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FAR INFRARED INTERFEROMETER TECHNOLOGY REFERENCE STUDY

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ABSTRACT

In response to ESA's call for space science themes in the frame of Cosmic Vision 2015-2025, the scientific community identified a Far Infrared mission with very high spatial resolution as a potential future science mission for Europe. A future far infrared mission would typically work at wavelengths between 25-300 microns and combine high sensitivity with an angular resolution better than 1 arcsecond at the shortest wavelengths. Such requirements would call for very large telescope diameters or for an interferometer based design.

To investigate the feasibility of this potential future mission the Science Payload & Advanced Concepts Office (SCI-A) at ESA initiated a Far Infrared Interferometer (FIRI) Technology Reference Study (TRS). The selected baseline concept for this study is a single spacecraft Michelson interferometer (i.e. pupil plane recombination) with two light collecting telescopes and a central hub beam combiner, all cryogenically cooled. To enable such a mission concept many innovative design solutions and technology developments would be required in the area of cryogenics, mechanisms and optics.

In this paper an overview of the result of the internal feasibility study of the FIRI concept will be provided. Specific emphasis is on critical subsystems and on required future technology development activities.

INTRODUCTION

ESA is currently defining its future science programme; Cosmic Vision 2015-2025. In a call for themes within this programme a Far Infrared mission was identified as a potential future project for Europe. This mission would be a European follow on from the Herschel mission, scheduled for launch in 2008. With a mirror of 3.5 m in diameter, Herschel will provide a very high spatial resolution compared to existing infrared missions. Nevertheless a further improvement in spatial resolution, especially at the FIR wavelengths, remains a main driver for a future far infrared mission.

Improving the spatial resolution to less than 1 arcsecond at wavelengths below 100 microns requires a much larger aperture than Herschel (~30 m in diameter) or alternatively an interferometer. To achieve the required angular resolution by using a large single aperture would result in a mirror too large to be technically feasible within the Cosmic Vision timeframe. Thus ESA decided to study a far infrared interferometer (FIRI) as a technology reference study (TRS).

In a TRS a feasible mission concept is established through a dedicated system level study. In such studies the critical technologies required to enable potential future missions are identified. This allows a coordinated and consolidated approach to technology developments.

MISSION CONCEPTS

Two concepts were identified as the most promising candidates for FIRI; a formation flying concept and a concept using a single spacecraft with telescopes located on a boom.

The formation flying concept would be similar to what is proposed for Darwin [1]. A formation flying mission would offer several advantages. For instance the constellation would be able to provide very large inter telescope distances (baselines) and thus superior spatial resolution. In addition, the formation flying concept could take considerable advantage of the ongoing developments for Darwin. In fact, many of the critical issues for a Far-Infrared formation flying interferometer will be investigated during the Darwin study. Nevertheless, a formation flying concept would also have considerable disadvantages. Not only is a formation flying concept technically very challenging, but it is also likely to be very costly as several independent spacecraft would have to be produced and individually tested. Complexity of operations is also an issue in the case of formation flying.

The other mission concept is based on apertures moving along a boom, which is fixed to a central hub. On one hand this approach will have a maximum Inter Telescope Distance (ITD) that will be constrained by the boom size. Therefore the spatial resolution achievable with this configuration will be lower than for the formation flying concept. On the other hand this concept is likely to be less expensive as only one spacecraft is used.

In the spirit of a TRS, it is also of interest to establish requirements for generic technologies needed for future science missions. As an example, in the case of the interferometer based on apertures moving on booms, ESA would be able to investigate in more detail the issue of large deployable booms and long stroke mechanisms.

Considering that the formation flying scenario is already under investigation for Darwin, the cost of the boom concept is likely to be lower than formation flying and the boom technology is of general interest, ESA decided to baseline FIRI on the single spacecraft concept.

Another main trade-off for the mission was whether to use direct detection or heterodyne detection for the interferometer. The two detection schemes would obviously lead to different types of science and it is clear that a final choice would need to be done together with the scientific community. Nevertheless, from a technical perspective the two detection schemes would lead to very different missions; in the case of heterodyne detection, optics could be warmer than for direct detection, which requires very cold apertures to obtain the required sensitivity. Hence direct detection is much more challenging from a system point of view. It was therefore decided that such a direct detection scheme would be investigated further, knowing that a heterodyne detection scheme could potentially enable an easier mission profile than the one selected.

