FISICA

Far Infra-red Space Interferometer Critical Assessment
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WP 1 - Scientific definition of Instrument Requirements

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Lead beneficiary for this deliverable: Science and Technology Facilities Council (STFC), UK

Lead author: Wayne Holland, UK ATC (STFC)/University of Edinburgh

Contributing authors: Giorgio Savini (UCL), Créidhe O'Sullivan (NUIM), Enzo Pascale (Cardiff), David Naylor (Lethbridge), Brad Gom (Lethbridge), Luigi Spinoglio (INAF), Kjetil Dohlen (LAM)

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PU	Public	■
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Summary

This document presents the design requirements for the next generation far-infrared space interferometer (FIRI) that will allow such a mission to achieve its scientific goals. Starting from the science case (outlined in submitted FISICA report D1.1) a preliminary set of requirements for the telescope/instrument are derived. These include a series of "top-level" conditions based on the need to carry out ultra-sensitive observations at high angular resolution in the far-infrared region of the electromagnetic spectrum. Further to this, requirements are generated for both the telescope system and the instrument (contained within the "hub" of the satellite). Calculations, based on a current "Strawman" model of the telescope/instrument have been performed to estimate achievable sensitivities, which in turn place stringent demands on the detector arrays. Finally, preliminary operational requirements are also discussed, particularly those that have a potential impact on instrument performance. It should be emphasised that this document represents an interim report on the identified preliminary requirements, largely as a result of the science case, and future/ongoing work in specific areas is highlighted. A final document, which will consolidate and expand upon the work presented here and in other work-packages, will be submitted at the end of the project.

History table

Version	Date	Released by	Comments
0.1	05/12/2014	Wayne Holland	Draft for comment
0.2	19/1/2015	Wayne Holland	Second complete draft
1.0	25/1/2015	Wayne Holland	Final version

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Key word list

Instrumentation: high angular resolution

Instrumentation: interferometers

Instrumentation: spectrographs

Instrumentation: detector arrays

Techniques: high angular resolution

Techniques: imaging spectroscopy

Definitions and acronyms

ALMA	Atacama Large Millimeter/Submillimeter Array
APE	Absolute Pointing Error
BETTII	Balloon Experimental Twin Telescope for Infrared Interferometry
JWST	James Web Space Telescope
PSF	Point-spread function
SCUBA-2	Submillimetre Common-User Bolometer Array
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure
SPIRE	Spectral and Photometric Imaging Receiver
SPIRIT	Space Infrared Interferometric Telescope

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Disclaimer

1. Introduction

1.1 Science drivers

The far-infrared region, which encompasses the spectral range from 30 to 300µm, contains a wealth of information about the cold Universe. Observations of gas and dust probe the earliest stages in the formation of galaxies, stars and planets. The recent success of the *Herschel Space Observatory* has highlighted the importance of studying astrophysics in the far-IR region. However, the limited angular resolution afforded by *Herschel* mean that the study of some of the most critical astrophysical phenomena, which are often found on small size-scales, remains elusive. The FIRI concept was proposed to fill the "resolution gap" by providing detail on sub-arcsecond scales in the far-IR, as a complement, for example, to the James Webb Space telescope (JWST) at shorter wavelengths (near IR) and the Atacama Large Millimeter/Submillimeter Array (ALMA) at longer (300µm onwards).

The primary goal of such a mission is thus to carry out ultra-sensitive observations at high angular resolution in the far-infrared region of the electromagnetic spectrum. The science case has been put together based on a mission that will achieve the following three main goals:

1. That will operate in the far-infrared region of the spectrum addressing a number of key scientific objectives, hitherto unanswered;

2. Will have the sensitivity and resolving power to measure a number of key ionic, atomic and molecular lines over a range of astrophysical phenomena;

3. Has sufficient angular resolution to be able to probe the previously unexplored inner regions of astrophysical phenomena, e.g. nuclei of galaxies, circumstellar disks and star-forming cores.

1.2 Science requirements

The science requirements for a FIRI mission have been studied in detail in the first year of the FISICA project. This culminated in a highly successful workshop, held in Rome in February 2014, and the subsequent publication of a report on "Definition/update of key science questions and relevant data products" (project deliverable D1.1; main author: Luigi Spinoglio). A number of key scientific themes have been identified each of which has one or more relevant science cases. An assessment was made on each in terms of the requirement on instrument sensitivity, angular-resolution, field-of-view and spectral resolution. These are summarised in Table 1 in terms of the requirements for medium resolution spectroscopy.

Theme	Science Case	Required field-of-view (arcmin)	Required angular resolution (arcsec)	Required spectral resolution	Sensitivity required (estimated line flux)
Star formation: Protostars	Resolve 100AU: detection of the first hydrostatic cores	0.5 – 1	0.25" @ 400pc 0.40" @ 250pc 0.66" @ 150pc	~3000	H_2O: 2.1 × 10^{-20} W/m^2 H_2O: 5.4 × 10^{-20} H_2O: 1.5 × 10^{-19}
Star formation: Protoplanetary disks/Formation of planetary systems	Resolve the outer structure (10 – 100AU) of protoplanetary disks	1 – 2	0.20" (30AU @ 140pc) 0.75" (100AU @ 140pc)	~5000	A: [OI]63µm: 2.4 × 10^{-16} [OI]145µm: 1.2 × 10^{-17} B: [OI]63µm: 3.7 × 10^{-16} [OI]145µm: 3.1 × 10^{-17}

Star formation: Binary and multiple systems	Resolve binary and multiple protostellar objects	0.5	0.25" @ 400pc	~3000	[OI]63µm: 9×10^{-19} H_2O: 8×10^{-19} – 4×10^{-18} CO: 2×10^{-19} – 4×10^{-18} HDO: 4×10^{-18}
Star formation: Massive star formation	Answer to the question if massive clumps form only one massive star or stellar clusters	1 – 2+	0.25" @3kpc	~3000	^{12}CO(10-9): 5×10^{-18} ^{13}CO(10-9): 8×10^{-19} C^{18}O(10-9): 1×10^{-19}
The Galactic Center	Map the central thousands AU around the SgrA* Black Hole in extinction free continuum and lines	1 – 2+	0.25" @ 8kpc	~3000	[OI]63µm: 2.4×10^{-17} CO(14-13)@186µm: 1.9×10^{-19} CO(24-23)@108µm: 2.0×10^{-20}
AGN in the local Universe	Resolving the torus and the emission-line regions in the circumnuclear environment of local AGN	0.5 – 1	0.10" @ 50Mpc	1500 – 3000	[OIV]26µm: 1×10^{-19}, 1×10^{-18}, 3×10^{-18} (min, ave, max) [NeV]24µm: 3×10^{-20}, 2.8×10^{-19}, 9×10^{-19} [OI]63µm: 6×10^{-19}, 2.6×10^{-18}, 7.6×10^{-18}
Galaxy formation and Evolution	Resolving starburst complexes and Narrow Line Regions along galaxy evolution	1 – 2	0.10" starburst (0.02" NLR)	1500 – 3000	Line fluxes are typically in the range 10^{-21} – 10^{-19}

Table 1: Summary of the main requirements for each science theme in terms of medium resolution spectroscopy

2. Top-level requirements

As outlined in section 1.2 the key drivers for a FIRI mission will be to carry out moderately-sized field imaging, with medium spectral, and high angular resolution to great depth in the far-infrared. FIRI will seek to maximise these capabilities within the constraints of a practical system. The science requirements dictate a number of key top-level requirements which are now discussed.

2.1 Wavelength range

To achieve the science goals requires a continual spectral coverage between 25 and 400µm. The vast majority of this wavelength range is inaccessible from the ground, necessitating a space-borne mission. To optimise performance it will be necessary to split such a wide spectral range into multiple bands, each of which, for example, will have its own optimised camera. The proposed bands are listed in Table 2.

Band	Central wavelength (µm)	Lower-edge cut-off (µm)	Higher-edge cut-off (µm)
1	37.5	25	50
2	75	50	100
3	150	100	200
4	300	200	400

Table 2: Proposed bands for the instrument

R2.1.1. The continuous spectral coverage for the instrument will be from 25 to 400µm.

R2.1.2. Over the spectral range there will be 4 discrete bands, each of which will be optimised with its own camera.

R2.1.3. Band 1 will be centered at 37.5µm and have low and high wavelength cut-offs at 25 and 50µm, respectively.

R2.1.4. Band 2 will be centered at 75µm and have low and high wavelength cut-offs at 50 and 100µm, respectively.

R2.1.5. Band 3 will be centered at 150µm and have low and high wavelength cut-offs at 100 and 200µm, respectively.

