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ORIGINAL ARTICLE

FIRI—A far-infrared interferometer

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Abstract Half of the energy ever emitted by stars and accreting objects comes to us in the far-infrared (FIR) waveband and has yet to be properly explored. We propose a powerful Far-InfraRed Interferometer mission, *FIRI*, to carry

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out high-resolution imaging spectroscopy in the FIR. This key observational capability is essential to reveal how gas and dust evolve into stars and planets, how the first luminous objects in the Universe ignited, how galaxies formed, and when super-massive black holes grew. *FIRI* will disentangle the cosmic histories of star formation and accretion onto black holes and will trace the assembly and evolution of quiescent galaxies like our Milky Way. Perhaps most importantly, *FIRI* will observe all stages of planetary system formation and recognise the birth of planets via its ability to image the dust structures in planetary systems. *FIRI* is an observatory-class mission concept: three cold, 3.5-m apertures, orbiting a beam-combining module, with separations of up to 1 km, free-flying or tethered, operating between 25 and 385 μm, using the interferometric direct-detection technique to ensure μJy sensitivity and 0.02” resolution at 100 μm, across an arcmin^2 instantaneous field of view, with a spectral resolution, R $\sim$ 5,000 and a heterodyne system with R $\sim$ 1 million. Although *FIRI* is an ambitious mission, we note that FIR interferometry is appreciably less demanding than at shorter wavelengths.

Keywords Instrumentation: interferometers · Infrared: general · Galaxies: formation · Stars: formation · Planetary systems: formation · Cosmology: early universe

1 Introduction

Half of the energy ever emitted by stars and accreting objects comes to us in the far-infrared (FIR) waveband and has yet to be properly explored. We propose a powerful *Far-InfraRed Interferometer* mission, *FIRI*, to carry out high-resolution imaging spectroscopy in the FIR. This key observational capability is essential to reveal how gas and dust evolve into stars and planets, how the first luminous objects in the Universe ignited, how galaxies formed, and when super-massive black holes grew. *FIRI* will disentangle the cosmic histories of star formation and accretion onto black holes and will trace the assembly and evolution of quiescent galaxies like our Milky Way. Perhaps most importantly, *FIRI* will observe all stages of planetary system formation and recognise the birth of planets via its ability to image the dust structures in planetary systems. It will thus address directly questions fundamental to

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our understanding of how the Universe has developed and evolved—the very questions posed by ESA's Cosmic Vision:

- What are the conditions for stars to form, and where do they form?
- How do stars evolve as a function of their interstellar environment?
- In which conditions do planets form around stars?
- How were the first luminous objects in the Universe ignited? How did the first stars form and evolve?
- How did the history of stars and supernovae give rise to current chemical element abundances?
- What is the history of super-massive black holes and how do they interact with their host galaxy?
- What is the nature of the FIR background, and of early, deeply embedded star formation?

The FIR region of the electro-magnetic spectrum is the last major band where poor angular resolution and lack of sensitivity hinders progress. Pathfinders *Herschel* and *SPICA* (see [21]) will provide major advances in sensitivity, but will lack the angular resolution necessary to resolve the cosmic FIR background radiation or to undertake detailed studies of individual objects. ALMA and the *James Webb Space Telescope* (*JWST*) will provide high angular resolution and sensitivity at shorter and longer wavelengths, but the crucial band between 25 and 300 μm is not covered by any comparable instrument: there exists a crippling lack of observational capability in the FIR, despite the vital role this band plays in exploring the formation and evolution of Active Galactic Nuclei (AGN), galaxies, stars and planetary systems, and the development of life-sustaining environments.

This "FIR gap" (Fig. 1) is recognised by the astrophysical community and has been noted by ESA's Astronomy Working Group. In the ESLAB 2005

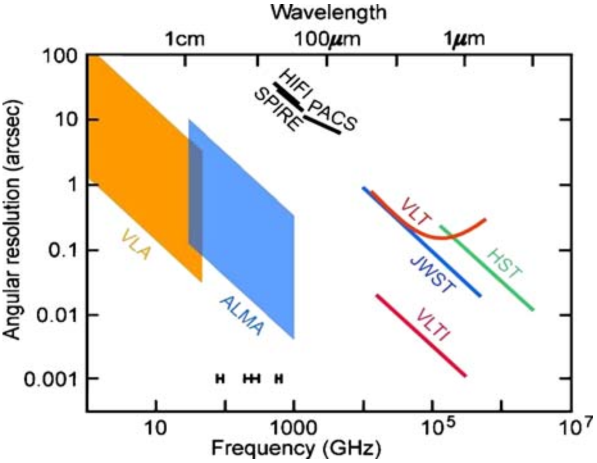

Fig. 1 With the advent of ALMA and VLTI, the FIR gap is deepening (picture courtesy of T. Wilson)

Cosmic Vision symposium, a high-angular-resolution FIR observatory with high angular resolution was listed as a major priority for ESA's science programme: *FIRI* is such a mission, strongly supported by the worldwide astronomy community and already studied extensively by ESA, NASA and others.

FIRI will make unique and key contributions to our understanding of the Universe, near and far. It will peer through the dust that shrouds stellar nurseries in our Galaxy, de-mystifying the process by which stars and planets are born. It will image proto-stellar and debris disks at the peak of their spectral energy distributions (SEDs), where the brightness is 1,000× that at a wavelength of 1 mm, with exquisite spectral resolution and sensitivity, revealing how planetary systems form out of gas, dust and ice. While the *Hubble Space Telescope* (*HST*) has produced beautiful pictures of merging and star-forming galaxies, crude submm observations have shown that the real action is in the FIR [19]. *FIRI*'s angular resolution will break through the confusion limit and allow us to determine the properties and internal structure of distant star-forming galaxies, and to examine the enigmatic symbiosis between host galaxies and their AGN. The earliest metal-poor galaxies will be very highly redshifted (i.e. at large look-back times), and we may even be able to detect their formation via molecular hydrogen emission red-shifted into the FIR. This would provide a unique probe of first light—the formation of the earliest stars in the Universe and the ensuing re-ionisation of the Universe.

Here, we outline the *FIRI* observatory-class mission concept: three cold, 3.5-m apertures, orbiting a beam-combining module, with separation of up to 1 km, free-flying or tethered, operating between 25 and 385 μm, using the interferometric direct-detection technique to ensure μJy sensitivity and 0.02" resolution at 100 μm, across an arcmin^2 instantaneous field of view, with a spectral resolution, $R \sim 5{,}000$ and a heterodyne system with $R \sim 10^6$. Although *FIRI* is an ambitious mission, we note that FIR interferometry is appreciably less demanding than at shorter wavelengths (Fig. 2).

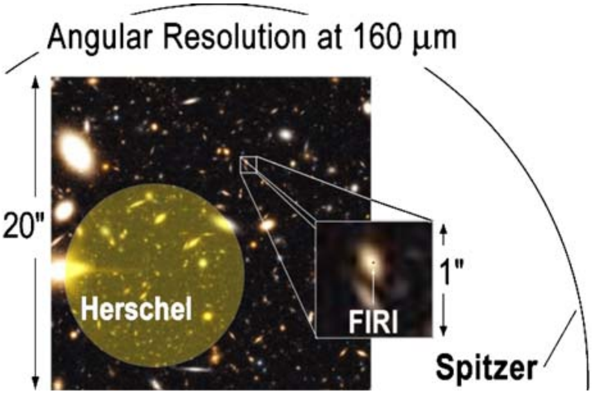

Fig. 2 Simulated *JWST* deep field, illustrating *FIRI*'s ability to distinguish the emissions of individual galaxies. For comparison, Spitzer's resolution at 160 μm is coarser than the entire 20-arcsec field shown, and the 3.5-m Herschel will see many objects per beam at this wavelength. *FIRI*'s synthesized beam is barely visible (*as a black dot*) even in the blown-up arcsec^2 image to the right

2 The far-infrared Universe

The untapped potential of FIR astronomy is most clearly illustrated by considering the three main components that dominate the electromagnetic energy content of the Universe (Fig. 3). The dominant component is the microwave background produced by the primordial Universe at recombination ($z \sim 1{,}089$) [8]. The second most important is the FIR background, produced by galaxies in the young Universe. The third is the optical background dominated by evolved stars/galaxies and AGN. The first and third of these components have now been mapped in detail over the entire sky, while virtually no sky has been imaged in the FIR to any reasonable depth.

Young stars are completely embedded in their natal dust cocoons, which limits access to their early evolution. Only at wavelengths less opaque to the dust a glimpse of the evolution of both the stars and their planets can only be obtained in the FIR (Fig. 4).

The FIR wavelength region is thus the least explored part of the electromagnetic spectrum yet it provides uniquely powerful tools to study material associated with the earliest evolutionary stages of galaxies, stars and planets. This waveband allows us to directly probe objects during their formation. We gain access to unique science—the peak of the FIR background radiation and emission from cold, proto-stellar cores.