SCIENCE

In the case of an approved science mission the science requirements would be defined by the scientific community. In the case of a TRS, mission requirements are based on typical science objectives of FIR astronomy.

Formation and evolution of stars

Stars form in molecular cloud cores that are optically thick even to wavelengths in mid infrared. The formation occurs when the cloud collapses which causes the temperature and density of the cloud to increase. The temperature and density is highest in the centre of the cloud where a new star, protostar, will form. Dust surrounds the protostar that absorbs visible light, thus the only way to image this area is by using longer wavelengths such as far infrared. FIRI would typically investigate the collapsing molecular cloud and obtain spectral maps that would enable internal chemical structure evaluation.

Most stars form in clusters which are the result of a giant molecular cloud collapse. In a cluster several stars with common heritage will typically be formed. Star formation in clusters is therefore important in the study of star formation and evolution.

Binary star formation is also of interest for FIRI as the theory behind such formation is not well understood. Further study to properly understand the theory of multiple star formation would typically be of interest to a mission such as FIRI.

Formation and evolution of planetary systems

When stars are formed they will be surrounded by a circumstellar disk. The current theory for the formation of planetary systems is that planets are accreted from the dust and gas in this protoplanetary disk. However, further knowledge on the formation of planets and planetary systems are required. This would require study of chemical content of protostars and protoplanets. FIRI would not be able to directly detect the light from extrasolar planets. However, imaging can detect the dust in the protoplanetary disk. The shape of this debris disk is perturbed by an orbiting planet around the star resulting in a resonant structure. Depending on the number of planets, their size, their orbit etc. the debris disk will obtain different resonant structures. Based on this type of measurements FIRI could detect a series of new extra solar planets and could be able to image the warmer dust, which is not accessible from ground measurements. The imaging of warmer dust will allow FIRI to better understand the relationship between planets and extrasolar objects similar to the ones in the Solar System's Kuiper belt.

Formation and Evolution of galaxies

Studying how galaxies form and evolve over time could be another main objective for a mission such as FIRI.

The Cosmic Infrared Background (CIB) is the universe's radiation content from all sources throughout the history of the universe. The red shifted starlight and dust absorbed and re-radiated starlight of the CIB can be used to determine star formation rates and metal production as a function of time, thus providing important input to the understanding of cosmic history. Studying the CIB and resolving it into discrete sources in the FIRI waveband would therefore be one of the science objectives of FIRI.

HII regions and supernovae remnants are characterized by warm dust continuum emission and are both, discrete IR sources. By studying these sources in a massive star formation region in a large sample of galaxies one can expect to gain new insight into the star formation process.

Payload Requirements

Based on the science topics some typical payload requirements were derived for the FIRI TRS. These requirements are described in Table 1.

Waveband	25-300μm
Angular Resolution	<~1.5" @ 200μm
Field Of View	>1'
Spectral resolution	$>3\cdot10^3$
Sun aspect angle	±25 degrees (Goal ±45 degrees)
Line sensitivity	$\sim10^{-19}$ W/m^2 (Goal: 10^{-21} W/m^2)

Table 1 Payload requirements for FIRI

PAYLOAD

The line sensitivity requirement of FIRI is very challenging, demanding the use of cryogenically cooled optical elements and a very sensitive detector. Generally the line sensitivity, particularly at long wavelengths, will be more sensitive to temperature than to mirror area. Assuming typical mirror emissivity the optics would need to be cooled to a temperature below 5 K to not be dominated by the thermal background at 300 μm. To meet the line sensitivity goal of 10^{-21} W/m^2 very large, cryogenically cooled apertures would be required. As the mirror size is a large driver for the spacecraft design, it was decided to design the spacecraft for the line sensitivity requirement of $<\sim10^{-19}$ W/m^2, leading to a mirror size of approximately 1 m and to detectors with background limited performance.

Interferometer

The interferometer optics consists of light collecting telescopes located on the boom and hub telescopes and beam mixer located in the hub.