R2.1.6. Band 4 will be centered at 300µm and have low and high wavelength cut-offs at 200 and 400µm, respectively.

The baseline instrument currently has the aforementioned 4 observing bands by default. It is possible that future iterations of the instrument may consolidate the spectral range, say from 30 to 300µm. This largely depends on factors such as whether overlap with ground-based facilities (such as ALMA at 350µm) would be beneficial. For example, an instrument working over the range from 30 to 300µm could, in principle be covered with high efficiency using only 3 bands.

2.2 Angular resolution

The science requirements point to the need to spatially resolve astronomical objects with angular sizes in the range 0.1 – 0.7 arcsecs. In particular, a key requirement for several of the science cases is to achieve a resolution of 0.1 arcsec at a wavelength of 40µm. Since this requires a telescope aperture of around 100m, an interferometer arrangement with 2 telescopes is the only realistic option. Within the FISICA study 3 options are being considered with a maximum inter-telescope baseline of 100m:

1. A tether connection between the 2 telescopes;
2. A rigid structure (boom) connecting the 2 telescopes;
3. A free-flying configuration.

The pros and cons of these options are subject to a separate design report (D1.3). For the baseline FIRI design there will be 2 telescopes, nominally connected on a rigid boom, performing **aperture synthesis interferometry** to achieve the required angular resolution.

R2.2.1. The minimum angular resolution achievable will be 0.1 arcsec at a wavelength of 40µm.

R2.2.2. The baseline will be variable from a few metres up to a maximum inter-telescope distance of 100m.

2.3 Spectral resolution

The science drivers require the ability to perform imaging medium-resolution spectroscopy (R ~ 1000 – 5000) as the key types of observations. This will allow ionic, atomic and molecular lines to be observed within the spectral range of the instrument.

R2.3.1. In "spectroscopy mode" the resolving power required will be in the range 1000 – 5000.

Although the aforementioned "spectroscopy mode" is key to the achieving many of the science requirements, the instrument should also not preclude complementary lower resolution spectroscopy (R ~ 100) and even a spectrophotometry (R ~ 5) mode. For example, a mode with R ~ 100 would be well-suited to measure the spectral energy distribution of objects within the wavebands.

R2.3.2. In "SED mode" the resolving power required will be around 100.

Finally, a spectrophotometry capability should be available (R ~ 5). This will not only give crucial information on the small and large-scale dust distribution but will also provide the ultimate sensitivity on faint objects with wide spectral features, including galaxies, dust grains, and planetary atmospheres.

R2.3.3. For "spectrophotometry mode" a spectral resolving power of ~5 is needed.

To achieve the range of spectral resolution needed it is proposed that a double Fourier spectro-imaging technique be adopted.

2.4 Sensitivity

Typical line fluxes are in the range a few $\times 10^{-16}$ to 10^{-19} W/m^2, and so the requirement for the sensitivity will be to reach the faintest levels of 10^{-19} W/m^2 in 1 hour of observing time (1σ). The goal is to improve on this by an order of magnitude i.e. achieve a level of 10^{-20} W/m^2 (1σ in 1hr, or 5σ in 24 hrs).

R2.4.1. The requirement for the line sensitivity is 10^{-19} W/m^2 (1σ in 1hr), with a goal of $\sim 10^{-20}$ W/m^2 (1σ in 1hr, or 5σ in 24 hrs).

For operating in spectrophotometry mode typical fluxes are in the mJy to few ×10μJy range and so the requirement is to be able to measure point-source fluxes to 30 μJy with a goal of again improving upon this by an order of magnitude.

R2.4.2. The point-source sensitivity is required to measure flux density levels of 30μJy (1σ in 1hr, or 5σ in 24 hrs) with a goal of <10μJy (1σ in 1hr, or 5σ in 24 hrs).

These are challenging levels to reach and will require careful consideration of the mission design, including not only the collecting area of the telescope but the thermal design of the system to keep background power to a minimum to avoid degrading sensitivity. To assist in this exercise Appendix A1 summarises the rationale (and current performance estimates) behind the **"FISICA Strawman sensitivity model"** which is being used to determine whether these sensitivity levels are feasible, particularly in view of an evolving instrument design.

2.5 Field-of-view

The requirements for the field-of-view, for the majority of the science cases, are satisfied by a field of 1 arcmin in diameter (assumed square) at the diffraction limit of the telescope. However, there are some cases for which a larger field would be highly beneficial (e.g. following up on deep "blank" surveys and the study of molecular clouds in nearby galaxies). For surveys of unresolved point sources with a Nyquist-sampled telescope, the performance metric is D^2N_{pix}, where D is the telescope diameter and N_{pix} is the number of detector pixels, so there is a clear motivation for having a larger field. Hence, there will be a goal of having a 2 arcmin diameter field for FIRI, and the optical design will take this into account if possible.

R2.5.1. The field-of-view of the instrument will be 1 arcmin in diameter with a goal of 2 arcmins.

3. Telescope requirements

The requirement for angular resolution in the typical range 0.1 – 0.7 arcsec, and crucially achieving 0.1 arcsec at 40µm, dictates that the telescope will be an interferometer with variable baseline of up to 100m. The default design is currently for a 2 telescope system performing aperture synthesis interferometry. The requirements of the telescopes and optical configuration to relay the beam to the instrument hub beam combiner will now be considered.

3.1 Collecting area of the primary

Ideally, the collecting area of the primary should be as large as possible to maximise sensitivity. However, practical limitations (e.g. size for launch, mass, manufacturability, cooling and pointing tolerances) dictate a compromise in terms of diameter. Based on modelling (predictions of achievable sensitivity – see Appendix A1), and taking into account practical sizes, the diameter of the primary mirrors should be of order 2m.

R3.1.1. The primary mirrors of the telescope will be 2m in diameter.

A number of factors can degrade sensitivity (aberrations and surface errors) causing a loss of throughput (see section 3.3) or distort the optical beam leading to poorer-than-expected image quality. In addition, diffuse stray light from the telescope and sun-shield will degrade sensitivity by adding noise to the observations (section 3.4).

3.2 Optical configuration

The optical configuration for each telescope has to ensure that the light collected from the sky is relayed to the instrument hub, beam combiner and the detector arrays. This has to be done taking into account the physical size of the relay optics (and subsequent hub optical components), whilst minimising beam truncation and aberrations across the field. Aberrations will be considered further in section 3.3.

One of the key consequences of the telescope optical configuration is the bearing on the diameter of the cryostat window, subsequent optics and cold stop. The cryostat window should be kept small to minimise background loading on the arrays and stray light, but accepting that a large de-magnification factor from the telescope may introduce an unacceptable level of aberrations. A practical upper limit for the size of the window and cold optics is 200mm.

R3.2.1 The instrument cryostat window and cold optics will not exceed 200mm in diameter.

Initial design work on the optical configuration was based on the original FIRI layout, having a 2m diameter aperture stop at the primary mirror. The result of this, the cryostat window and subsequent hub optics required were very large (approaching 0.5m for the latter). As an alternative, designs that adopted compression (de-magnification) of the beam to reduce the size of the window and cold optics were investigated:

1. Condensing optics at the primary element followed by a flat to direct the beam to the hub (referred to as the "FIRI-type");

2. A flat primary mirror (siderostat) with condensing optics near the hub (referred to as the "BETTII-type").

These will now be considered in turn.

3.2.1 FIRI-type design

The FIRI-type design incorporates an off-axis Cassegrain telescope together with an afocal beam condenser arrangement as shown in Figure 1. Placing the aperture stop at the cryostat window minimises its size but at the expense of needing a larger primary mirror (where the input beams no longer overlap). The cryostat window size then just depends on the de-magnification chosen.