A large, single, actively cooled aperture in space would provide unprecedented increases in sensitivity and mapping speed over any existing or planned facility. However, it is clear that to make significant advances on *Herschel* and *SPICA* in all areas of astronomy, from nearby planetary systems to the highest redshift galaxies, even the largest conceivable dish would be inadequate. These areas call for exquisite angular resolution, around 0.02 arcsec at 100 μm, as well as sufficient sensitivity to allow photon-starved spectroscopy across an arcmin^2

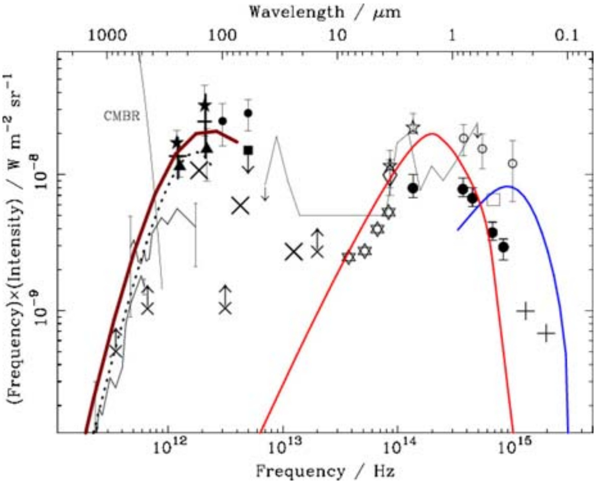

Fig. 3 Observed UV-radio intensity of the cosmic background radiation. A major goal of observational cosmology is to resolve the FIR background, thus probing the earliest formative episodes of stars and galaxies and revealing the effects of feedback on the IGM. It will allow us to piece together the transformation of galaxies, through dust-enshrouded episodes, as well as links with populations selected at X-ray-radio wavelengths

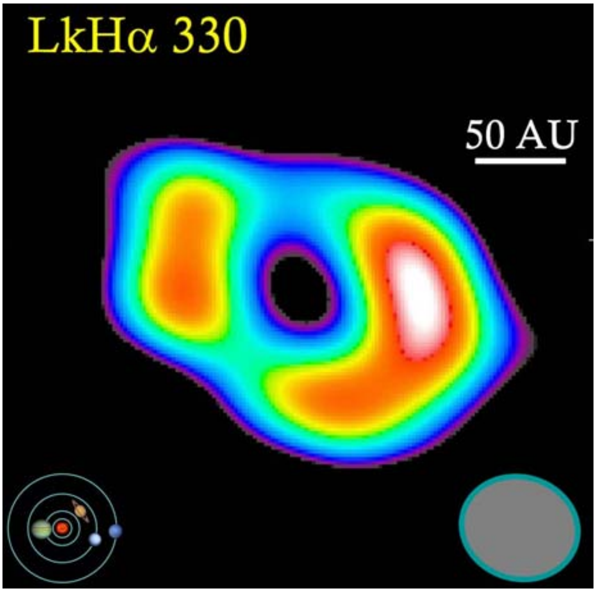

Fig. 4 SMA image of the dust continuum emission from the transitional disk around LkHα 330, a G3 pre-main sequence star in Perseus. The putative outer gap radius of ∼50 AU, derived from an SED analysis, is confirmed. Gas is detected well inside the transitional radius, raising the possibility that the gap is caused by a planetary companion

field of view in the 25- to 385-μm band. These science requirements lead us inexorably to an interferometer.

3 The FIRI science programme

A space-based FIR interferometer will enable the following unique science:

3.1 Planets and life

The FIR is a critically important wavelength range for studying the origin and evolution of planetary systems. Most solar systems, including our own, are pervaded by dust, which is very bright at FIR wavelengths. By studying the structure and dynamics of this dust, with many times the effective sensitivity of ALMA since we are operating at the SED peak (for 10–120-K dust), we gain information on how such systems were formed. More importantly, we can infer the presence and orbital motions of planets, which influence the distribution of the dust. Complementary to this, the FIR is the natural place to observe the emission of organic molecules through rotational lines or low-lying vibrational bands that could literally be the building blocks of life in the Universe, including water which has a profound influence on both the formation of the planets as well as for life (e.g. [5]). By better understanding the contents and chemistry of the interstellar medium (ISM) throughout the wide range of different environments found in the Milky Way and nearby galaxies, it will be possible to get a better idea about the potential for life in these planetary systems.

3.2 The interstellar medium (ISM) in quiescent galaxies

In relatively quiescent local galaxies, including the Milky Way, the bulk of the ISM is relatively cool, with characteristic temperatures of order a few tens to a few 100 K. Therefore, the chemistry and dynamics of the ISM in these galaxies is often accessible only through FIR observations, as "cool" material radiates most strongly in the FIR. In particular, emission lines of CO offer a powerful tool for investigating dynamic processes in local (and distant) galaxies, and when combined with emission lines from atoms and ions of O, N and C, can be used to build up a picture of the chemical composition of the ISM. Other useful probes of the "cool" ISM include emission and absorption features from solid grains, most notably polycyclic aromatic hydrocarbons (PAHs), and large amorphous silicates.

3.3 The ISM in active galaxies

Conversely, the most luminous sources of radiation in galaxies are either very hot, very young stars, or the accretion disk around the central super-massive black hole (SMBH). Both hot young stars and accretion disks emit nearly all their energy at UV, X-ray and even gamma-ray wavelengths. However, these sources are in most cases embedded in large amounts of gas and dust; for example, the earliest stages of star formation invariably occur deep inside clouds of interstellar gas and dust—their raw material, and AGN require the accretion of large amounts of gaseous fuel onto the central SMBH. This surrounding gas and dust absorbs most or all of the UV and soft X-ray radiation which is directly emitted by the sources, and re-radiates the bulk of it in the FIR; the surrounding clouds are transparent at these wavelengths and the grains can achieve an energy balance between radiation absorbed at short wavelengths and emitted at long wavelengths. As a result, most of the energy originally emitted by the high-temperature primary sources is converted into FIR and submm radiation. Only by observing at these wavelengths can we measure fundamentally important parameters such as total energy budgets (L_{bol}), accretion disk geometries and star-formation rates.

Indeed, there is already strong evidence that the growth of the SMBHs found in the centres of nearby galaxies probably takes place at the same time as the formation of the bulk of stars in the central bulge (e.g. [13]). As a result, this growth likely adds to the energy output of a galaxy in the FIR, but not at any other waveband. FIR observations thus provide the only way to detect this SMBH growth; even hard X-ray observations cannot penetrate the Compton-thick shrouds of gas in a forming galaxy (e.g. [17]).

3.4 Cosmology

There is now convincing evidence that the bulk of star and galaxy formation occurred in the first half of the history of the Universe. The FIR waveband contains by far the greatest part of the energy output from these galaxies [4]. Thus, FIR wavelengths provide insight into transformational processes taking place from 100 Myr to the present day, resolving the FIR/submm background produced by galaxies in the young Universe (Fig. 5).

Perhaps the biggest impact of FIR observations will come from studies of the first luminous objects in the Universe, only ~100 Myr after the Big Bang. At these epochs, before the Universe was fully re-ionised, observations at optical/NIR wavelengths are impossible due to the Lyman opacity of hydrogen. FIR data, on the other hand, can provide fundamental new insights into the transformational processes taking place in the ~100-Myr-old Universe. We expect the first stars in the Universe to be extremely massive, metal-poor and very short lived. The earliest formation stages of these stars will be signposted by the FIR-bright rotational–vibrational transitions of molecular hydrogen as it cools and collapses under its own gravity, while the SNe explosions

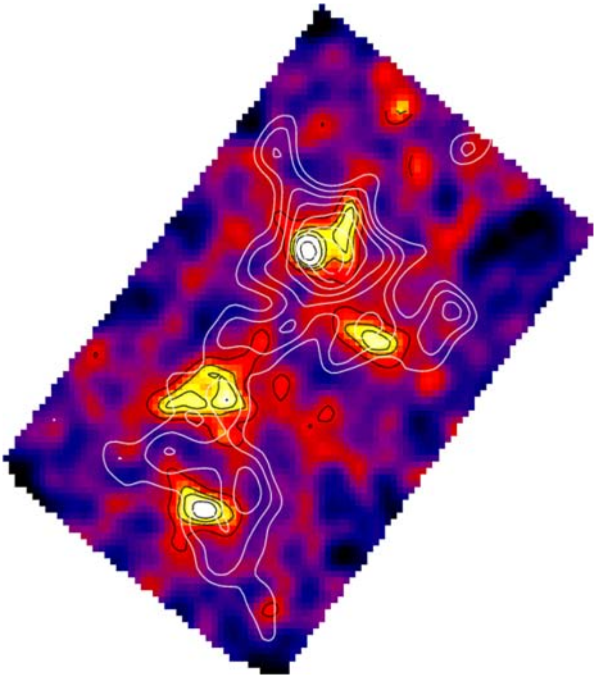

Fig. 5 SCUBA imaging of the ~1-arcmin^2 field around an absorbed $z = 1.8$ QSO revealing a remarkable ~400-kpc-long chain of galaxies, each with an obscured star-formation rate sufficiently high to build a massive spheroid in <1 Gyr (450-μm image; 850-μm contours—[20]). The genesis of spheroids is central to our understanding of galaxy formation: they are relatively simple systems containing about half the stellar mass of the Universe. A major subset—massive elliptical galaxies—are preferentially found in clusters where they exhibit old coeval stellar populations suggesting that they formed synchronously at early epochs. The over-density of galaxies relative to expectations for a random field implies they reside in a structure associated with the QSO. This star formation is probably associated with galaxy mergers, or encounters within a filament, such as those predicted by hierarchical models. These observations suggest that strong absorption in the X-ray spectra of QSOs at high redshift may result from a veil of gas thrown up by a merger or merger-induced activity, rather than an orientation-dependent obscuring torus. It is possible that these systems are the precursors of cluster ellipticals found today

associated with the end of the lives of these massive stars will seed the IGM with metals and dust, which will also emit strongly in the FIR.