To achieve the FOV requirement of 1 arcmin either image plane recombination (i.e. Fizeau-type interferometer) or pupil plane recombination (Michelson-type interferometer) with a detector array could be used. As the image plane recombination implies stricter control requirements than for the Michelson interferometer, the Michelson interferometer was selected as the baseline. In addition, a Michelson interferometer can easily operate in a double (spatio-spectral) Fourier mode and the detector array size is reasonable.

Telescopes design

The two telescopes on the boom are identical on-axis (Figure 1) telescopes, consisting of two aspheric reflectors, a parabolic reflector and a folding mirror. The mirrors would be fabricated in Silicon Carbide, with a single layer of Aluminium coating and a diameter slightly above 1 m. A refocusing mechanism is located on the M2 mirror in order to compensate for the changes in telescope structure and reflector shape at cryogenic temperatures. The telescopes have a magnification of 5, resulting in a collimated beam diameter of about 20 cm being transmitted to the hub.

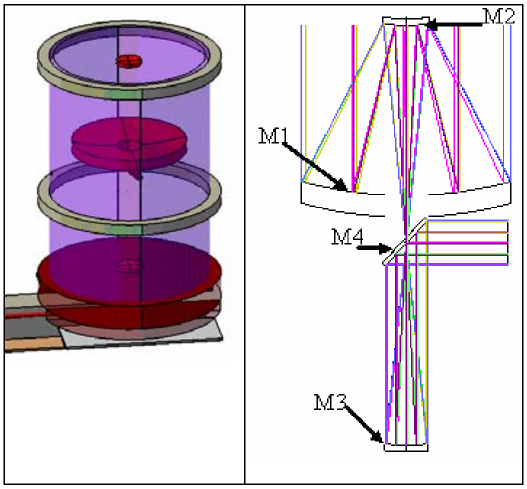

Figure 1 Optical layout of the telescopes

The two telescopes have strict positioning and pointing requirements with respect to both each other and the hub. An error in position would result in an error in the optical delay, thus the position needs to be stable during measurements. The pointing of the telescopes needs to be well known and the relative pointing between the telescopes has to be very accurate in order to have coherent overlapping of the two collimated beams in the beam combiner. This alignment will be provided by the pupil conditioner units located after the hub telescope.

Hub telescope design

In the hub two identical off-axis light collecting telescopes are located (Figure 2). These telescopes are slightly oversized with respect to the incoming beam diameter in order to compensate for the specified maximum deflection of the booms and diffraction effects. Such an off-axis design allows for mass and volume saving compared to an on-axis design. The magnification of the hub telescopes would also be about 5, resulting in an overall magnification of approximately 25.

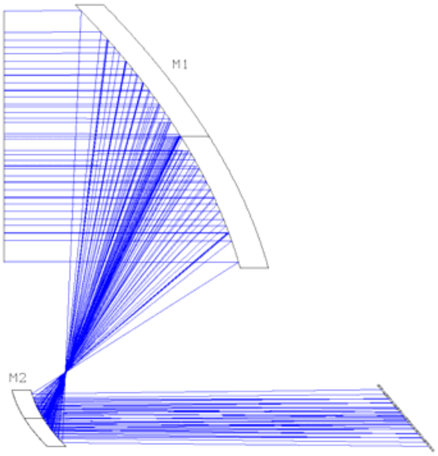

Figure 2 Optical layout of the hub light collecting telescopes

Beam mixer

The overall optical chain (from the collector telescope to the science detector arrays) and the different signal paths (science, fringe tracking and internal metrology signals) are represented in Figure 3.

The beam mixer is designed for a Michelson interferometer. To limit the size of the optics and considering diffraction effects an internal beam pupil of ~40 mm is selected. The recombination of the beams is based on using double-Fourier spatio-spectral interferometry [2], which has been demonstrated at shorter wavelengths in [3]. Using this method over such a large band as 25-300 µm requires a very long stroke optical delay line (ODL) in the order of ± 300 mm including margins. By splitting the complete wavelength range into several sub-bands, e.g. 4 (~1 octave per sub-band), several benefits is obtained; reduction of the observation time, better spectral resolution uniformity on each sub-band, separate optimized focusing optics, etc. The main disadvantage is the increased complexity of the ODL. In principle one ODL is required for each sub-band. However, it is possible to merge all ODLs into a single compact one; for each sub-band the internal reflections in the ODL is increased by a multiple of 2 from those of the shortest wavelengths. The mechanical stroke of the ODL is thereby reduced to ± 35 mm.