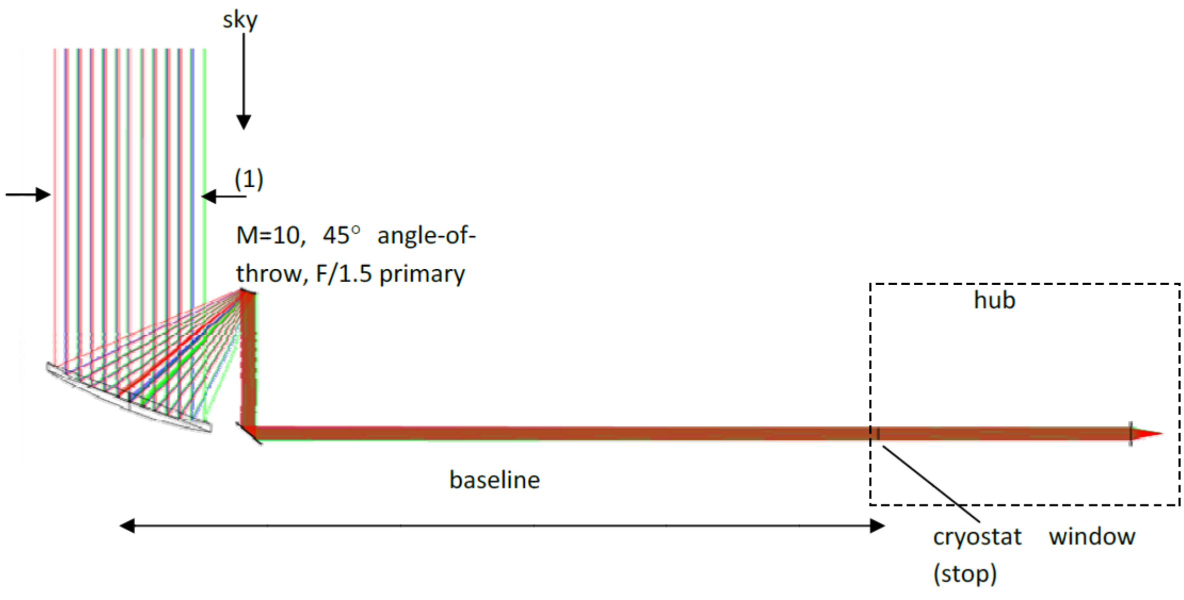

Figure 1: Optical configuration for the “FIRI-type” design.

In the example in Figure 1 the diameter of the primary mirror needed to keep the cryostat window to 200mm with a de-magnification of 10 is ~3.5m. Hence, this configuration requires one (very) large component (the primary) but more modestly-sized relay optics.

3.2.2 BETTII-type design

An alternative configuration is based on the design being built for BETTII as shown in Figure 2. In this arrangement a flat siderostat relays the beam to an afocal telescope placed close to the hub. The aperture stop is now at the primary. This design means that 2 large mirrors are needed and the subsequent size requirements depend on the magnification of the condensing optics.

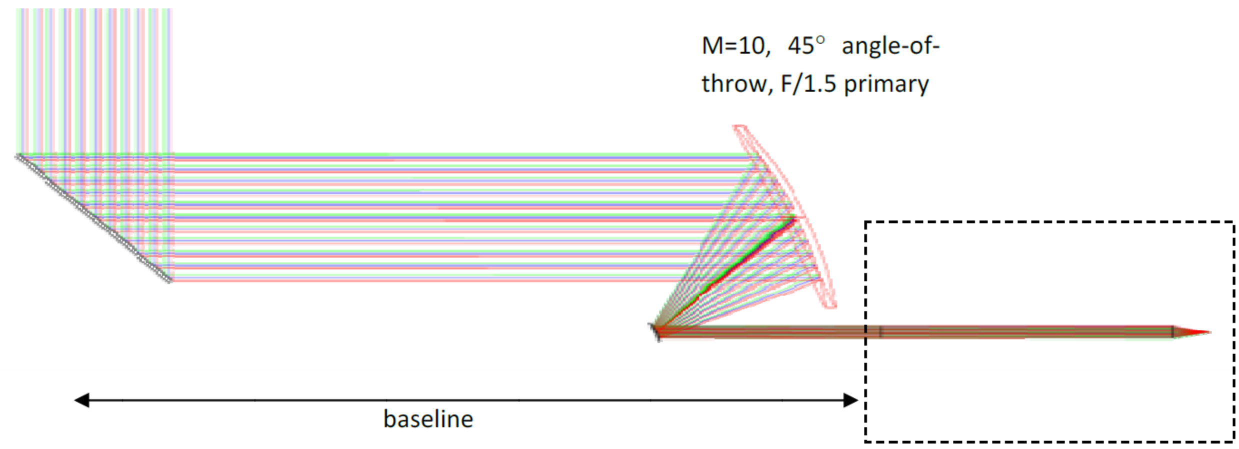

Figure 2: Optical configuration for the “BETTII-type” design.

In the example in Figure 2, and based on a flat and primary of ~2m, the cryostat window of 200mm in diameter is achievable with a demagnification factor of 10. Hence, this configuration requires 2 large components (the flat and primary) of order 2m in diameter.

These two designs remain under consideration with further modelling underway to look into the effects of diffraction and the levels of aberrations. The practicalities of each design (to include thermal considerations) will also be taken into account when making a final decision.

3.3 Image quality

Surface errors (e.g. roughness and form error) in the telescope optics lead to deformation of the primary beam of the instrument, decreased fringe contrast and a general degradation in overall image quality. A surface accuracy of $\varepsilon_{RMS} \leq \lambda/180$, which equates to ~140nm at 25μm, will be needed to keep the consequent visibility loss to below 0.0025 (O’Sullivan, 2014). At this level the errors will not significantly alter the shape or symmetry of the primary beam. Although visibility loss is currently used as a performance metric, in future, as the design develops the output of the optical models (e.g. far-field beam patterns) will be used as input to the instrument simulator (WP 4).

R3.3.1. The surface accuracy of the optical components within the telescope should be 140nm RMS or better.

R3.3.2. The instrument is to have diffraction-limited performance at the shortest wavelengths (25μm).

Losses in the optical throughput of the telescope optics (as specified by the Strehl ratio) will be governed not only by small-scale mirror surface roughness but also the aberration performance of the optical system. Given the tolerances on surface accuracy it will be necessary to tightly control aberrations within the system to minimise losses and keep the Strehl ratio at 90% or higher.

R3.3.3. The overall Strehl ratio for the telescope optics is to be > 90% at all wavelengths.

Another key issue for the optical design is to minimise field distortion (field dependent magnification) across the focal plane of the detector array (particularly near the edges). These need to be at such a level that one part of the array does not have a significantly worse point PSF than any other. Field distortion should never be sufficient to mean that when performing an observation one part of the array is left less than critically sampled. This criterion requires that field distortion at the shortest wavelengths is less than 3% across the detector arrays.

R3.3.4. Field distortion across the detector arrays is required to be < 3%.

Further work:

1. *Requirements (science-driven) for the maximum amplitude of near and far side-lobes ("error beam").*
2. *The maximum level of cross polarisation allowed.*

3.4 Thermal considerations and stray light

The telescope components need to contribute as little as possible to the error budget for the background photon noise, which in turn should ideally set the limit for the overall instrument sensitivity. Figure 3 shows the contribution of photon noise from the telescope mirrors as a fraction of the total background NEP as a function of mirror temperature. This was derived from the sensitivity model (see Appendix A1). As can be seen the telescope mirror temperature is crucial at the longer wavebands, and needs to be 4.5K or less to contribute 50% of the background power at band 4.

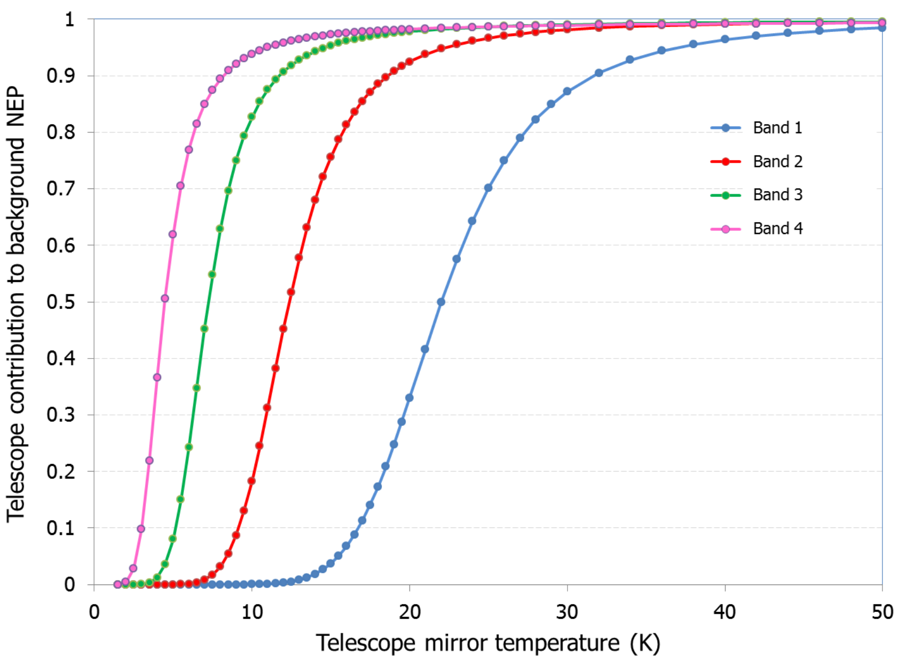

Figure 3: The contribution of photon noise from the telescope as a fractional of the overall background NEP as a function of telescope temperature. This assumes any subsequent optics has a negligible contribution to the background.