The bulk of galaxy formation is thought to occur after re-ionization, between 500 Myr and 6 Gyr after the Big Bang. Nearly all of the stellar and black hole mass build-up in these galaxies occurs while shrouded in dust, making FIR observations essential to our understanding of how these galaxies are forming. Though high-redshift galaxy surveys in the optical have detected many distant galaxies, they are virtually all systems that have already built up a significant fraction of their stellar mass. At FIR wavelengths we can probe both the direct formation phase, and the degree of on-going star formation embedded deep in giant molecular clouds, to provide a view of galaxy formation that is orthogonal to that taken in optical/NIR surveys.

FIR telescopes probe the peak of the SED of galaxies so *FIRI* will reveal, being immune to the effects of extinction, the links between morphology, environment, gas content, metallicity and the decline in specific star-formation rate that has occurred since $z \sim 1$, commonly referred to as “downsizing”. By tracking the total luminosities of galaxies, all the way to the present epoch, the true form of evolution of the luminosity function of galaxies will be revealed and we can be sure for the first time about the systematic change in opacity, luminosity and extent of star-forming regions in galaxies as a function of their environment, mass and luminosity. Without direct FIR imaging, these quantities can be inferred only by proxy.

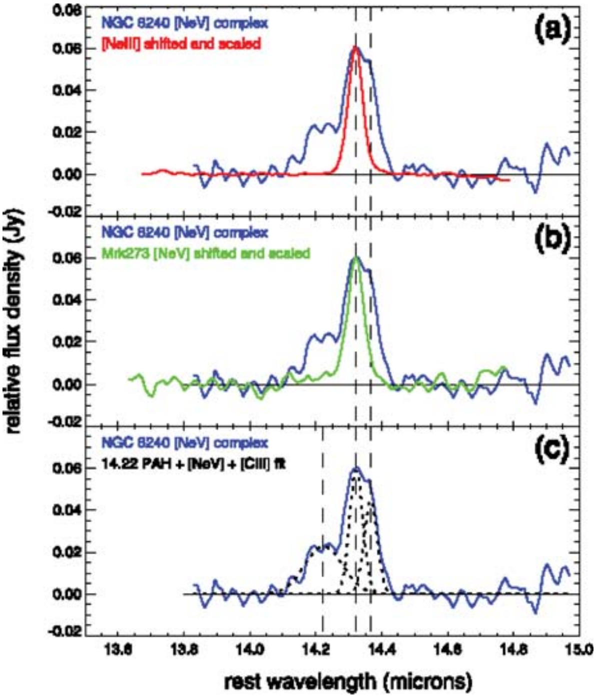

Fig. 6 *Spitzer*-IRS observations of NGC 6240 [1]. The signatures of AGN activity are apparent in this Compton-thick source from the identification of [Ne V] at 14.3 μm. These lines are redshifted to >40 μm for $z > 2$, i.e. beyond the coverage of *JWST*, but far short of ALMA’s wavebands. The luminosity distance of NGC 6240 is ~100 Mpc, two orders of magnitude closer than $z \sim 2$ AGNs, indicating the need for a sensitive FIR imaging spectrometer to identify Compton-thick AGN in the distant Universe

In summary: *FIRI* will thus revolutionise our knowledge of the formation of galaxies, stars and planetary systems and the development of life-sustaining environments. We will be able to probe the universality of the IMF across a range of galaxy environments and map out star- and planet-forming disks in stellar nurseries through resolved spectral lines. *FIRI* will break the cosmic background radiation into its constituent parts—many thousands of faint, dusty high-redshift galaxies, resolving them individually to yield otherwise hopelessly obscured information about their formation and evolution. It will root out Compton-thick AGN and differentiate between gas heated by active nuclei and stars, thus disentangling the formation histories of SMBHs and stars. *FIRI*'s "discovery potential" is also extremely high. The biggest surprise would be if there were no surprises. *FIRI* is therefore capable of answering many of the most important questions posed by Cosmic Vision (Fig. 6).

4 Summary of science requirements

FIR community workshops were held in Madrid (2004), Leiden (2005) and Obergurgl (2006). The participants have quantified the requirements of 26 use cases, resulting in the science requirements summarised in Table 1. The most consistent requirement—found in nearly every Galactic use case, in many extragalactic cases and in virtually all of the most important use cases—is the need for high angular resolution, 0.02 to 1 arcsec. Sensitivity is an equally demanding driver, especially for extragalactic science. Requirements on spectral resolution span the whole range, up to several 10^6; extragalactic science and around half of the Galactic use cases are satisfied with $R \sim 5{,}000$.

5 Mission profile

5.1 From science to mission requirements

From the science requirements the following conclusions can be drawn: the mission should be able to resolve proto-planetary disks and distant galaxies down to a few AU at about 100 pc distance, or ~100 pc at $z \sim 10$, i.e. angular resolution of ~0.02". In terms of wavelength, the mission should provide access to the 28-μm rotational transition of H_2 and overlap with ALMA, so 25 to 385 μm. Most of the science requires extremely high sensitivity, so adequately large and cold telescopes are a necessity, as well as next-generation detectors. A field of view rather larger than the primary beam is also desirable for virtually all the high-profile science.

To achieve the required angular resolution, long baselines are necessary, ~1 km, longer than can be achieved with rigid structures. A free-flying or tethered interferometer capable of delivering excellent image fidelity is thus the instrument of choice. Unlike the optical and radio regimes, where point sources are common, the FIR wavelength region is full of structure on every spatial scale, at the angular resolution of *FIRI*. This has profound implications

Table 1 Science requirements culled from use cases gathered over the period 2004–07

Type	λ (μm)	$\Delta\lambda, \Delta\nu, \Delta v$	$R = \Delta\lambda / \lambda$	Area, Ω (arcsec^2)	Ang res (arcsec)	N_{fields}	S_{min}, ΔT_{min}	UV constraints	Dynamic range
Water p-planetary disks	180, 269	100 km/s	10^6	10×10	0.02–0.1	40	20 K	Short/zero	100
Dut protoplanetary disks	27–150	40 μm	1,500	200×200	< 0.01	10	5 μJy		1,000
Dust debris disks	27–150	40 μm	1,500	10×10	< 0.01	10	5 μJy		1,000
HD—total gas	112	100 km/s	6×10^6	10×10	0.01–0.1	40	0.1 K		10
Temp/structure in trans. Disks	63, 145 158	100 km/s	6×10^6	10×10	0.1	40	0.1 K	Incl compact	100
The origin of outflows	27–300	40 μm	30,000	1×1	0.05	20	50 mJy	Short spcgs	$> 1,000$
Lum function in clusters	50–300	20–40 μm	3–10	900×900	0.01	50	1 mJy		$> 1,000$
Cloud core stellar content	50–300	70	1–5	900×900	< 0.1	10	5 μJy	Short/zero	$> 1,000$
Water tracing infall	50–600	Few μm	3×10^6	20×20	< 0.1	40	0.5 K		> 100
Giant planets in pp-disks	30–150		1,500	10×10	0.001	40	5 μJy		$> 1,000$
Solar system	50–600	0.1–10 GHz	10^6	30×30	0.1	10	0.1 Jy		> 100
PDRs	63,158	100 km/s	10^6	10×30	0.1	10	1 K		> 20
AGB shells/young PNe	63–300	200 km/s	10^6	5×5	0.01–0.1	> 15	< 0.2 Jy		> 30
Turbulent ISM	75–600	500 km/s	6×10^6	30×30	0.1	10	0.1 K		> 100
Dust in ULIRGS	24–240		$R < 5$	10×10	< 0.05	1	1 mJy	Strong driver	> 100
Gas in ULIRGS	Fine-struct	1,500 km/s	10^3	10×10	< 0.05	1	10^{-18}		> 100
Merging AGN	40–220		< 5	2.5×2.5	< 0.02	1	10 μJy	Point sources	> 100
Gas evolution	25–200	1,500 km/s	$\sim 10^3$	1×1	0.3–1	1	2×10^{-22}	Short	> 100
Dust evolution	25–200	~ 50 μm	~ 100	2×2	0.3–1	1	10 μJy	Short	> 100
Timing of starburst and AGN phenomena	40–660		< 5	5×5	< 0.02	1	2 μJy		$> 1,000$
Probing Compton-thick AGN	25–300	~ 40 μm	~ 300	5×5	0.5–1	1	2×10^{-23}		> 100
Line diagnostics for AGN/gals	25–660		$\sim 5,000$	20×20	< 0.05	1	5×10^{-21}		$\sim 1,000$
Probing H_2 in blank fields	90–400		$\sim 10^3$	60×60	~ 0.1	1	$< 10^{-23}$		$\sim 1,000$
Probing H_2 at known z	50–300		$\sim 10^3$	3×3	~ 0.1	1	$\sim 10^{-21}$		> 10
Imaging first massive galaxies	30–300		< 5	10×10	< 0.05	1	10 μJy		$\sim 1,000$
IMF in external galaxies	50–200		< 5	5×5	0.005–0.02	10	1 μJy		~ 100

We list a short title; the wavelength to be observed; the wavelength range; frequency or velocity range; the spectral resolution required; the area to be covered; the angular resolution required, the number of fields to be measured in order to fulfil the use case; the noise level to be reached; particular constraints on the interferometer and the dynamic range required. This table also shows the versatility of *FIRI*, although we don't expect all the use cases to be completed in a 5-year period for the way data must be obtained. An interferometer works well only when good (u,v) coverage is achieved, with attention to the short or zero spacings to allow full image reconstruction.