Concerning the science beam combiner, the main drivers are the compactness and the symmetry. To relax the component specifications, an inherent perfectly symmetric beam combiner is the preferred option.

The fringe tracking is done by observing interference of light coming from objects in the field of view of a dedicated fringe sensor. As the science targets might be too faint for fringe tracking, the fringe tracker will use visible or near infrared objects in the 3 arcmin FOV of the fringe tracker. The fringe sensor unit will target OPDs and tilt accuracies of about 100 nm and 10-20 mas respectively.

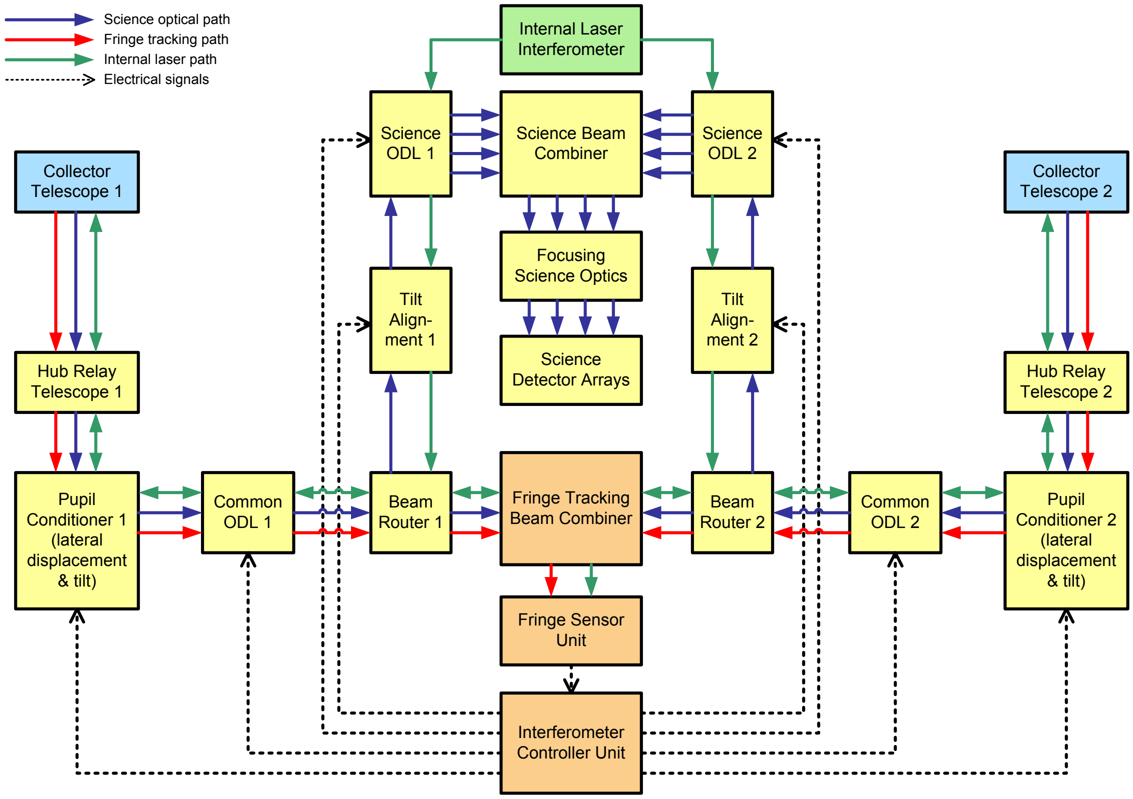

Figure 3 Block diagram of the interferometer

Metrology system

In order to acquire and track fringes and lock into the zero-OPD position of a reference object and the fringe tracking system, it is proposed to have an absolute metrology system that estimates the position of the telescopes with respect to the hub with ~10 µm accuracy, in addition to an internal laser interferometer that calibrates for internal OPDs and provides relative OPD measurement between the collecting telescopes with ~100 nm accuracy. Such systems would be based on developments carried out in the frame of the Darwin mission.