R3.4.1. The temperature of the mirrors in the telescope will be 4.5K or less.

This also assumes that the mirrors in the telescope have low emissivity values of 3% or less at all wavebands.

R3.4.2. The emissivity of each telescope mirror will be < 3% at all wavelengths.

Understanding and controlling stray light to low levels is an essential requirement for success in the deep exposures planned for FIRI. Diffuse stray light limits sensitivity by adding noise to the observations. The diffuse stray light from the telescope and sunshield must contribute negligible amounts to the overall background power budget. These levels can be determined by modelling leading to enhancements in the design as needed (e.g. provision of baffles etc.). This also applies to potential stray light sources within the instrument.

R3.4.3. Diffuse stray light will contribute less than 5% to the overall background power levels.

Local stray light sources (i.e. within the field-of-view) can produce ghost images and ultimately limit image quality and the dynamic range of an observation. It should be the case that no more than 2% of the light from point sources will appear in the form of stray light or ghosts in the focal plane.

R3.4.4. A point source within the field-of-view will contribute < 2% of the light that appears as a ghost image.

3.5 Pointing accuracy

The overall instrument (including telescope) needs several highly accurate metrology sub-systems. Knowledge of the origin and propagation of phase and positional errors along the optical path is critical to fringe visibility and interferogram reconstruction. Further discussion is given in section 5.4, and it is clear that minimising these errors will be a major operational challenge.

The requirements for the pointing and tracking (drift) accuracy depend on the science aims, observing efficiency desired and the ultimate angular resolution to be achieved. To generate a requirement assume that at the shortest wavelength (25µm) the normalised coupling (thus observing efficiency) due to pointing error in one-dimension be greater than 90% over long integrations. Goldsmith (Goldsmith 1998) considers the case of a perfectly pointed telescope, for which the point source coupling, or aperture efficiency, is limited by the illumination edge taper and the secondary blockage (Goldsmith equation 8.8). A telescope pointing error of θ manifests as a beam waist offset of $\delta = F\theta$ at the focal plane, where F is the focal ratio of the telescope optics. Figure 4 shows the fractional loss of signal due a RMS pointing offset (Goldsmith equation 4.30) assuming a F/10 telescope illuminated with Gaussian beam with 10dB edge taper.

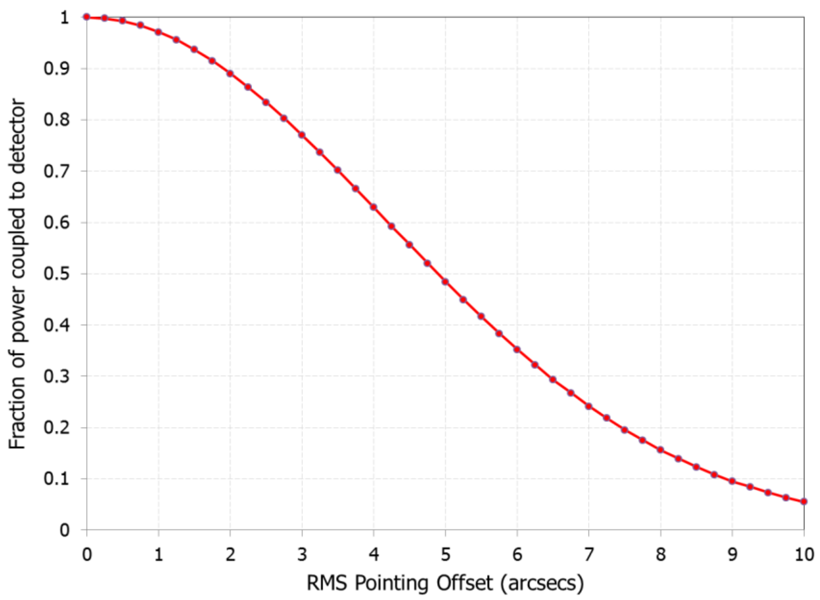

Figure 4: The coupling efficiency to a point-source as a function of RMS telescope pointing error.

Hence, if a loss of 10% coupling can be tolerated the "blind" absolute pointing accuracy (absolute pointing error or APE) of 2 arcsec will suffice. These requirements are far less stringent than if the telescope was coupling to, for example, a long-slit spectrometer. After data acquisition, pointing must be known well enough to compare observations with those from other observatories. This places requirements on the knowledge of the optical field distortion of the telescope and instruments, and on the accuracy of any guide star catalogue used.

R3.5.1. The absolute pointing error will have a requirement of <2 arcsec RMS and a goal of <1 arcsec.

The accuracy to which the telescope can maintain a position over some time interval is the tracking accuracy (or pointing drift error, or jitter). This must be tightly controlled as small variations can lead to phase noise contributions in the measured interferogram. Furthermore, high frequency oscillations can cause blurring of the individual fringes, leading to a reduction in the fringe visibility and overall image quality. This may be maintained, for example, to high precision using active tracking of guide stars, but considerations of mechanical design (structural rigidity) of the entire satellite structure is crucial in this regard.

R3.5.2. A tracking accuracy of <1 arcsec RMS will be maintained over a 24 hr period (typical observing period) with a goal of <0.5 arcsec.

Further work:

1. *To investigate if there will be a source of pointing error due to the finite offsets between the 2 telescopes.*

4. Instrument requirements

The instrument cryostat will be located at the hub of the interferometer. There are a number of key challenges associated with the cryostat design:

1. Minimise size of the optical components (and cryostat window);
2. Provide support, cooling and mechanism control for the optical delay lines;
3. Split the beam into 4 channels with each feeding a separate camera system;
4. Combine the beams from both telescopes with high accuracy and efficiency;
5. Provide an ultra-low temperature environment for the detector arrays.

Figure 5 shows a schematic representation of a possible layout for the cryostat, highlighting the main features. It should be emphasised that this is only one possible option and there could be variants of this (e.g. moving the delay line outside the main cryostat).

The collimated beam from each telescope enters the cryostat through a window. The first folding flat mirror could be a dichroic which transmits the near-IR to be used as part of a fringe tracking metrology sub-system. The beam passes through the beam delay line, consisting of a block of roof-top mirrors which move as a single unit with high precision. Each channel being picked off via a dichroic and it is likely that the shortest wavelength channel will be picked off first. For each channel the beam is further folded as needed and interferes with that from the other telescope at the beam combiner. The resultant beam is then focussed onto an array via an off-axis parabolic mirror. Each spectral band will have 2 detector arrays recording both the resultant interferogram and its inverse. The requirements of the instrument hub will now be considered.

4.1 Cryostat and cooling systems

The instrument cryostat should be, as far as possible, designed in simple modular sections, making maintenance and upgrades relatively straightforward. A key goal from the opto-mechanical design is to minimise the size of the optical elements within the cryostat (and hence the size and mass of the cryostat itself) as specified in section 3.2. A key factor for the cryostat design itself is to provide the ultra-low temperature environment in which to operate the highly sensitive detector arrays.

The cryostat window must ideally be as small as possible to minimise thermal loads inside the cryostat (see R3.2.1). The window must be made of a highly transmissive material for wavelengths beyond 25μm. In addition, optical/IR rejection baffles will be needed at the window to keep the thermal loads on the cryogenics to acceptable levels.

R4.1.1. The cryostat window must be made of a highly transmissive material with a requirement of >90% transmission at all wavelengths.

R4.1.2. The opto-mechanical design should allow for the provision of optical baffles at the cryostat window.