In recent years, four studies of FIR/submm interferometers have been performed. These were the American SPECS [7] and SPIRIT [10] studies and the European ESA-FIRI [12] and ESPRIT [24] studies. Studies for the direct-detection interferometer SPECS (two cold 4-m telescopes plus central beam combiner) and the heterodyne interferometer ESPRIT (six ambient antennas) show that the incoherent and coherent variants of *FIRI* can take very different shapes. Neither concept on its own is capable of fulfilling all science requirements nor is any ready for immediate implementation. The science community's demands on spectral resolution range from $\sim$5 to 10^6. The latter is only achievable with a heterodyne system, while greater sensitivity is available at lower spectral resolution ($<10^4$) with a direct detection system. Neither the SPECS nor the ESPRIT concept is mature enough at this point to know with confidence which mission concept represents the better choice of detection technology. The SPECS study looked briefly at the possibility of combining both techniques—direct detection and heterodyne—and found no showstopper. Thus it is possible to take the prioritised science requirements and create a straw-man mission, whilst conceding that many development steps have to be taken by ESA, space industry and science/technology institutes to prove elements of the concept and assess the possible trade-offs. This straw-man mission profile should be adapted and modified according to the results of the development phase and could evolve towards the SPECS or ESPRIT designs, or neither.

Our straw-man mission profile consists of a multi-telescope (all elements of the same size) free-flying or tethered interferometer, equipped with photometric and high spectral-resolution instrumentation. Combining the high sensitivity offered by direct detection and the high spectral resolution offered by the heterodyne technique fulfils all the science requirements in this paper. We recommend that separate direct detection and heterodyne systems be studied as well as our hybrid straw-man concept.

Together with knowledge acquired from ALMA and *Darwin* studies, we can create a concept for *FIRI* as a starting point for assessment studies, with a list of trade options to be studied in the assessment phase.

5.2 *FIRI* concept

Our straw-man *FIRI* concept consists of three 3.5-m, actively cooled afocal off-axis telescopes and a separate beam combining instrument with scanning optical delay lines and direct detectors. Because optical path length differences of the order of centimetres can be compensated with the delay line, *FIRI* does not require nanometre-precision formation control. The primary purpose of the delay line is to enable the temporal coherence measurements required for low- to moderate-resolution spectroscopy (up to 10^4), as in a conventional Fourier Transform Spectrometer, secondary purpose is to compensate for the delay between the telescopes. A metrology system provides real-time measurements of the optical path length between the telescopes and the light combination plane. The telescopes are moved to sample many baseline lengths and orientations, enabling high quality image construction. The beam combiner includes a heterodyne spectrometer, which can intercept the combined sky signals to provide high spectral resolution.

At the start of operations, as the dishes continue to cool, data will be acquired with the heterodyne system. This allows for early science to be carried out on proto-planetary disks and allows relatively simple calibration of the metrology system. When the active cooling of focal plane and telescopes is complete, direct-detection operations will start, switching back to heterodyne operations if and when assessment of the cooling-phase data suggests this is merited.

Multi-layer sunshields and cryo-coolers should be used to cool the telescopes and the beam combining optics to 4 K, where the optical elements contribute negligibly to the photon noise of the natural astrophysical background. Cryo-coolers will supplant the need for massive, voluminous cryostats, enabling *FIRI* to be launched on a single expendable rocket. *FIRI* will point approximately anti-Sunward to allow flexible baseline sampling, and the Sun shields should be sized to provide adequate field of regard. All of the desired science observations can be made if the viewable zone in a year stretches at least 20° above and below the ecliptic plane.

5.3 Payload

All studies so far have, for good reasons, concentrated on imaging spectroscopy of FIR sources. An interferometer is very well suited for this: a direct-detection interferometer can easily combine signals from the sky and extract spectral information when using scanning delay lines and a Fourier Transform Spectrometer. Similarly a heterodyne interferometer naturally combines both the spectral and spatial domain. We regard the equipment necessary to implement these two techniques as the payloads: the beam combiner for the direct detection interferometer, together with LO system, mixers and correlator for the heterodyne system. See Section 6 for more details on the payload.

5.4 Orbit

The preferred location for *FIRI* is the Sun–Earth Lagrange point, L2, which offers deep radiative cooling and minimum interference from the Earth and Moon, requiring only a single-sided sunshield. SPECS studies showed that all the major science goals can be achieved with the field of regard available in a large Lissajous orbit around L2. In ESA's *FIRI* study, a trailing orbit (like Spitzer) was also mentioned, but discarded because of ground-station difficulties. As an ESA-NASA-CSA mission, the ground station problem may vanish, but the *FIRI* direct detection data rate of 100 MB/s may be prodigious, weighing against a drift-away orbit.

5.5 Launch vehicle

An Ariane 5 ECA (or the even larger American Ares V) is capable of bringing ~6,600 kg to L2. The fairing length is up to 15 m while the fairing diameter is 4.57 m. The mission, as described, needs one launcher to contain sun shields, telescopes and beam combiner.

Fuel will be needed to re-orient the interferometer and for orbit maintenance, as well as for the movements necessary to fill the (u,v) plane if the array elements are free flying. Thrusters with low thrust and high specific impulse will be needed. Dense coverage of the (u,v) plane is achievable without using fuel, potentially enabling a longer mission, if the array elements are joined by tethers [11].

5.6 Ground segment requirements

We expect that ESA will lead the Ground Segment. European national space agencies would also participate, as well as the agency partners, NASA and CSA. For *Herschel*, the ground segment set-up used the natural capabilities of all the partners, e.g. the scientific institutes were more involved in data analysis while ESA concentrated on flight dynamics and user support. We envisage a similar scheme for *FIRI*. The ground segment set-up should be part of partner negotiations.

5.7 Special requirements

FIRI requires the simultaneous operation of multiple satellites. We have adopted free formation-flying with small thrusters as our default method of sampling the (u,v) plane; however, American studies show tethers as a strong alternative [11], as a tethered formation could sample the (u,v) plane densely. Further studies should assess the costs and risks associated with tethered formation flying and determine the best operating strategy. Cooling technology is another issue. Dedicated studies should be done with respect to cooling focal-plane instruments, as well as the dishes, telescope structures and beam combiner/FTS. Cryo-coolers, such as those developed for *JWST*/MIRI and *Planck*, will supply the required cooling power for the telescopes and optics. Sub-Kelvin (~50 mK) coolers will also be required for the detectors of the direct-detection instrument. Active coolers are preferred to cryostats because cryostats are massive and bulky, and their cryogen supply is a life-limiting resource.

At present, many of *FIRI*'s parameters may seem not as well defined as for other L-class missions. Integrated system studies will be necessary to put *FIRI* at a more advanced level of technological readiness. Many of the technical challenges associated with *FIRI* are common to any likely large ESA missions, though some aspects of *FIRI*, like formation-flying, are easier because the wavelengths of interest are longer.

6 Proposed payload

6.1 Direct detection interferometer

A direct detection "optical" interferometer can be used to obtain high-angular-resolution images and spectra simultaneously over a wide field of view with a single instrument. Such an interferometer is analogous to the VLTI. For *FIRI* we envisage an extension of the optical interferometry techniques commonly used along the direction suggested by Mariotti and Ridgway [14], who described the possibility of combining an imaging interferometer with a Fourier transform spectrometer. A further natural extension of this "double Fourier" technique involves the substitution of a detector array for the single detector used in a traditional Michelson beam combiner, a spatial multiplexing method which enables the simultaneous observation of many contiguous primary beams to cover a wide FoV, and which is currently under development in the laboratory [16, 18].

At FIR wavelengths, space-based optical interferometry is not as difficult as it may seem. *JWST*, currently in development for operation at 10× shorter wavelengths, may be the largest practical single-aperture space telescope. Its 6.6-m primary mirror is comprised of 18 segments whose light must reach a common focus. That will be accomplished with a wavefront sensing and control system [2], a system now considered sufficiently mature for flight application. A direct detection interferometer is the optical analogue of a pair, or multiple pairs, of *JWST* mirror segments. Because wavefront sensing and control becomes easier with increasing wavelength, a FIR interferometer will be able to adopt proven *JWST* technology.

6.1.1 Direct detection interferometer principles

Fourier transform spectroscopy is analogous to the method employed famously by [15]. In this case light from a source is split into two beams and recombined after a moving mirror inserts a variable time delay between one beam and the other. The combined light can be recorded on a single detector or camera pixel. The output signal intensity, when plotted against the optical delay, makes an "interferogram." The spectrum of the source can be constructed from the Fourier transform of the interferogram. If the optical delay range $R\lambda$ is sampled, the resulting spectral resolution will be R. In imaging interferometry, spatial coherence (interference "fringe visibility") measurements at many interferometric baselines (telescope spacings and orientations) are Fourier transformed to produce an image. Each baseline samples a single spatial Fourier component of the brightness distribution of the target scene, a component commonly identified by its coordinates in the spatial frequency (u,v) plane. The Van Cittert–Zernike theorem explains that an image can be constructed without information loss if enough (u,v) plane positions, or baselines, are sampled. By combining these techniques, as suggested above, *FIRI* will do integral field spectroscopy. When equipped with

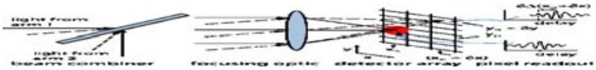

Fig. 7 Interference fringes from field angles outside the primary beam (*red ellipse*) can be recorded simultaneously in the separate pixels of a detector array. If light from a source located on the optical axis of the interferometer (*solid lines*) is focused onto pixel (x_o, y_o), then light from an off-axis source (*dashed lines*) might reach pixel ($x_o + \delta x$, $y_o + \delta y$) after traversing opposite arms of the interferometer. The white light fringe packet in the interferogram from the latter pixel (*top*) is displaced relative to the interferogram from the on-axis source (*bottom*). The FoV is dictated by the number of pixels in the array

a detector array of modest pixel count the *FIRI* field of view can readily be expanded to 1 arcmin^2, as illustrated in (Fig. 7).