Detector

The presence of four different sub-bands implies that four different detectors and associated focusing optics are needed. The number of pixels will be different for each band (Table 2).

Band #	λ_{min}	λ_{min}	# of pixels
1	25	46.5	18x18
2	46.5	86.6	10x10
3	86.6	161.2	6x6
4	161.2	300	4x4

Table 2 Sub-bands for the interferometer

In order to provide background limited performance the detector needs to have a noise equivalent power of the order of 10^{-20} W/Hz$^{1/2}$. Detectors with this performance are not yet available and thus significant technology development is required.

One promising detector technology for achieving this sensitivity is Transition Edge Sensors (TES) [4], [5]. The TES consist of an absorber, a resistive thermometer and a link to a heat bath. The TES is biased at the transition temperature between superconducting and normal resistive. When an incoming photon deposits heat in the absorber the temperature of the absorber will change, causing a change in resistance over the TES and the current flowing through it. This change in current is measured by superconducting quantum interference devices (SQUIDs).

The absorber size of a typical TES is rather small and to have a filled array would therefore require a large number of pixels. To reduce the number of pixels a lens matched to the wavelength of interest would be located in front of the TES. This would allow to easier match the TES size to the telescope optics in addition to increase the efficiency of the detector.

To achieve the required sensitivity the TES is expected to operate down to about 50 mK, which is a major design driver for the cooling system. To avoid different focusing optics for each detector, it is envisioned that all the detectors have the same overall dimensions.

SPACECRAFT

The FIRI spacecraft consists of two main elements; the payload module (PLM) and the service module (SVM); The PLM contains all the optical elements, the detector and the cooling system, while the SVM contains spacecraft subsystems, including the translation mechanism. A mission summary is provided in Table 3.

To obtain the required angular resolution a maximum ITD of 30 m is needed. This implies that the booms are deployed after launch. Figure 4 shows the final configuration of the spacecraft once in orbit.

FIRI mission summary		
Mission	Launcher	Ariane 5 ECA
	Orbit	L2, Wide Lissajous
	Lifetime	5 years
	Interferometer	Michelson
	Max. ISD	30 m
Payload Module	Mass (dry)	2590 kg
	Telescope	Ø ~1 m
	Detector	4 x TES
	Detector T	50 mK
	Optics T	5 K
Service module	Mass (dry)	2180 kg
	Power	1395 W
	Propellant	420 kg
	AOCS	RW
	Communication	Ka-band 26 GHz

Table 3 FIRI mission summary

Due to the very long booms the launch configuration is a major design driver for FIRI. The baseline launch configuration is shown in Figure 5. This configuration is based on having the two telescopes located on top of the hub. In order to have a direct load path to the launcher adapter additional support beams are connected to the telescopes sides. These support beams would be jettisoned after launch. To minimize the design complexity of the hinges and the mechanisms, the configuration is such that the load from the telescopes will not go through any of those items.

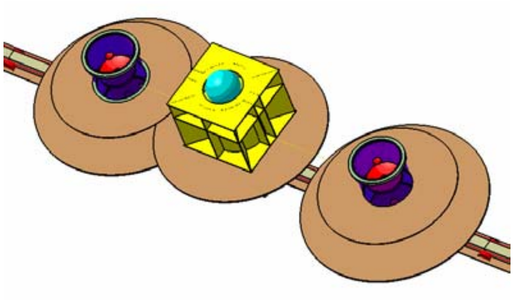

Figure 4 Short ITD configuration in orbit

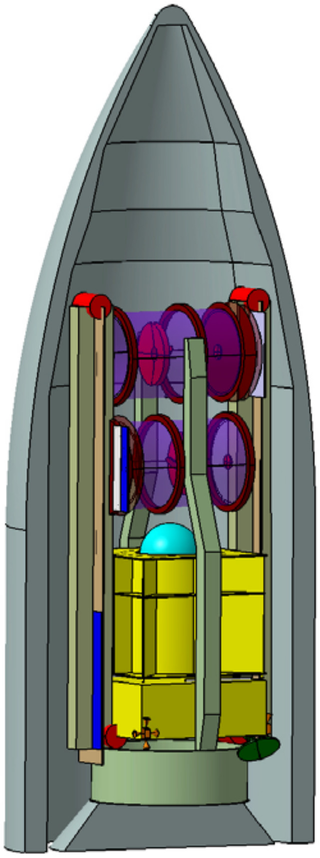

Figure 5 FIRI launch configuration

Science Operations

In order to make a proper image an interferometer needs to sample the uv-plane. This is done by moving the telescopes to different positions thereby obtaining different ITDs in different directions. Good sampling of the uv-plane is needed to meet the imaging requirements. For FIRI this is done by rotating the spacecraft at the same time as the mirrors are moving radially along the deployed booms.