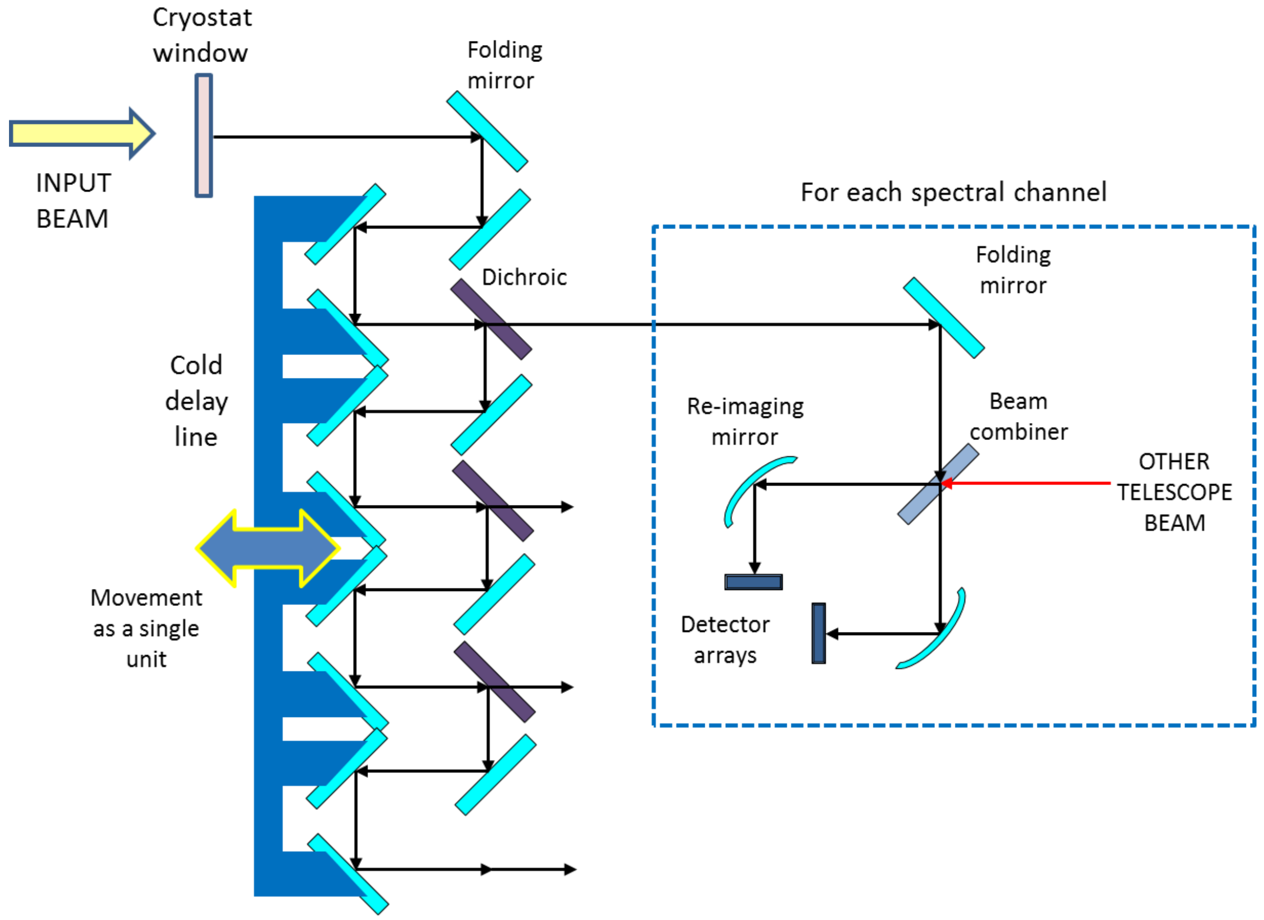

Figure 5: A schematic representation for the possible layout of the instrument cryostat.

Common practice is to design a modular system having nested radiation shields at decreasing temperatures to minimise loading and stray light at the detector arrays. Having the temperature of all optical components within the cryostat ("optics box") as cold as practical will also minimise the power loading on the detector arrays.

R4.1.3. To minimise stray light and heat loads the cryostat should have nested radiation shields, nominally at 4, 2 and 1K.

Figure 6 shows the contribution of photon noise from the optics box mirrors as a fraction of the total background NEP as a function of mirror temperature. As can be seen the mirror temperature is crucial at the longer wavebands, and needs to be 3K or less to contribute <20% of the background power at band 4. A negligible contribution to the total background would be achieved by having the mean optics box temperature at 2K or less.

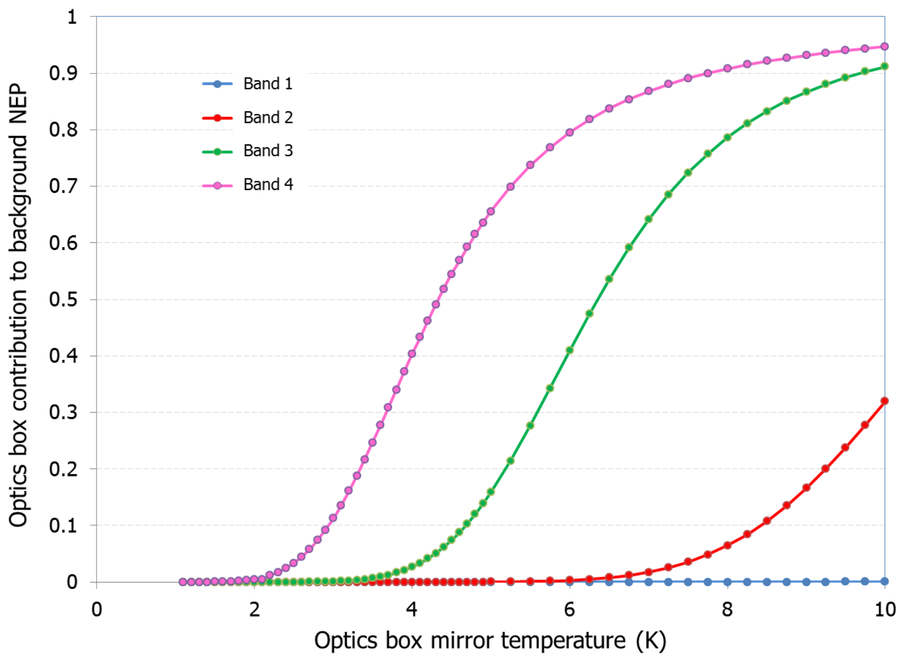

Figure 6: The contribution of photon noise from the optics box mirrors as a fractional of the overall background NEP as a function of mirror temperature. This assumes the telescope mirrors are operating at 4.5K.

R4.1.4. The internal cryostat mirrors should be cooled to <3K, with a goal of <2K to avoid excess power loading on the arrays.

Given the number of cold optics it is likely that mechanical coolers will be used (e.g. pulse tube coolers). Careful baffling and the provision of a cold, black enclosure (1K focal plane unit) surrounding the arrays will be required. Other stray light paths also need to be avoided. These paths include wiring channels, holes in shields for thermal straps and mechanical supports and control of light paths through entry tubes in refrigerators.

The sensitivity (NEP) levels required for the detectors (see section 4.7) mean that they must operate in the 100mK regime. Within practical limits the lower the detector temperature the lower the detector noise contribution to the overall NEP.

R4.1.5. The detector arrays need to operate at temperatures of < 100mK.

This will need the provision of a system providing sufficient cooling power, operating in the mK temperature regime.

It is a goal that a fully-trained team, consisting of 3-4 people, can gain access to the arrays within a reasonable period of a working day when the instrument is undergoing testing (e.g. in a lab environment). This assumes the cryostat has been positioned for such work (i.e. is not undergoing field tests mounted within the hub).

R4.1.6. The cryostat should be modular, with a goal of allowing access to the arrays in < 4 hrs once the instrument warm-up has been completed and the cryostat positioned for disassembly.

4.2 Delay line and re-imaging optics

Interferometry and spectroscopy with FIRI rely on accurate delay lines. For accurate spectroscopic phase retrieval and ghost line suppression, it has been shown that sampling accuracy better than 0.1% of the shortest wavelength is required (Davis et al. 2001).

R4.2.1. The sampling accuracy required for the linear translation stage for the delay line is 0.1% at the shortest wavelength.

A major challenge is to achieve this requirement in space and at cryogenic temperatures. This is the subject of a separate work-package (D3.1) led by the University of Lethbridge. In this activity a Renishaw differential laser interferometer will be used to evaluate the performance of a cryogenic translation stage mounted in a pulse-tube cooled 4K cryostat. In addition to studying cryogenic metrology issues, the work will investigate the performance of critical components such as beam splitters and filters at their nominal operating temperatures.

The opto-mechanical design will determine the exact requirement for re-imaging optics within the cryostat. The mirrors that make up the optical delay line and re-imaging optics (e.g. flat or powered mirrors) should be easy to manufacture, and have a surface finish (micro-roughness) of < 140nm RMS to contribute negligible efficiency loss due to scattering (see section 3.3).

R4.2.2. The surface accuracy of the delay line and re-imaging mirrors should be 140nm RMS or better.

The emissivity of the mirror surfaces should ideally be minimised with a goal of less than 3% across the spectral band per mirror.

R4.2.3. The emissivity of the mirror surfaces within the cryostat should be < 3%.

In addition, the choice of optical components that make up the delay lines is crucial. For example, roof-top mirrors allow the most compact configuration minimising the overall optical path length in the cryostat as well as diffraction effects.