6.1.2 Description and key characteristics

Michelson stellar interferometers can be constructed with any number of light collectors N, and the light may be non-redundantly combined pairwise in up to $N(N-1)$ / 2 baselines. For *FIRI*, we restrict ourselves to one of the simplest configurations, three light collectors (three baselines) and a beam combiner, all of which are on different spacecraft. The entire array rotates in a plane perpendicular to the line of sight, keeping the optical pathlength differences external to the instrument to a minimum (a few cm). The residual pathlength difference will be well within the range (~1 m) of the scanning optical delay line required both for spectroscopy and to equalise path lengths for off-axis field angles.

Guide stars are used to orient the spacecraft in absolute coordinates, and distinct sources in the science field of view—possibly NIR point sources—serve as phase references for the optical path external to the instrument.

To synthesize as complete an aperture as possible, the baseline length B between the two telescopes can be varied continuously between ~10 m and 1 km. The minimum baseline length is determined by how close the light collectors can approach each other, and depends primarily on the sizes of the sun shields, and the architecture of the spacecraft formation. The maximum baseline is dictated by the science requirements on angular resolution (0.02 arcsec).

A direct detection interferometer has three distinct positive attributes. First, with sufficiently cold (~4 K) optical elements and low-noise detectors, its sensitivity will be limited only by statistical noise in the sky background radiation. Second, a FoV wider than the primary beam can be observed without repointing the interferometer and resampling the (u,v) plane. Third, the interferometer can provide uninterrupted access to a wide range of wavelengths. Because the detectors typically operate well over a single octave, *FIRI* will use four different detector arrays to cover the range from 25 to 385 μm. Potentially, filters could be used to narrow the bandwidth and limit background photon noise when the source of interest is seen against a bright background. A single mechanism can be used to provide the optical delay scan for all four spectral channels.

6.1.3 Optical delay lines

Cryogenic optical delay lines been used in space before, notably in the *Cosmic Background Explorer* FIRAS instrument and the *Cassini* CIRS instrument. The FIRAS mechanism is comparable in many respects (operating temperature, lifetime requirement, physical size, and rate of motion) to the delay line mechanism needed for *FIRI*. *Darwin* has similar requirements.

6.1.4 Beam combiners

The beam-combiner is the heart of the interferometer system. FIR beams are more easily combined than mid-IR or shorter wavelength beams because of the relaxed tolerances on wavefront flatness. Metal mesh filters with customized spectral response functions are well suited to serve as beam combiners and dichroics to divide the broad *FIRI* wavelength range into octaves specified to permit an optimal match to the detectors.

The beam combining instrument grows geometrically in complexity when additional light collectors are added to a direct detection interferometer, as an additional delay line and two more detector arrays, one for each Michelson output port, are needed for each interferometric baseline. A three-telescope system should be feasible if the telescopes and beam combiner are launched together. To minimize complexity, a two-telescope system was considered in the SPECS study. We recommend further studies of two and three-telescope architectures.

Considerable experience in the design and operation of imaging FTS systems in the FIR is now being established. *Herschel*/SPIRE and SCUBA-2 will both have an imaging FTS and will provide experience in spectrometer operation and data reduction. This will be extended by *SPICA*/ESI, for which an imaging FTS with transition edge sensor (TES) arrays is proposed.

6.1.5 Detectors

In order to meet the performance requirements quoted in Section, multi-pixel detector arrays with NEPs of $\sim 10^{-20}$ W $\mathrm{Hz}^{-1/2}$ will be needed. The *FIRI* detectors will be based on superconducting sensors and will require an operating temperature of ~50 mK. Superconducting TES arrays operating at ~0.1 K are being implemented for SCUBA-2 at the James Clerk Maxwell Telescope and are planned for other ground-based submm telescopes. While these instruments are developing and demonstrating much of the fabrication and multiplexing technology appropriate for *FIRI*, they are optimised for higher backgrounds, requiring NEPs of $\sim 10^{-17}$ W $\mathrm{Hz}^{-1/2}$.

However, low-background TES arrays are also being developed for the proposed ESI instrument on the Japanese *SPICA* satellite (the subject of a complementary Cosmic Vision proposal). Cardiff University, SRON, and other *SPICA*/SAFARI collaborators are developing TES arrays with frequency domain multiplexing, with a target NEP of 10^{-19} W $\mathrm{Hz}^{-1/2}$, deemed appropriate for *SPICA*, requiring a detector technology selection in 2009. The implementation of *SPICA*/SAFARI will constitute a thorough development programme for TES array and systems technology, and sub-100-mK cooler running as the last element of a cryogen-free cooling system. A natural extension of the *SPICA* detector programme would be to develop detectors with NEPs of $\sim 10^{-20}$ W $\mathrm{Hz}^{-1/2}$. Similar FIR detector programmes are underway in North America. There is also a great deal of overlap between the fabrication techniques, cooling needs, and basic sensitivity requirements of detectors suitable for the next generation X-ray mission (*XEUS* or its equivalent), and a post-*Planck* CMB anisotropy mission (such as B-Pol).

The largest *FIRI* detector arrays, for the shortest wavelength channel, will have 32 × 32 pixels if the primary beam is Nyquist sampled and the FoV is 1 arcmin^2, or 16 × 16 pixels if Nyquist sampling is determined unnecessary. Smaller array dimensions cover the FoV in longer wavelength channels because the primary beam is larger.

6.1.6 Cryo-coolers

CEA-SBT is currently carrying out a strategic development programme for sub-100-mK cooler systems for future space science experiments, including *XEUS* and *SPICA*, and we expect these will be considered a mature technology in the next decade. A hybrid ^{3}He sorption cooler/Adiabatic Demagnetisation Refrigerator is under development for *SPICA*/SAFARI, which can provide continuous cooling at or below 75 mK, and NASA Goddard has already achieved cooling to 30 mK with a Continuous ADR [6].

Telescope cooling to 4 K will demand a somewhat more powerful cryo-cooler than the cooler developed for *JWST*/MIRI. The *JWST* cryo-cooler was recently declared to have matured to TRL 6, and it will be adopted for flight. Experienced cryogenic engineers say that the development path from the *JWST* cooler to a cooler powerful enough for *FIRI* is straightforward.

6.1.7 Operation of the interferometer

A *FIRI* observation sequence comprises a slew to the target field, target acquisition (including lock on angle and zero path difference tracking), and science data acquisition. The telescopes can move during the delay line scan as long as their positions are known accurately. Data analysis will be simpler if the delay line is scanned faster than the time it takes for a telescope to move a distance equal to its diameter. The detectors will be calibrated at regular intervals. The measurements continue until all of the desired baselines are sampled.

A direct detection interferometer has a great deal of flexibility in its operation, enabling the *FIRI* to satisfy optimally a variety of measurement requirements. For example, if a particular observation calls for angular resolution coarser than 0.02 arcsec, spectral resolution <3,000, or a FoV smaller than 1 arcmin^2, then only short baselines, a restricted delay line scan range, or a smaller number of pixels can be read out, respectively.

Thermal sources similar to the micro-lamps used in *Spitzer*/IRAC are sufficient for calibration. These lamps should ideally be installed near a pupil stop or an image of the pupil. The lamps will need to be sized to produce a reasonable power per detector (for instance, 500 aW, 5 fW, and 50 fW), tailored for each band. The illuminators should be stable and fast ($t < 1$ s). To calibrate data, the illuminators would be cycled on and off as necessary after every delay line stroke, while the mirrors are moving. This illumination response would be used to transfer calibrations from standards to unknown sources. Calibration can take place in about 5 s, much less than the time to move a mirror.

6.1.8 Performance with respect to the science requirements

A direct detection interferometer satisfies all of the extragalactic science use cases, as well as all of the Galactic use cases asking for low to intermediate spectral resolution, as indicated in Table 1.

6.1.9 Current heritage and technology readiness level

J-T and Stirling coolers for telescopes and instrument cooling: based on upgrades of flight-qualified coolers. Laboratory tests have demonstrated heat lift capacity exceeding requirements. MIRI cryo-cooler: TRL 6.

Sub-K cooler: Development activity within Europe to develop ADR coolers for *XEUS* and *SPICA*, and the Goddard Continuous ADR: TRL 4.

TES Detectors: Europe: SCUBA-2 (being built) and *SPICA*/SAFARI (in development). TES systems are in development in North America for ground-based and space-borne applications (e.g., JPL, Berkeley, NASA-GSFC) Additional development will be needed to achieve lower NEP: TRL 4.

Imaging FTS: SCUBA-2 and *Herschel* will operate imaging FTS instruments in the 2008 time frame. A low-background space-borne imaging FTS is being studied and developed for *SPICA*/SAFARI: TRL 6.