Not all the measurements would require a complete uv-coverage. Nevertheless, the main strategy is to provide full uv-coverage from maximum ITD to minimum ITD in less than one day. In addition FIRI would be able to accommodate a slower sampling of the uv-plane thus facilitating more sensitive observations and a sparser sampling of the uv plane, for instance in the case of preliminary investigations. A range of different observation strategies can therefore be accommodated, allowing the scientists to tailor the uv-coverage to each specific observation.

Orbit

An orbit around L2 was selected in order to simplify the thermal design and to minimize perturbations. At L2 eclipses and insertion manoeuvres can be avoided by selecting the right orbit. In the case of FIRI this is achieved by placing the spacecraft in a wide Lissajous orbit with a semi-major axis of about 800 000 km. By selecting this orbit the Ariane 5 can perform a direct insertion into the operational orbit without the need for insertion manoeuvres at L2. Such transfer yields a launch performance of about 6270 kg when Ariane 5 ECA is used.

Another benefit of the wide Lissajous orbit is the limited need for orbit maintenance manoeuvres. Such manoeuvres require only a small Delta-V and are necessary only a few times per year. The selected mission profile therefore greatly reduces the propellant needed for FIRI.

Thermal

The cryogenic systems are large resource drivers for the FIRI mission. Not only is the thermal design of the mirror challenging, but also the very low temperature of the detector complicates the thermal design.

Three independent cryogenic systems are required, one on each telescope and one in the hub. The two telescopes have the same requirements and thus the cryogenic systems are the same. However, the hub cryogenic system would be quite different in order to accommodate the low temperature detector and the large heat dissipation coming from the mechanisms.

The general concept of the thermal design of FIRI is to minimize the heat load by sun shields. The sun shields are sized to accommodate a sun off pointing angle of 45 degrees. This sun aspect angle can be traded against the minimum ITD that FIRI can achieve. With a 45 degree sun aspect angle the two telescopes on FIRI cannot be closer than 8 m due to the presence of the shields. If the sun aspect angle was reduced to about 25 degrees the minimum ITD would decrease to about 5.5 m.

Telescope thermal design

The thermal design of the telescopes uses passive cooling as far as possible. Two sun shields are used to provide two different low temperature areas on the telescope. These areas are used as low temperature radiators for the sorption compressors, similar to what is envisioned for Darwin [6]. The lower radiator operates at ~ 100 K and serves as a heat sink for the H_2 sorption JT compressor, which pre-cools an intermediate shield and the He-JT line to below 20 K. The upper radiator acts as a heat sink for the He-sorption compressor at ~50 K, which cools the optical compartment and the optical elements down to 4 K. Due to the large distance between the various elements, multiple cold-heads are foreseen to minimise the temperature gradients within the optics. The outline of the telescope cryogenic design is shown in Figure 6.