4.3 Filtering and dichroic

The instrument will use two types of filters: bandpass filters to select the passbands for the observations and low-pass (or edge) filters to block shorter (optical/IR) wavelength radiation. The bandpass filters must have high efficiency (>80%) and low harmonic leaks so as not to contribute to a potential stray light issue.

R4.3.1. Bandpass filters have a requirement of >80% transmission and <1% out-of-band power.

The bandpass is to be located close to the array (in the near-field of the detector to aid the control of any ghosting), and will have a circular cross-section (in manufacture). As an alternative to a bandpass filter the passband could also be defined using high-efficiency low- and high-pass edge filters. The optical design and their chosen location in the instrument govern the diameter of the filters. Filters of the anticipated size required have been manufactured before.

It may be necessary to fine-tune the gap between bandpass filter and the array. Hence, there should be provision for varying the gap between the filter and the array (probably using shims).

R4.3.2. Provision is needed to vary the gap between the bandpass filter and the array by up to 3λ.

Infrared blocking and low-pass filters will also be needed on the radiation shields at 10, 4 and 1K (temperatures to be confirmed upon completion of the cryostat design). Again these will be manufactured as circular components. The diameter of the filters is dictated by the opto-mechanical design.

R4.3.3. IR blocking and low-pass filters on radiation shields will each have > 95% transmission for wavelengths longer than the cut-off.

Observations at 4 wavelengths simultaneously mean that high efficiency dichroic beamsplitters are needed. Such dichroics have been developed for other instruments. The dichroic must also work with high efficiency at the angle of incidence required for the opto-mechanical design of the focal plane units.

R4.3.4. High efficiency dichroics with > 95% transmission and reflectance at an appropriate cut-off wavelength are required for each spectral band.

4.4 Beam combiner

The beam from both telescopes interferes at the beam combiner with the subsequent interferograms recorded by the detector arrays. The beam combiner needs to have excellent transmissive and reflective properties with low emissivity.

R4.4.1. The beam combiner will have ≥ 49% transmission and reflection over the spectral band.

R4.4.2. The beam combiner will have ≤ 1% emissivity over the spectral band.

4.5 Cold stop and baffling

One option for the detector architecture is to use bare arrays (i.e. not feedhorn-coupled). If this is the case then it will be necessary to control the 2π steradian detector field-of-view with a cold stop, ideally placed near to the detector focal plane, possibly at the entrance of a 1K box surrounding the arrays and bandpass filters.

R4.5.1. For bare arrays a cold stop will define the detector field-of-view.

Hence, the optics needs to be designed to ensure a high-quality pupil image of the secondary mirror at a cold stop within the cryostat. It must also be ensured that the pupil imaging at the cold stop is maintained with minimal variation in illumination as the telescope aspect changes. The optical design will determine the cold stop diameter and optimum location.

R4.5.2. The optical design will determine the optimum diameter and location of the cold stop.

It may also be necessary to change the cold stop to optimise the detector coupling and control background power. Therefore, the design should allow for the stop to be manually changed if needed.

R4.5.3. The cold stop design must allow changeable apertures to be inserted.

The cryostat should contain optical baffles and other measures (e.g. low emissivity surfaces) to minimise stray light. This includes sources of stray light such as wiring ports, thermal links and heat generated by mechanisms.

4.6 Detector arrays

At the heart of the instrument are the detector arrays which are crucial to achieving the science goals of the mission. The detectors must operate with high efficiency over the spectral range of the instrument and meet the demanding sensitivity requirements. Kinetic inductance detectors are the most promising candidate for the choice of detector technology at the current time. They also have the potential to be mass-produced into the large-format arrays needed for low-background operation at these wavelengths. However, other technologies should not be precluded at this stage with the final choice being made after further assessment.

R4.6.1: The choice of detector technology will be down-selected from an assessment of the available options at the time.

To produce an instantaneous, fully (Nyquist) sampled image of the sky requires that the detectors be spaced by 0.5Fλ in the re-imaged focal plane (where F is the focal ratio of the final optics). This will be assumed to be the preferred pixel spacing pending further discussion on the relative merits of using bare arrays, feedhorns or Winston cones to couple to the telescope beam.

R4.6.2: The pixel spacing in the focal plane at all wavelengths will be 0.5Fλ.

Representative pixel counts, required to fully-sample the sky within the 1 arcmin diameter field-of-view (2 arcmin goal) are given in Table 3. The final pixel totals will depend critically on the optical design. For the example case shown in Table 3 it has been assumed that the telescope focal ratio is f/10 and at the arrays the optical beam is f/3. To ensure Nyquist sampling across the band the lower-edge cut-off wavelength has been used.

Band	Lower cut-off wavelength (μm)	Pixel geometry/count 1 × 1 arcmin f-o-v	Pixel geometry/count 2 × 2 arcmin f-o-v
1	25	48 × 48 (2304)	96 × 96 (9216)
2	50	24 × 24 (576)	48 × 48 (2304)
3	100	12 × 12 (144)	24 × 24 (576)
4	200	6 × 6 (36)	12 × 12 (144)

Table 3: Representative pixel counts for the instrument

R4.6.3. The pixel geometry/count for band 1 will be of order 48 × 48 (2304) with a goal of 96 × 96 (9216).

R4.6.4. The pixel geometry/count for band 2 will be of order 24 × 24 (576) with a goal of 48 × 48 (2304).

R4.6.5. The pixel geometry/count for band 3 will be of order 12 × 12 (144) with a goal of 24 × 24 (576).

R4.6.6. The pixel geometry/count for band 4 will be of order 6 × 6 (36) with a goal of 12 × 12 (144).

Ideally, the overall instrument sensitivity should be limited by the background photon noise (from the sky and telescope) and not by the intrinsic detector or electronics/readout noise. This means adopting a detector noise equivalent power (NEP) of half that of the minimum background noise.

The FISICA sensitivity model spreadsheet (see Appendix A1) estimates the background NEP from the sky, telescope and instrument using a representative model for the overall "Strawman" system. The requirement for the detector NEP is that it be half that level or less, so when added in quadrature will add no more than 12% to the total NEP. The detector NEP values are summarised in Table 4.

Band	Central wavelength (μm)	Background photon noise NEP (W/√Hz)	Required detector NEP (W/√Hz)
1	37.5	1.6×10^{-18}	7.7×10^{-19}
2	75	1.1×10^{-18}	5.6×10^{-19}
3	150	9.4×10^{-19}	4.7×10^{-19}
4	300	1.8×10^{-18}	9.1×10^{-19}

Table 4: Summary of the background photon noise and required detector NEP values for the 4 bands

R4.6.7. The requirement NEP for a B1 detector is < 7.7×10^{-19} W/√Hz.

R4.6.8. The requirement NEP for a B2 detector is < 5.6×10^{-19} W/√Hz.

R4.6.9. The requirement NEP for a B3 detector is < 4.7×10^{-19} W/√Hz.

R4.6.10. The requirement NEP for a B4 detector is < 9.1×10^{-19} W/√Hz.

To achieve such NEP levels will require detector operating temperatures of < 100mK (see section 4.1).

Assuming a stare mode of observation the pixel yield on each array should be maximised to avoid having perform a micro-step (e.g. using the secondary mirror) to maintain Nyquist sampling of an area of sky. A realistic requirement is to have array yields of at least 90%.

R4.6.11. The pixel yield for each detector array will be ≥ 90%.

If a stare mode is to be used then the distribution of bad pixels is also important. Therefore, in addition to the 90% yield criterion there is also a specification on the distribution of bad pixels on an array. There should be no two (or more) adjacent bad rows or columns, and there should be no "clusters" of more than 4 × 4 bad pixels.

R4.6.12. The detector array must not have adjacent bad columns or rows, as well as no dead clusters of greater than 4 × 4 pixels.

Power from a source must be coupled as efficiently as possible to the detector element. For example, when coupling to a point source this depends on the relative size of a pixel with respect to the Airy disk. For 0.5Fλ sized pixels the maximum coupling efficiency to a point source is 16% (assuming a near perfect illumination pattern of the primary, negligible obscuration by the secondary). The requirement is that the coupling be maximised with a goal of >15%.

R4.6.13. The optical coupling efficiency for an individual 0.5Fλ detector should be maximised with a goal of ≥15% for all spectral channels.

The detector element must also been designed to maximise the radiation absorption efficiency. It should be possible to design absorbing substrates that can achieve at least 80% absorption efficiency.

R4.6.14. The absorption efficiency for an individual detector should be ≥ 80% for all spectral channels.

Not only do the detectors need to have the required sensitivity to meet the science goals but they also need a fast enough response time to accommodate the observing strategies. In particular, the detector time constant must be shorter than the time required by the delay line to move one sampling step.