The Wide-field Imaging Interferometry Testbed [18] at NASA Goddard collects data representative of those obtainable with *FIRI* (only instrumental effects contribute to the phase noise) and will address three unsolved problems: (a) For astronomically interesting scenes, what combinations of photon noise, spatial frequency undersampling, and motion smearing during the observation are tolerable?, (b) How good will *FIRI*'s spatial–spectral images be?, and (c) How sensitive can we expect a direct detection FIR interferometer to be, and what factors will limit the achievable sensitivity?

6.1.10 Assembly, integration and verification

The assembly, integration and verification (AIV) process for *FIRI* should begin with high-fidelity software simulations and test-beds to validate designs, and should lead to the development of proto-flight hardware. Unique cryogenic test facilities (similar to that proposed for *SPICA*) owned by ESA and NASA can be used to test the individual *FIRI* telescopes and the beam combiner. Performance testing of the entire interferometer may be impossible or impractical, but verification of the beam combiner's performance will suffice if appropriate tests are conducted, if the telescopes are separately proven to provide collimated FIR beams, and if tests are conducted to ensure that stray thermal radiation in excess of the design tolerance will not be able to reach the detectors.

6.1.11 Critical issues

Although the direct detector interferometer has a lot of heritage from *Herschel*, and probably from SAFARI on *SPICA*, there are several critical issues:

- Detector array development to achieve very low NEPs and high read-out rates;
- Thermal model validation and verification
- What is the best optical design and how do we do stray-light suppression?
- Beam combiner engineering design
- High specific impulse propulsion system
- Power system to drive thrusters, operate mechanisms, detectors, cryo-coolers, communication system, etc.
- How best to actuate mechanisms intended to work at 4 K with minimal parasitic heat load?
- Sky density and quality of phase reference sources in the field of view?
- What is the best AIV approach?

6.2 Heterodyne interferometer

The heterodyne interferometer will be the instrument of choice when high spectral resolution is required. It provides this resolution naturally in the mixing and down-converting process; at the same time, unlimited amplification and splitting of the down-converted (Intermediate Frequency, IF) signal is possible. A description of the principle is given below, followed by a more detailed description of key elements: mixers and local oscillators; correlators; and observing modes, metrology and (u,v) plane filling.

6.2.1 Heterodyne interferometer principles

In a heterodyne system the sky signal is combined with an internally generated Local Oscillator (LO) signal. When this combination is done in a non-linear mixing element, the result is a copy of the sky signal but amplified and down-converted from the THz range into the GHz range. In this regime, low-noise amplifiers are available to further amplify the signal. At this stage the signal is electrical rather than optical. The amplified signal can be split when needed and correlated with other "sky" (or better, amplified IF) signals in digital correlators. The only actively cooled parts in the spacecraft at this time are the detectors (mixers). The high angular resolution guarantees that the telescope background is not an issue. An ambient telescope, like *Herschel*, suffices at these early stages.

There are several ways of correlating the IF signals. The ALMA case is based on a XF correlation scheme, while the advantage of novel FFT Spectrometers is that they can operate in a FX correlation scheme. For *FIRI*, a hybrid correlator (FX then XF) may well be the best option. A big advantage of a heterodyne interferometer is that the very high spectral resolution guarantees a very high correlation length; delays can thus be applied electronically or in software based on a geometrical model. This feature makes it possible to keep the metrology of a multi-telescope system rather relaxed, i.e. observing is possible while the telescopes are moving. In fact, correlation is possible with a prediction of the position of the spacecraft within tens of cm while the metrology of spacecraft position with respect to each other should be a few μm to guarantee good phase calibration. The heterodyne concept could make use of a central correlator, like the direct-detection beam combiner, but a distributed correlator (in all available spacecraft) is also possible and probably preferred.

Since moving the telescopes while observing is not a problem, (u,v) plane sampling can be achieved by letting the dishes move outwards (after acceleration), sampling during this floating phase. Deceleration to a stop and acceleration inwards is necessary to bring the array back to its initial configuration, after which the array can move to another source. Since delays can be done electronically or in software, the array could even fly in a 3-D configuration, thereby mitigating collision risks.

The heterodyne interferometer thus consists of several telescope spacecraft with, in their focal planes, several heterodyne mixers tunable at spot frequencies in the FIR. Mixers receive their LO signal from dedicated Local Oscillators, with phases tuned to a master LO phase distributor which distributes phases using a detailed geometrical model. These signals are down-converted in the mixers and amplified several times. The IF signals (which are led to the service module of each spacecraft) can be split and distributed to the other spacecraft for correlation, where delays will be applied in electronics and software, without moving optical parts. An alternative would be to send all IF signals to a central correlator where visibilities are calculated and sent to Earth at a low data rate. Mosaicing will be possible during each observation, increasing the field of view of the heterodyne *FIRI* complement.

6.2.2 Mixers and local oscillators

Based on knowledge of ground-based telescopes and the developments for *Herschel*/HIFI, we have identified two possible types of mixer: Hot Electron Bolometer (HEB; >1.5 THz) and Superconductor–Insulator–Superconductor (SIS; <1.5 THz). These mixers can be used immediately in an interferometer, but for optimal bandwidth, stability and sensitivity, extra development is needed. With HIFI, in principle the technological readiness rises to 9, while very high frequency HEBs have been demonstrated in the lab (TRL 5).

Below 2 THz, HIFI shows that solid state LOs as provided by JPL (USA) and RPG (D) can be built. However, above 2 THz the solution should come from new developments, e.g. Quantum Cascade Lasers. These devices need development to decrease their power consumption and improve phase locking. If these developments lead to improved QCLs, these are promising devices at THz frequencies. With HIFI, the TRL of the solid state LOs is 9. The QCL TRL is 4.

6.2.3 Correlation

There is a choice of two different correlation schemes (multiplication and Fourier transform) generally known as XF, FX or hybrid schemes. All these schemes are planned to work on ground-based telescopes (e.g. ALMA: XF; SKA: FX) or work already (e.g. APEX: FX). The current development of FPGA's is very fast and it is clear that cross-correlation will not be an issue for *FIRI*. There is, however, a need to do a thorough trade-off study between the different correlator concepts. These studies should include the correlation schemes, the IF treatment (in steps of 1 GHz, or larger), and the distributed versus central correlator approach. Power, volume and mass could be better estimated than at present. The rapid electronic revolution to FPGA-based devices makes that 10× less power in a few years is likely achievable. Also mass and volume are reduced.

6.2.4 Geometrical model, LO distribution and locking

In a submm or FIR heterodyne receiver, the LO that drives the mixer must operate at a fixed and well-defined frequency, with a high degree of spectral purity. In the case of a heterodyne interferometer, this is taken one step further, in that the coherent combination of the IF signals from each antenna requires that the LOs at each antenna are operating in phase. Moreover, in combining the signals from each antenna in a correlator, it is also necessary that the total optical and electrical path lengths from source to correlator are equalized for each antenna by introducing antenna-specific delays somewhere in the system. Due to the coherent nature of heterodyne detection, precise optical delays lines (which require precision optical systems and high-reliability mechanisms) can be replaced by precisely defined timing delays in the correlation of the data.

It is assumed that for *FIRI* all the reference signals originate at one central point, which can be any of the satellites. For redundancy purposes, each satellite can be provided with its own reference oscillator. This oscillator can also be used in the GPS-like coarse positioning network, which will require an independent time/phase reference at each satellite to be compared with the received signals.

Gross delay compensation should be done after digitisation and requires accurate computer control. It can either be done on-board, at the receiving element, or in the correlator element. It is probably preferable to have it where the (rest of the) fringe stopping is done.

It seems attractive to accommodate the fringe stopping entirely in the correlator by accomplishing fringe rotation after digitisation. This has the advantage that it reduces the complexity of the LO distribution and limits the number of interfaces. If, however, the large desired bandwidth reduces the number of bits in the signal representation, this approach has limited ability to track the phase, resulting in a loss of signal to noise. This could be remedied by fringe stopping in an FX scheme, or after correlation, but *FIRI* fringe rates are still high. Further study is probably needed. Thus, the classical approach to modifying the LO seems to be the appropriate solution for *FIRI*, despite the fact that it implies some extra complexity for the distribution scheme. In any case, some complexity is inevitable in order to accommodate phase switching and possible side-band rejection.

In the preferred scheme, each element has the necessary logic to evaluate the correlator model. Input to the model calculations is the detailed geometry of the array and the most demanding part for *FIRI* is that the relative location of the antennas must be known a-priori. However, as the antennas are moving on perfect linear tracks this is not a problem. Furthermore, the orientation of the array in space must be known, as must the direction of the target and the motion of the array with respect to the target.

Detailed overall system design is required to validate the above approach. Although we see no fundamental problem, it is difficult to verify it without details of many different components.

6.2.5 Operation of the interferometer

Heterodyne interferometers can boast of their large correlation length. WSRT, VLA and ALMA benefit from the Earth's rotation, which ensures that the projections of baselines on the sky change continuously, thus filling the (u,v) plane, necessary to create high-quality images. However, there is no daily rotation that can be used at L2, so filling the (u,v) plane must be accomplished in a different way. An advantage of the ESPRIT [24] design stems from its coherence length. Due to its very high spectral resolution, about 2 MHz, this length is about 150 m (for continuum with 4 GHz resolution, this reduces to 75 mm). Within this distance wave fronts can be considered to be coherent in nature, and thus when signals from two telescopes need to be correlated their path length difference needs to be known within this coherence length and correlation can take place using electrical delay lines. This allows for observing while the telescopes are moving and thus the (u,v) plane can be filled "on-the-fly". For single spectral lines, the advantage is even greater.