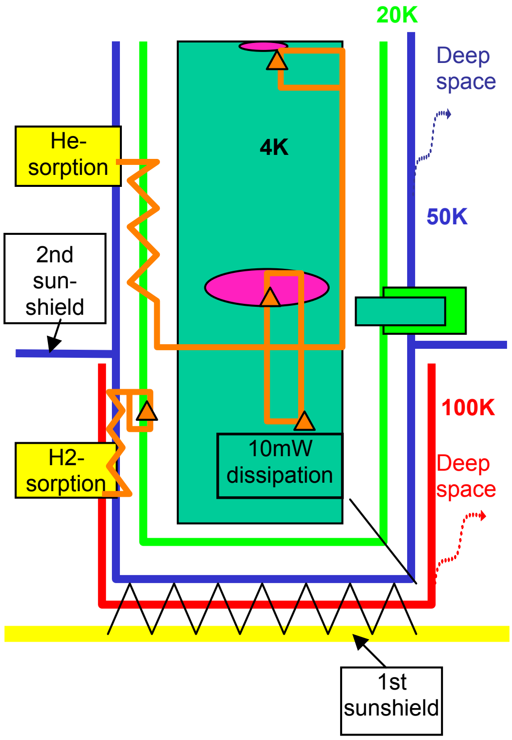

Figure 6 Outline of the telescope cryogenic design

The 50 K radiator is mounted via isolating struts on the moving mechanisms, below the primary sunshield. This design enables to cool the telescope down to 4 K, even when the tip tilt mechanism dissipates on average 10 mW.

Hub thermal design

Similar to the telescopes, the Hub takes advantage of passive pre-cooling, but the area available for radiators at 50 K is not sufficient to support the use of Helium sorption cooler. In order to keep the design as simple as possible, a solid Hydrogen cryostat has been selected for cooling a shield at 8 K, and by using the Hydrogen vapour, another shield is cooled at around 30 K. Finally, in order to minimise the residual force on the Spacecraft, the hydrogen gas will be vented to deep space via a low thrust vent head.

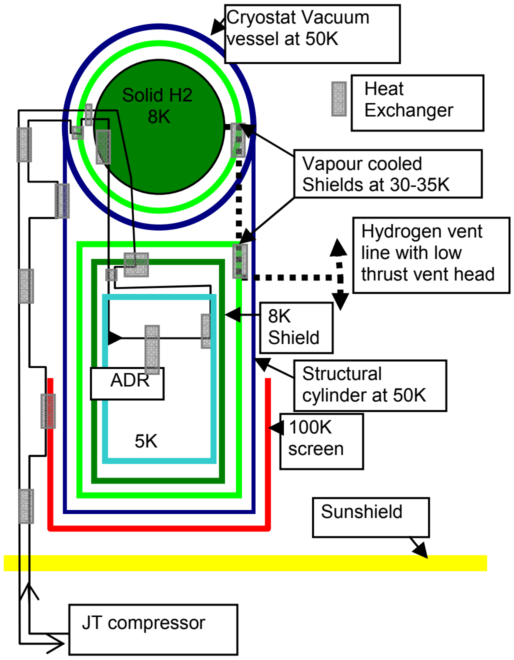

Figure 7 Hub cryogenic cooling concept

A Helium Joule Thompson (JT) cooler cools the hub to about 5 K in addition to transport heat between the 8 K shield around the optical compartment and the solid hydrogen.

Detectors are cooled by a continuous Adiabatic Demagnetization Refrigerator (ADR). To minimise the heat load on the 5 K stage, the ADR would use superconducting magnets that can operate at temperatures above 8 K and are therefore thermally coupled to the thermal shields.

Mechanisms

Another resource driver for FIRI is the mechanisms. The largest and most demanding mechanism is the one responsible for the translation of the telescopes. Nevertheless there are also several mechanisms that are needed for alignment and optical path control, such as refocusing mechanisms, tip/tilt mirrors and optical delay lines, in addition to larger mechanisms such as mechanisms used for deploying the large booms and the sunshields. Many of these mechanisms need specific technology development activities due to the very low operating temperature required, the limited heat dissipation that is allowed for the specified operational performances and the long duty cycles needed.

In the FIRI study the main design driver for the telescope carrier mechanism was to minimize complexity and cost rather than minimise mass. This implies that a very simple and robust design was selected. The mechanism can be divided in two parts; a drive unit and a guide unit. The drive unit uses mostly off the shelf components. The design is simply based on a pinion and rack design. The drive unit of the pinion would be a brushless DC motor. A torsion bar is used to provide a backlash free system. The guiding unit is based on a design solution used for MIPAS [7] although the mechanical stroke for this mechanism was only about 10 cm. Hence a significant development effort is required to achieve a stroke of about 14 m. This guiding unit uses 3 pairs of preloaded ball bearing rollers. One pair is mounted on flexible blades to ensure constant preload and backlash free configuration all along the stroke. To limit the contamination issues dry lubrication would be used.

