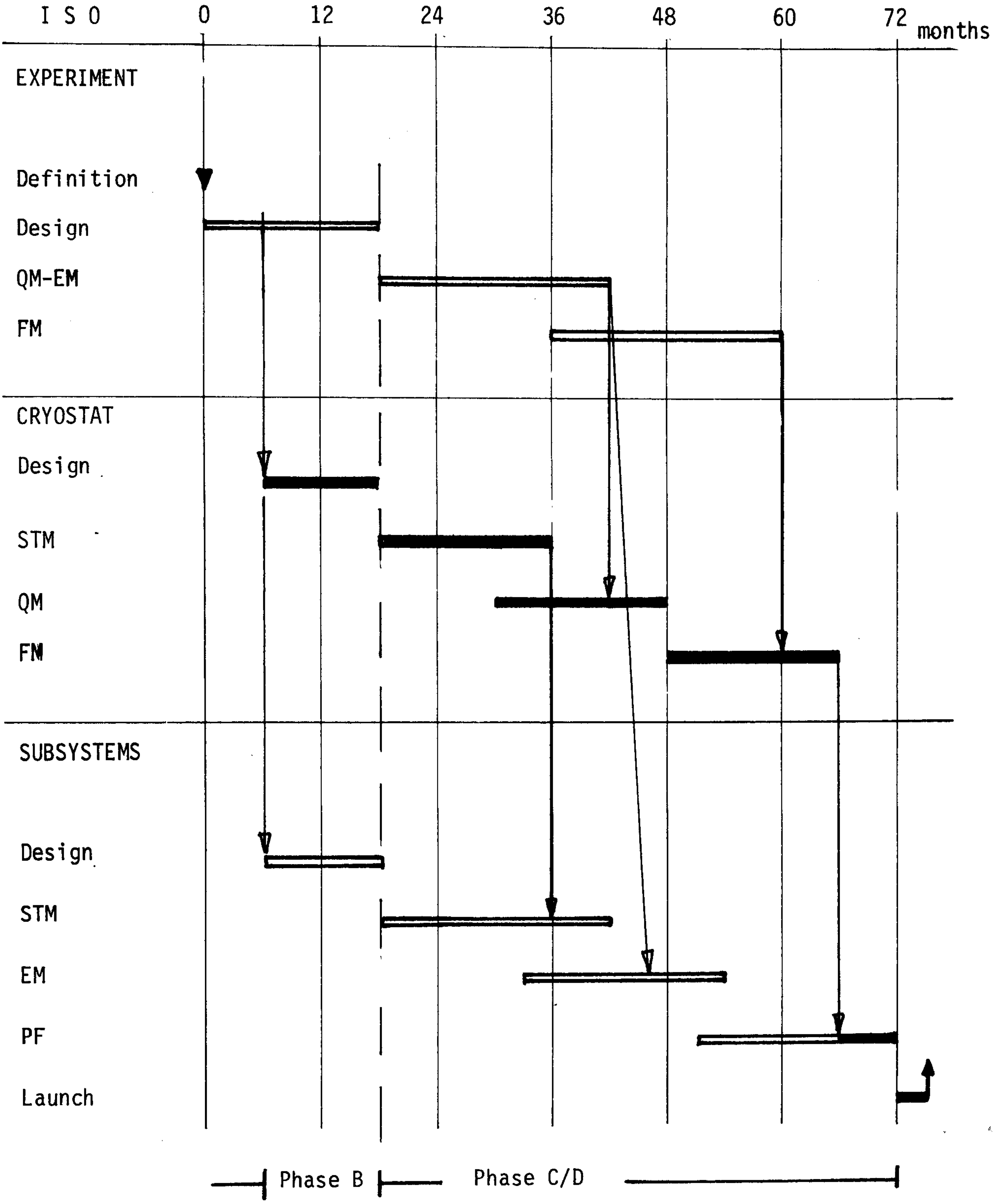


FIGURE 13. Spacecraft Development Plan

data reduction system. The initial process of performance verification will be followed by a period of exclusive use of ISO by the PI teams, the total period being of about 3 months.