R4.6.15. The detector time constant needs to be of order 0.2 msec.

Future work:

1. *Depending on the operational mode(s) it may be necessary to set a requirement for the "1/f knee" frequency for the detector noise. Other things to potentially consider:*

4.7 Electronics/signal readout requirements

The data acquisition system must read out the detector signals at a rate of at least 3× detector time constants to avoid possible aliasing of noise into the signal band. This corresponds to a minimum data acquisition frequency of approximately 1.7 kHz per pixel. Assuming frequency domain multiplexing the read out rate should be of order 2 kHz.

R4.7.1. The data acquisition system must read out each detector signal at a rate of ~ 2 kHz.

For example, the maximum scan speed (set so that sampling yields a Nyquist frequency coincident with the high frequency edge of the band) depends solely on the data acquisition rate and the Nyquist (over)sampling factor.

The number of bits required to digitise the detector output also needs to take into account engineering requirements, such as the necessity to measure "system noise" with the cryostat window blanked off (i.e. there will be negligible photon noise from the sky or telescope). The data acquisition system must therefore have at least 16-bits over the entire dynamic range of input signals.

R4.7.2. The data acquisition system must have at least 16 bits to digitise the signal.

As discussed in section 4.7 the requirement is that the background photon noise from the sky and telescope dominate the overall noise levels. This means adopting a design detector NEP at least half that of the minimum background noise. Noise levels due to non-TES sources (i.e. associated with the readout scheme) should cause the detector NEP to increase by no more than 20%.

R4.7.3. Non-detector noise should cause no more than a 20% increase in the detector NEP.

FIRI is expected to observe astronomical sources over a wide range of flux levels. The achievable dynamic range in an image will most likely be limited by crosstalk. The effect of crosstalk manifests itself as an unwelcome or ghost signal falling onto a neighbouring pixel. Crosstalk can be split into two components: *electrical crosstalk* (arising, for example, from the way the signal readouts are wired) and *optical spillover* (caused by the diffraction pattern of the telescope). It is the level of optical spillover that sets the (unavoidable) crosstalk limit for the instrument. For nearest neighbour pixels the diffraction pattern of the telescope means that optical spillover dominates. It is the electrical crosstalk from non-nearest neighbours that is potentially a problem.

For observations for which the signal dynamic range is low in any case (e.g. deep extragalactic) this should not be a major concern. It is more critical for observations that contain one or more “bright” point-like sources in the field surrounded by fainter emission (which contains additional sources of interest). Hence, it will be quite likely that observations of galactic star forming regions (which contain at least some “bright” sources) will set the crosstalk requirement for the instrument. The specification for this depends on the map dynamic range (MDR) that is acceptable. A MDR of 200–300 might be reasonable and so this sets the crosstalk limit to be around 0.3%.

R4.7.4. The distant pixel crosstalk is required to be < 0.3%.

Future work:

1. *Consider requirements for the attenuation of stray magnetic fields (e.g. from motors).*
2. *Consider requirements for RF shielding (perhaps of particular concern for the FDM?).*

5. Operational requirements

5.1 Observing modes

The ultimate scientific potential of FIRI depends critically on the ability to observe survey fields for very long times with possible multiple field orientations, with possible total exposure times of several days. Long exposure times will be needed to provide scans covering the entire u-v plane. To obtain an image of a sky area is necessary to perform spectrographic interferometry for every single point in the u, v plane maintaining the spatial coherence (compared to some known sources). Every single (u, v) point acquired by the interferometer, gives the spatial Fourier component for a fixed distance between the sources contained in the sky area in observation and in a direction parallel to the telescope baseline and for the various spectroscopic components.

Future work:

1. *Derive any specific requirements related to either exposure times or the ability to cover the u-v plane for particular observations (really part of a future Operational Concept Definition).*

5.2 Calibration

Observations in the far-infrared from space rely on three basic kinds of calibration. Firstly, at the instrument level calibration sources are used, for example, to disentangle uncertainties in the optics and to regularly measure the linearity of the detector arrays ("flat-field"). The design of such calibrators is the subject of a separate work-package report (D3.5) by University College London.

R.5.2.1 The instrument will have the provision for one of more internal calibrators to assess the performance of the optics and detector arrays.

Another possibility is that a compact "telescope simulator" could be used to mimic the full-sized interferometer, providing diffraction-limited beams that would be used to evaluate the optical system (and potentially carry out simulated observations).

Secondly, it will be necessary to measure well-characterised astronomical objects to provide flux and line calibration for the detector outputs.

R.5.2.2 The instrument will be capable of rapidly carrying out routine, calibration observations of flux and line standards.

Finally, it is also necessary to be able to periodically make an accurate measurement of the telescope beam shape, using observations of a bright, point-like source, to ensure that the full optical system is performing as expected (e.g. diffraction-limited beam size and sidelobe levels are well characterised).

R.5.2.3 The instrument will carry out periodic measurements of a bright, point-like source to enable a full characterisation of the telescope beam shape.

5.3 Sky coverage

The field of regard should allow access to all desirable science targets. This needs to be determined but a nominal field of 40° band centered on the ecliptic (i.e. similar to proposed for SPECS and SPIRIT) is a reasonable first assumption.

R.5.3.1 The field of regard for the satellite should be a 40° band centered on the Ecliptic (TBC).

5.4 Time to acquire an object

To time to acquire a target needs to be minimised as far as is practical. The time to slew to a target over a large angle (anywhere on the sky, but noting that large slews should be few in numbers within a well-planned programme) should be 10 minutes or less.

R.5.4.1 The time to slew to a target over a large angle (anywhere on the sky) should be < 10 mins.

Similarly, the time to slew to relatively nearby targets, e.g. next science target or calibration source, say within 45 degrees cone angle, should be less than 2 mins.

R.5.4.2 The time to slew to a target over a small angle (within a cone angle of 45 degrees) should be < 2 mins.

After a slew is complete it will be necessary to allow some time for the entire satellite and instrument to settle. Again, this should be minimised with a requirement of 0.5 minutes.

R.5.4.3 After a slew a settling time of 0.5 minutes will be allowed, with a goal to reduce this time as far as practical.

5.5 Metrology

The overall instrument (including telescope) needs several highly accurate metrology sub-systems. Knowledge of the origin and propagation of phase and positional errors along the optical path is critical to fringe visibility and interferogram reconstruction. Ultimately, an overall error budget will need to be constructed that assesses all possible causes or error. Further work on this is also presented in report 1.3.

For example, further work is needed to assess the maximum allowable optical path difference (OPD) of the two beams. Sporadic, modest "jumps" of order $\lambda/4$ can most likely be contained, but bearing in mind the wideband of operation, the RMS of the OPD will need to be constrained to much tighter tolerance (of order tens of nm).

Other metrology information:

1. Requirements on fringe tracking/monitoring/OPD accuracy.
2. Telescope position and altitude monitoring.
3. Relative tip/tilt displacement monitoring of the beams.
4. Alignment sensing for the telescope optical axis with respect to the detector array focal planes.

Future work:

1. *Assess the requirements of these metrology systems.*

5.5 Mission lifetime

The mission lifetime should be dictated by the science to be undertaken, but in practical terms is likely to be limited by the amount of propellant to manoeuvre the spacecraft and the mechanical reliability of key system (e.g. telescope motors, closed-cycle coolers). To maximise the lifetime will require the careful planning of observations to minimise spacecraft movements. Hence, the lifetime should be maximised with a minimum requirement of 5 years.

R.5.5.1 The mission lifetime should be maximised with a minimum requirement of 5 years.

References

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Spinoglio L., 2014, "Definition/update of key science questions and relevant data products, FISICA deliverable report D1.1" (July 2014).

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Appendices

Appendix A1

FISICA sensitivity model

A spreadsheet-based model has been constructed to estimate the performance of the current "Strawman" instrument for astronomical observations. This approach has considerable heritage from pervious instruments (such as Herschel/SPIRE and SCUBA-2) and also borrows concepts and ideas from current missions and conceptual studies (e.g. BETTII, SPIRIT and SPECS).

The spreadsheet is designed into separate worksheets (or modules) that detail all areas of the system, such as the spacecraft, interferometer, telescope system, instrument cold optics and detectors, and electronics and readout. The current version assumes a near-perfect optical system with component parameters (e.g. sizes, temperatures, emissivities etc.) as specified in this document. There are a number of further assumptions that have been included in the current version of the model:

Sensitivity model assumptions:

1. Telescope: A 5-mirror telescope system (conservative, to, for example, allow for more beam folding if required or the need for a beam steering mirror).