Data Handling

The current payload design implies a large data production. For each UV point about 100 Mbit of data is created, resulting in a maximum data volume of about 140 Gbits. As the ground station will only be available for certain time periods the spacecraft needs to be able to store at least two full images. In addition, there will be a large amount of data created by the onboard metrology. This resulted in the need for a total mass memory of about 1.3 Tbit including margin and redundancy.

To simplify the interfaces between payload and spacecraft an independent payload computer is envisioned, which would also be responsible for the science data management. This payload computer would be based on LEON2 processors. The same technology would also be used for the spacecraft computer.

TT&C

The TT&C system is based on a one-way, high rate downlink in the 26 GHz Ka-band for science telemetry and a two-way, low rate link in the X-band for telecommand, housekeeping telemetry and navigation, to the ESA 35-meter Cebreros ground station. In order to minimise the impact on science observations, we have assumed that the data created by collecting two images should be downloaded during one ground station contact period. Under this assumption, the X-band cannot be selected for the science data downlink as even 8 hour contact periods would result in a data rate that is too high for X-band, due to bandwidth limitations in this band. A move to the higher frequency 26 GHz Ka-band is thus necessary to comply with the science data rate needs for FIRI, although this requires some developments within both ground and space segment. The current baseline is to have a TT&C system compatible with almost 50 Mbps max downlink data rate, allowing a full download of the science data in about 2 hours.

AOCS

In the case of FIRI the large and changing moment of inertia is one of the main drivers for the AOCS design.

As the telescopes travel towards the hub conservation of angular momentum dictates that the angular velocity of the spacecraft would increase. To avoid such velocity variations, manoeuvres will be required each time the telescopes move in the radial direction. A system based on large reaction wheels is envisioned to avoid the need for large amounts of propellant. A novel concept using two large magnetic bearing wheels mounted with their spin axis co-aligned with the FIRI spin axis would avoid using propellant except for the initial spin up and re-pointing. A regular reaction wheel based system with four reaction wheels mounted as a tetrahedron is used for rejecting perturbations. By using this AOCS strategy about 420 kg of Hydrazine is needed over the mission lifetime including propellant needed for launcher dispersion and orbit corrections.

Power

The total power demand for the spacecraft is about 1395 W; about 175 W is required for the two telescopes while about 1220 W is required for the hub. The payload is the clear driver of the power budget, not only do the cooling system and instrument require large amounts of power, but also the mechanisms would need significant power during observations.

The configuration of FIRI implies that power would need to be transported over large distances, leading to a complicated harness design. To minimize this complexity a decentralized power system is preferred. Three independent power systems are therefore accommodated; one on each telescope and one on the hub. A wireless data link avoids the need for having harness routed through the booms.

TECHNOLOGY DEVELOPMENTS

To enable a mission as complex as FIRI substantial technology development effort would be required. In Table 4 some of these technologies and the respective Technology Readiness Level (TRL) are listed. The main effort is within the areas of cooling, optics and detector technologies.

The number of technologies that needs to be developed and their low technology maturity entails that significant effort is required before a mission such as FIRI could be launched. It is of interest to notice that many of the required technology developments would be needed for other far infrared interferometry concepts, including those based on formation flying. If direct detection is to be used, cooling developments, detector developments and many of the mechanism developments would certainly be required. This implies that some of the technology developments are of more general interest for future science missions.

Technology Development	TRL
ADR	3
H Sorption cooler	3
He Sorption cooler	4
H cryostat	4
Detector	3
Interferometer	3
OPD lines	1
Metrology system	4
Integrated rail/rack	1
Linear actuator	1
High accuracy position sensor	1
Tip/tilt mechanism	1
Long stroke linear stage	1
Telescope 5 DOF mechanism	1

Table 4 Some enabling technologies required for FIRI

CONCLUSION

The current FIRI study has shown that the selected mission concept is quite ambitious and challenging and can be considered as feasible only assuming the completion of significant technology developments.

Substantial development effort is therefore required to enable such a mission. Nevertheless, assuming the successful completion of the technology developments, the baseline selected for FIRI would still be less complex than a far infrared mission involving formation flying. On this basis the concept remains of interest for future far infrared science interferometer mission studies.

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