In general, asymmetric configurations like those used for LOFAR, ALMA or the VLA are preferable. An interferometer in space can benefit from the possibility of using a continuously changing 3-D configuration; a study should look at the possibility of adding elements.

An important aspect is the geometrical LO distribution model, as defined above. This model needs, as inputs, the absolute velocities and positions of each element's phase center in order to calculate clock adjustments for the correlator and the phase differences that are sent to each LO. In doing so, one ensures only the geometrical delay must be dealt with by the correlator.

Determining interferometer configurations is not easy. No standard has ever been established for ground-based interferometry, let alone for space. Darwin studies have been conducted, but these concentrated on symmetric configurations which are less suitable for a heterodyne interferometer. It is therefore necessary to study optimal configurations. This should take into account the following restrictions: (1) each "observing run" should result in a good image; thus, the (u,v) plane needs to be properly sampled; (2) it should be possible to point the telescopes in the same direction within 1/20th of the primary beam size; (3) it should be possible to keep the metrology system working (i.e. each telescope needs to see the other telescopes' metrology receivers); (4) it should take into account the acceleration the array gets from its thrusters, and it should take into account any velocity within the configuration.

6.2.6 Performance with respect to science objectives

At 100 μm, with a velocity resolution of 1 km s^{-1} and a angular resolution of 0.02 arcsec, in one day, a line sensitivity of 18 K can be obtained for mixers with a 1,000-K system temperature (2× better than HIFI). Continuum sensitivity is 3 mJy beam^{-1} (r.m.s.). Since almost all radiation emitted in the FIR is thermal emission coming from regions of 30 K and higher, it is clear that every optically thick line coming from 0.02-arcsec areas can be seen in 1 to 2 days. In our strawman mission profile we have used three dishes to optimise the synergy between the two detection systems, so the same cases will take longer to reach the same sensitivity. However, adding dishes is an option that should be studied, because it adds to the sensitivity of the system and it provides a big leap in the speed with which the (u,v) plane is filled.

A heterodyne interferometer tackles the high-spectral-resolution science in Section 3. As such, a heterodyne instrument suite on FIRI is compliant with Cosmic Vision in the area of planet and star formation.

6.2.7 Bandpass calibration

In the FIR, most sources are extended, so the usual method of measuring gains is not easily applied. *FIRI* has to rely, in the heterodyne case, on careful regular observations of its own antenna-based calibrators, together with (periodic) observations of the astrophysical objects suitable for bandpass calibration (these will probably be the same for ALMA and *FIRI*).

An overview on bandpass calibration for submm interferometers is given by Bacmann and Guilloteau [3]. Their method is applicable to *FIRI*, when all atmospheric contributions are assumed to be equal to 0 (or atmospheric gains equal to unity). Inspecting their equations 10 and 11, we see that the amplitude bandpass is independent of time and is equal to the product of the respective gains of the receiver, IF, filters and converters. Together, these two antenna-based quantities can be used to determine the baseline-based visibility gains that are necessary for real calibration. The phase bandpass is, to first order, the delay and this geometrical effect is treated below

So, it only remains to determine the antenna-based amplitude and bandpass. This can be done in several ways for ALMA, depending on loads at each telescope. Detailed calculations should show whether this, as for HIFI, is a feasible option. For *FIRI* the bandpass calibration will probably rely on the availability of internal calibrators. Further studies into the applicability of antenna-based gains for the determination of baseline-based bandpass solutions are necessary.

6.2.8 Phase calibration

Every interferometer relies on accurate knowledge of the phase, because this is where the information is that is used to create images. Therefore, the phase differences between the different telescopes have to be known accurately, which is in space only the geometrical path difference or delay, and the internal phase differences. The advantage of a heterodyne *FIRI* over ground-based radio telescopes is the lack of the Earth's atmosphere. This means that there are no phase fluctuations in front of the array. All phase errors are either geometrical, electronic (generated in the system itself), or due to jitter of the (master-) LO.

A very stringent limit on the electronic behaviour of phase is needed and geometrical errors must be as small as possible (as a rule of thumb, 0.1 rad is generally used in ground-based interferometry). Once suitable celestial sources for phase calibration are found, an algorithm is needed to tie the phases together. In principle, ALMA- or SMA-like schemes can be used where observations of phase-calibration sources in three places in the sky and separated at least by 30° yields enough information to obtain the phases of each individual telescope.

In general, *FIRI* should be much less susceptible to phase changes than a ground-based interferometer. This should offset the poor availability of phase calibrators.

For *FIRI*, the main LO phase change is from the geometrical delay. A well-designed metrology system will provide exact delays that can be fed into the correlator and sent out to change the slave LO phases with respect to the "master" LO. The second-most important change in LO phase stems from drifts in the electronics within each satellite. Thus, priority should be given to producing designs for the electronics that suppress drifts. As a second step, information about electronic phase drifts should be derived from comparisons of signals produced by the electronics units with external references. Implementation of such a technique is still to be investigated.

A geometrical model must be made that implements all known positions, velocities and accelerations, and outputs specific LO phase differences to all LOs in the system. Studies should show whether this is a viable plan. Secondly studies should be started that address the question of synchronizing the LO drifts from all elements of the satellite. Third, sources on the sky should be found in which an SMA-like scheme (observing three sources to obtain the phase of each element) can be applied. A study should be undertaken to determine an optimal calibration strategy.

6.2.9 Critical issues

While many aspects of the heterodyne payload can be based on HIFI heritage it is clear that much development is still needed. Amongst these we single out the following:

- Detector development: can we approach the quantum limit whilst increasing IF bandwidth?
- Can we make reliable LOs at THz frequencies?
- What is the best, most compact, power-efficient cross-correlator?
- Focal plane: how do we cool the mixers to 4 K?
- What is the best AIV approach?

7 Basic spacecraft key factors

This paper should be seen as the next step to achieve a *FIRI* that is based on existing, European technologies as far as feasible, but also includes new technologies in order to be able to remain within reasonable cost, mass and power budgets and to achieve the desired performance. Many of the new technologies proposed here are related to the interferometry character of the mission, and can be borrowed from the mission studies done for *Darwin* or *LISA*; NASA's interferometry missions (e.g. TPF) can also contribute. Technologies developed for micro-satellites by several scientific groups and companies (e.g. Surrey Space Centre, Guildford, UK, http://www.ee.surrey.ac.uk/SSC/) may lead to a light-weight bus suitable for larger missions like *FIRI*. The weight goal should be 300 kg/satellite.

7.1 Number of spacecraft

There are a number of reasons that lead to our current concept of three dishes plus one beam combiner for *FIRI*. It should be possible to have phase closure between the interferometer elements which leads to at least three heterodyne elements. Furthermore, there must be enough sensitivity to reach the line brightness in the warm gas, which would benefit from as many elements as possible. For the cooled *FIRI* complement, however, there is little benefit in using more than three collector spacecraft. Calculations for a three-element heterodyne interferometer with dishes of 3.5-m diameter show that this is sufficient to fulfil the sensitivity requirement for the high spectral resolution cases as long as the detectors have near-quantum limited performance. A similar sensitivity can be reached with more baselines in a shorter time when more elements are used.

The direct-detection interferometer needs a central beam-combining satellite in addition to the collector apertures. All four have to be well shielded from the heat loads of sun, earth and moon with several sun shields and baffles, making the four satellites rather heavy using today's technology. However, with clever low-weight instrument design it will be possible to pack everything in one launcher fairing. This should be confirmed by a dedicated assessment study. The three-element direct-detection interferometer will fulfil the sensitivity requirement as long as the detectors reach NEP values close to 10^{-20} W $\mathrm{Hz}^{-1/2}$, and the cooling of the whole system attains temperatures close to 4 K.

7.2 Attitude and orbit control

From first principles, the elements should be pointed with an accuracy of 0.3 arcsec. Focal plane arrays can live with more relaxed pointing requirements. We assume that the interferometer should be three-axis stabilized in each element.

For thermal reasons, and because of its benign radiation environment, L2 is the orbit of choice for *FIRI*. The interferometer should be able to move its elements inwards and outwards to fill the (u,v) plane in a controlled fashion. This will require, e.g., small ion motors. Repointing the whole array is necessary to move to another source.

We should ensure that the number of guide stars is adequate. In the SPECS study it was found that the only safe way to point with sufficient accuracy was to run NIR radiation from stars through essentially all the optical components of the interferometer. To do this efficiently, this would need to be done at wavelengths of about 2 μm, so the telescopes and optics need to be of NIR surface quality and NIR cameras will be needed for guiding. This may be a problem that needs significant attention in a phase A study.

7.3 On-board data handling and telemetry requirements

A heterodyne interferometer collects data at high speed and in large quantities. Assuming we will have (for two polarisations) a conservative 4-GHz-wide Intermediate Frequency (IF) signal out of the mixers, we can do the following calculations. The IF signal needs to be sampled at roughly twice (Nyquist) the IF frequency in order to prevent aliasing. This signal can be digitised by a two-bit A/D converter. There are several ways to proceed with correlation, of which one is a distributed correlator, where the IF signal is split in e.g. three or more basebands before it is sampled in the A/D converter. With the redundant properties of distributed correlators the single-point failure of a central correlator can be avoided and the data flow in the interferometer can be reduced. For a three-element interferometer and three basebands each element transmits 10 Gb/s and receives 20 Gb/s. These data rates are high, but within each element such rates are easily handled. Outside the elements simple IR links can transmit and receive these data rates. Finally, after correlation, the visibilities (of order 100 kb/s averaged over 1 day) can easily be transmitted with radio links as used e.g. for *Herschel*. There is a need for mass-memory on-board, for data storage, when no downlink is possible, similar in size as available to *Herschel* (~220 Gbits).