In general, the observing time on ISO should be assigned to proposers satisfying review by a peer group selection committee. This selection committee could include or evolve from the ISO Instrument Working Group which has monitored the design and construction of ISO. Two calls for proposals should be made, one some time before and the other immediately after launch, as soon as the in-orbit performance of ISO is known.

A fair and equitable allocation of observing time for the P.I. instrument groups and the Observatory team is necessary to ensure that the instrument building and also the operations are well motivated scientifically. This time would be distributed to cover the whole of the first 2 months of routine operation in the case of the PI teams and two 8-hour shifts per week for the PI groups and their Observatory staff thereafter. The commissioning, calibration and demonstration of the in-orbit capabilities of the satellite will take an estimated 4 weeks after aperture cover release, during which time the instruments will be used solely by the P.I. teams.

Observers should have sole access to their own data until a fixed period after data delivery. This period should be long enough to prevent attempts to publish undigested data in the journals, yet short enough to avoid the temptation to make duplicate observations. Bearing in mind the short lifetime of the satellite, a reasonable choice for the sole access period might be 9 months. ESA will maintain a data bank to archive and deliver the raw and processed data after the end of this reserved period.

8. COMPARISON WITH OTHER SYSTEMS

Other space infrared astronomy systems have been proposed or are in the hardware development phase. Here, we will briefly present their prime characteristics and compare them with the present proposal.

The present proposal is perhaps closest to the proposed SIRTF mission, being studied by NASA. Both the scientific objectives and the proposed focal plane instrument complement are quite similar. The striking difference between the two missions is in the mission duration. This difference is especially important when one considers the effects of the learning curve involved in operating complex scientific instruments in a novel environment. Especially for an observatory type mission the one to two years foreseen for ISO are extremely important to achieve maximum science benefit (IUE illustrates this point). We believe that the gain associated with the extended duration of the ISO mission offsets any advantage of the Spacelab environment. Obviously, there are many basic scientific reasons to prefer a long duration mission, such as the opportunity to study more objects, to obtain higher sensitivity, to achieve maps to lower surface brightness levels or of larger regions, to study variability, etc.

An interesting comparison can also be made with GIRL. This telescope will carry photometric and spectroscopic instruments. In many respects the GIRL mission will be a precurser of ISO and many studies of an exploratory nature in the infrared wavelength domain can be made by GIRL, thus paving the way for more comprehensive studies by the more powerful ISO. GIRL will be most important in directing the research areas in which ISO could be most usefully deployed.

In comparison with LIRTS the major differences with ISO are mission duration, telescope size and telescope temperature. The LIRTS primary aim was to perform high resolution spectroscopy in the far-infrared and to achieve high angular resolution. Very high resolution spectroscopy in the far-infrared does not require a cryogenic telescope, it can best be accomplished by a very large telescope using heterodyne receivers. In comparing the two types of mission, it was decided that a cooled telescope with instrumentation which concentrates on the region below 200μ was to be preferred. It is in this 1-200μ regime that the transitions occur due to vibration and vibration rotation in molecules and solids, where the atomic and ionic fine structure lines occur and where the infrared excesses are observed in galactic sources. It is in this wavelength region also that major improvements are occurring in photoconductor detector performance, giving NEP's of $10^{-17}\mathrm{W}/\sqrt{\mathrm{Hz}}$, which will allow very large increases in sensitivity when coupled with a space cryogenic telescope. Indeed, it is this very fact of improved detectors that led to a reassessment of the value of the LIRTS concept. The table below summarizes the status of infrared space astronomy projects.

	TELESCOPE			DURATION	MISSION OBJECTIVES	LAUNCH	STATUS
IRAS	cryogenic	0.6 m	satellite	1 year	sky survey/photometry	1981	approved
GIRL	cryogenic	0.5 m	spacelab	7 days	spectroscopy/photometry	D4(>1983)	approved
SIRTF	cryogenic	1.2 m	spacelab	7 days	spectroscopy/photometry	1985	study
LIRTS	uncooled	2.4 m	spacelab	7 days	spectroscopy		studied
COBE	cryogenic	0.6 m	satellite	1 year	cosmic background	1985	study