2. Throughput: The optical throughout ("etendue") is assumed to be single-moded ($A\Omega = \lambda^2$). There is no account for imperfect coupling of the beam from the detector to the telescope primary mirror (e.g. edge-taper illumination).

3. Instrument: The baseline layout for the instrument is as given in Figure 5.

4. Stray light: Although a modest factor of 1% has been included for the internal optics it is possible that this is underestimated.

Further worksheets then estimate the background power arriving at the detector, taking into account the sky (e.g. Zodiacal light, infrared and microwave backgrounds), and emission from the telescope and instrument components. These levels are then used to derive the expected background photon noise level at the detector. To gain a level of confidence in the results an independent approach was also adopted (using MathCad) to model the sensitivity for subsets of the optical system. This method led to agreement with the spreadsheet approach to within 10%.

Figure A1.1 shows a plot of the relative contribution to the overall background photon noise NEP from the sky, telescope and instrument for all 4 bands. For band 1 it can be seen that the unavoidable zodiacal light provides the overwhelming limit to sensitivity. At band 2 the zodi contribution is also dominant but with an increasing contribution from the cosmic infrared background. For band 3 the CIB and zodi dominate, whilst at the longer band 4 it is the telescope and CIB that are the main contributions.

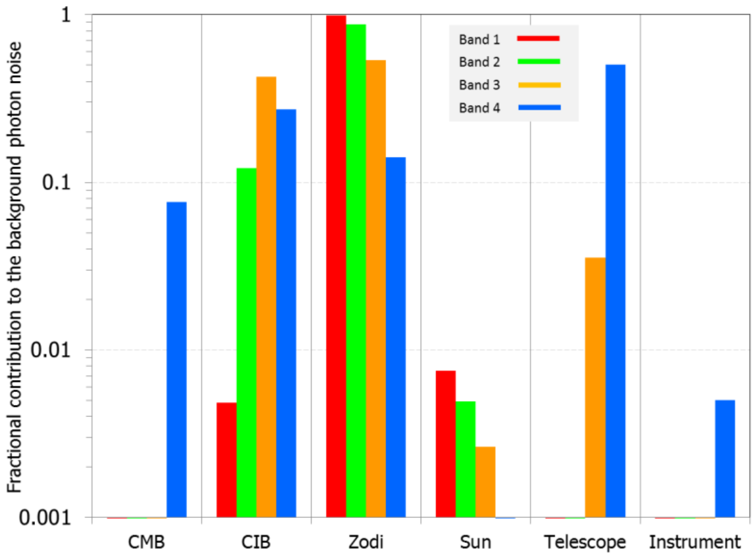


Figure A1.1: The relative contribution to the overall photon noise from the sky, telescope and instrument for the 4 wavebands.

Table A1 summarises the estimated background power and NEPs (per detector element) for each of the 4 spectral bands. The results of the point-source sensitivity (NEFD) and line fluxes calculations at each waveband are also given.

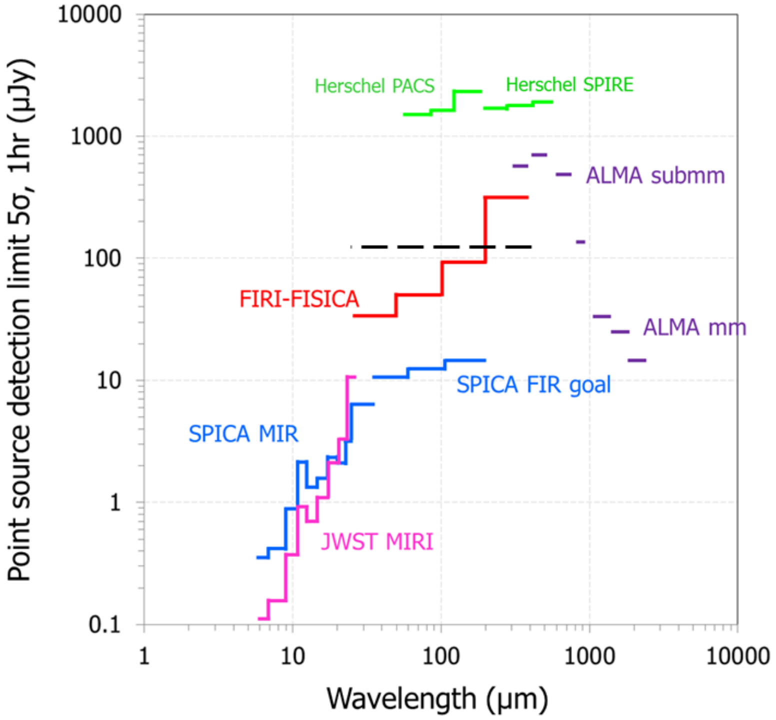
Parameter	**Units**	**Band 1**	**Band 2**	**Band 3**	**Band 4**
Background power	W	4.03×10^{-16}	3.16×10^{-16}	2.78×10^{-16}	1.33×10^{-15}
Background photon noise NEP	W/√Hz	1.55×10^{-18}	1.07×10^{-18}	9.37×10^{-19}	1.81×10^{-18}
Detector NEP(1)	W/√Hz	7.74×10^{-19}	5.57×10^{-19}	4.69×10^{-19}	9.06×10^{-19}
Overall system NEP(3)	W/√Hz	2.50×10^{-18}	1.25×10^{-18}	1.09×10^{-18}	2.11×10^{-18}
Noise equivalent flux density (NEFD)	μJy/√Hz	266	448	903	3823
Point-source detection limit(3) (5σ, 1hr)	μJy	9.9	16.7	28.5	110
Point-source spectro-photometry(3) (5σ, 1hr) at R=5	μJy	37.2	51.7	90.3	349

Point-source limiting line strength[(3)] (5σ, 1hr)	W/m^2	6.0×10^{-19}	4.1×10^{-19}	3.6×10^{-19}	7.0×10^{-19}

Table A1: Summary of the results from the FISICA sensitivity model per detector. The table also includes estimates of the point-source detection limit, detection limit for spectrophotometry at R=5 and a limiting line strength.

Table notes:
[1] The detector NEP is set to be half that of the background photon noise NEP (see R4.6.7-10)
[2] The overall NEP is the quadrature sum of the background NEP and detector NEP (allowing for an extra 20% to the detector NEP for non-detector noise contributions (e.g. from the readout – see R4.7.3).
[3] Includes the contribution from both telescopes, taking into account interferometric efficiency.

To put these results into perspective Figure A1.1 shows how the performance of FIRI, based on the current FISICA study design and sensitivity model, compares with other recent and future missions in terms of sensitivity.



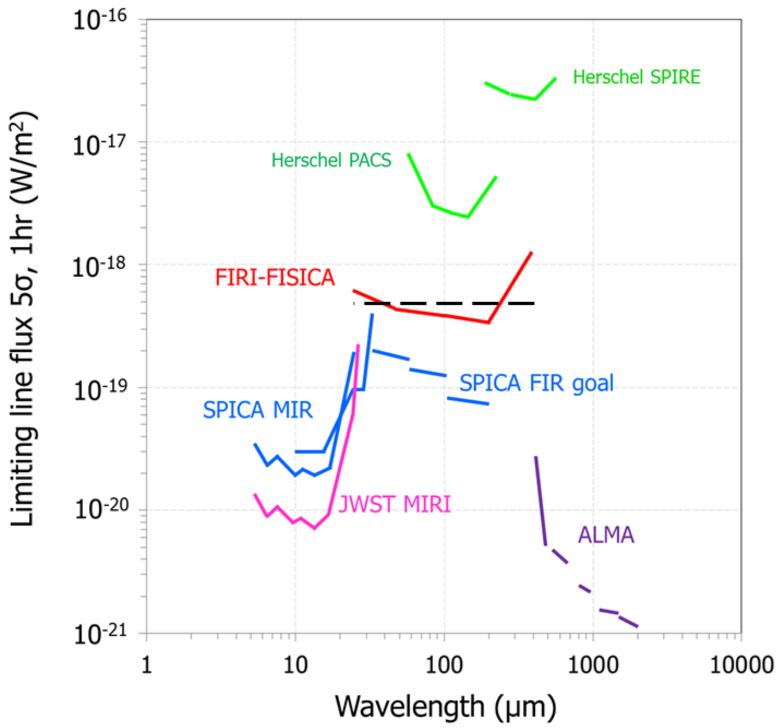


Figure A1: (Top) Point-source detection limit (5σ, 1hr) for spectrophotometry (R=5) for FIRI-FISICA and other missions; (Bottom) The limiting line flux achievable from a point-source (5σ, 1hr) for FIRI-FISICA and other missions. The dashed black lines give the approximate sensitivity requirements levels as outlined in this document (section 2.4) in each case.