The raw data rate from a direct detection interferometer is approximately $b_{\max}^2 \eta_{uv} \theta_{\mathrm{FOV}}^2 n(R\lambda + b_{\max} \sin\theta_{\mathrm{FOV}}) / \lambda^3 t$, where $b_{\max} = 1$ km, the longest baseline length sampled, η_{uv} is the (u,v) plane filling fraction, θ_{FOV} is the field of view diameter, n (~4) is the number of samples per fringe, R is the spectral resolution, λ is the wavelength, and t is the observation time per target field. By implementing the inteferometer design features, mode of operation and sampling compromises recommended in Appendix F of the SPECS study report, the data rate can be reduced from a raw rate of 2 Gb/s to ~100 Mb/s.

Since the interferometer has only one operating mode, telecommands will be very simple and mainly deal with setting up the instrument and with internal calibration procedures. Downlinked telemetry of science and housekeeping data can be handled via high gain antenna in K_{a} band and delivered to a single ground station in approximately 30 min/day.

7.4 Estimated overall resources (mass and power)

Reasonable estimates have been assembled from the literature, but further assessment studies should reduce the uncertainty in the budget numbers presented below.

7.4.1 Attitude determination and control

The ESA study report on FIRI (hereafter, ESA-FIRI) [12] describes in pages 250 to 257 "Guidance, Navigation and Control". Their design is classical: RWs, thrusters, sun sensors and rate sensors.

The large reaction wheels of ESA-FIRI are used to rotate the 30-m boom and that is not relevant for our *FIRI* design. Each *FIRI* satellite only needs to maintain its pointing. The classical RWs of ESA-FIRI could be replaced by Control Moment Gyros (CMGs)—a momentum wheel, spinning at constant speed, mounted in gimbals fitted with torque motors. The motors torque the momentum vector to change its direction. As the momentum direction is changed a reaction torque is created on the spacecraft. These are more efficient than reaction wheels, but presently complex and expensive. CMGs have been used in military-related missions. Fortunately, cheap and light-weight micro CMGs are presently developed to be used for agile small satellites and have been tested in orbit [9].

Four wheels are needed (one for redundancy) and these four will weigh 19.4 kg. CMGs will weigh less: four Lappas CMGs will weigh 8.8 kg. As other equipment the ESA-FIRI study report lists three sun acquisition sensors, three star trackers and their associated electronics box, two internal reference units, and two attitude anomaly detectors. All these together weigh 17.7 kg and consume 68 W. Each *FIRI* spacecraft will need this classical equipment.

The inertial reference unit will presumably contain two gyros. A mechanical gyro, a mass on a gimbal senses the rotation rate and therefore accumulates error. By using the star tracker regularly the gyros are calibrated. Nowadays there also exist ring laser gyros, where time around loop and speed of light are used to calculate rate. Such ring laser gyros require much less star tracker calibrations. They are used on the Boeing 757 and 767. They can be bought from a number of firms, e.g., Kearfott's KN-4070, weighing less than 5 kg. Lighter space-qualified units are developed by several firms. These units can be considered to be of TRL 7–8.

The *Darwin* system assessment study (page 28) says that each *Darwin* spacecraft needs 63 kg hydrazine to move it to L2 and uses 4.5 kg of propellant for manoeuvres, over 10 yr. For *FIRI* this will be similar, but more studies are needed to assess the fuel constraints. The TRL status of thusters like FEEPs is ~7; they have been demonstrated in a mission to the moon. The 63 kg hydrazine is ascribed to the launch system.

Total weight of Attitude Determination and Control sub-system could be 25 kg, while the thruster system will weigh 40 kg, so 65 kg for the whole system. The attitude system will consume 50 W (extrapolating the conservative 68 W to the future).

7.4.2 Telescope and support structures

The telescope of *Herschel*, made of SiC, weighs 310 kg, too heavy for *FIRI* with three telescopes. New techniques are needed to reduce this mass to acceptable values. Tan et al. [22] describe a 5-m diameter inflatable parabolic reflector; a model has been made and integrated. The complete weight is presently 33 kg. It has a TRL of 4. Alternatively, Composite Mirrors Associated in the USA, is capable of producing carbon-fiber mirrors of *Herschel* size weighing <100 kg.

Tromp [23] describes making structures using a five-axis milling machine. The trick is that each excavated component has a front- and backside stiffening the structure considerably. This may decrease the weight of many mechanical components with 50%.

The telescope and all its structures may weigh <50 kg. When all other mechanical structures are made according to the ASTRON–Tromp method this may lead to a weight allotted to telescope, mechanisms and connecting/supporting structures of 100 kg.

7.4.3 Thermal sub-system

The functions to be provided consist of: (1) passive control by selection of surface properties, (2) control of conduction paths and thermal capacities, and use of insulation, (3) active control by heaters, louvers and shutters, refrigerators, (4) absorptivity and emissivity of external surfaces should be controlled, (5) multi-layer Insulation (MLI) blankets may be used or single-layer radiation shields.

While L2 is a benign thermal environment, baffles and sunshields are necessary to reach the ~4 K needed for a direct-detection interferometer. The ESA-FIRI study assigned sunshield diameters 5× the telescope diameter. This would not be acceptable for the 3.5-m dishes of *FIRI*, so detailed studies are needed to pin down the numbers. This should take into account the number of layers, the temperature of each layer, the cryo-cooler and passive radiators to reach each temperature stage, etc. Since the shields will be too large to be easily stowed in the fairing, a mechanism to deploy the structures is needed. These mechanisms should be designed such that redundancy prevents failure.

The weightiest elements will be the sunshields and a cooling system for the detectors. ESA-FIRI (page 249) lists 173 kg of equipment for boom, hub, and the two telescopes. Relevant for one *FIRI* telescope are: a sunshield (29.1 kg), heaters (1.3 kg), WP-radiators (13.8 kg), MLI (2.5 kg). *FIRI*'s sunshield needs to be deployable and much larger than that for ESA-FIRI. By making use of the lightweight techniques described elsewhere in this section 60 kg may be sufficient.

The thermal sub-system of one *FIRI* satellite may weigh 75 kg, excluding cryo-cooling (see next section).

7.4.4 Special requirements

The first major special requirement, common to most proposed large missions, is formation flying. *FIRI* would benefit from having data available from *GRACE*, *STEREO* and in the future *PROBA-3* as well as from ESA, NASA and industrial studies on this topic. The relaxed requirements with respect to *Darwin* may make it even possible to scale these studies to the *FIRI* case. However, the *FIRI* team does not have access to these data and therefore we consider formation flying as special requirement as well as a critical issue. Studies of formation flying should address the following:

- What accuracy is needed to keep control of the elements?
- What is the closest distance between any two elements; how is the risk of collisions treated?
- What is the best way to fill the UV plane in a reasonable amount of time?
- What propulsion system must be used to generate images with adequate UV plane filling?
- Can tethers save fuel? What are the risks?

The second major special requirement is the cooling of *FIRI*. This cooling consists of two components: for heterodyne observations, the mixers must be cooled down to 4 K. For direct detection, active cooling of the dishes and beam combiner allows for very sensitive direct detection measurements. While studies should show the exact requirements, we note that cooling is an issue for many proposed missions and that *FIRI* can benefit from existing studies. For *Darwin*, studies have been performed for vibration-less sorption micro-coolers. At first glance this seems very appropriate for the mixer cooling described above and the study results applied to *FIRI* could provide the detailed numbers on cooling power versus power consumption, mass and volume. Cooling the telescopes to 4 K is a difficult task, but the SPECS and SPIRIT studies show it to be feasible, and cooling a 3.5-m aperture to 4 K is expected to be demonstrated by *SPICA*. Confirmation of the numbers from these studies for *FIRI* is necessary.

7.5 Critical issues

Although *FIRI* has not benefitted from years of industrial studies, other mission studies have encompassed much of what *FIRI* needs. There are open questions which need answers before *FIRI* enters Phase A:

- Direct detector array development to very low NEPs with high frequency read-out;
- Heterodyne detector development: can we approach the quantum limit whilst increasing IF bandwidth?
- System: How can we ensure an adequate number of guide stars?

Other issues include:

- LO development: how do we make reliable LOs at THz frequencies?
- Beam combiner: what is the design for a 4 K three/two-input beam combiner?
- Delay lines: what is the best way to design optical delays employed at 4 K?
- Correlator: what is the best, most compact, power efficient cross-correlator?
- Telescopes: how do we make the best light-weight dish with off-axis movable secondary?
- Focal plane: how do we cool the mixers to 4 K?
- Telescopes: how do we cool dishes to 4 K?
- System: What is the optimal number and optimal temperature of light-collecting spacecraft?
- System: What is the spacecraft thermal design?
- System: What is the best propulsion, thruster, tether scheme for the whole system?
- System: What is the best metrology approach?
- System: What is the best optical design and how do we do stray-light suppression?
- System: What is the best AIV approach for a system that is extremely difficult to test on ground?

In order to bring *FIRI* to the required level these studies are absolutely necessary. Science and technology institutes in Europe and North America are well equipped to tackle the fundamental issues like detector development. Space industry has the required capacity to solve the system issues.

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