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WP 3 – Interferometer Instrument Technology Development

# D3.8
# Final Report on Instrument technology readiness for a FIR interferometer

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| **Dissemination Level** (please refer to the list of deliverables in Annex 1 and complete also | | |
| PU | Public | |
| PP | Restricted to other programme participants (including the Commission | |
| RE | Restricted to a group specified by the consortium (including the | |
| CO | Confidential, only for members of the consortium (including the Commission Services) | |

# History table

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| 3.0 | 23/01/2016 | UCL(+Cardiff and EAP) | Comments on document implemented |

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# Disclaimer

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# 1 Introduction

## 1.1 General context

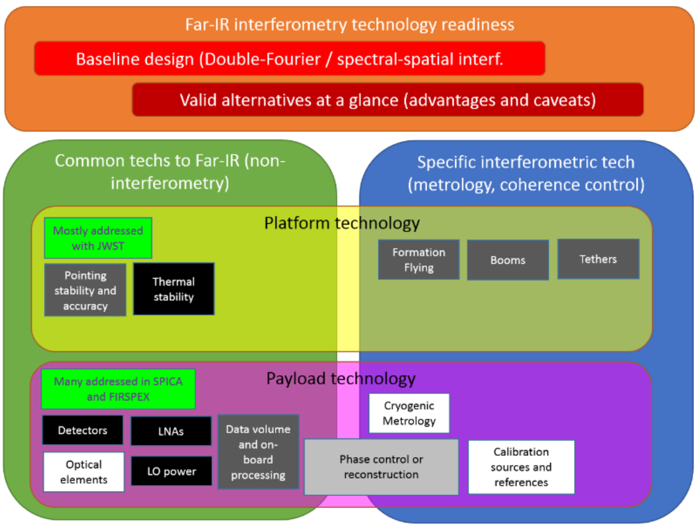
The third work-package of the FISICA programme addressed a few specific activities related to the study and development of instrumentation elements for a Space-based Far-infrared interferometer payload. Concepts have been studied for such a mission, but with no committed mission adoption and many technology hurdles in need of investigation or development, a number of technological aspects necessary to achieve an interferometric payload have been developed only in the context of other instruments or missions which happened to require them. In this program, we have pursued a few specific technologies some of which have specific use for an interferometer and others which have wider applicability.

## 1.2 Deliverable description

From the Description of Work, this final deliverable of Workpackage 3 activities has the purpose of summarizing the activities related to the instrumentation relevant to a Far Infrared Interferometer as well as detailing the current state-of-the-art of this technology as well as progress achieved in far-infrared quasi-optical interferometry tied to the optics and the associated metrology.

## 1.3 Document structure

The following block diagram is a simple representation of the logic flow of the technology readiness assessment. At the origin of this activity, a technique which seemed very promising




was chosen to be a potential baseline for our concept interferometer which would be investigated and developed further. This technique was also the basis of two earlier mission studies (the ESA FIRI CDF and the NASA Goddard SPIRIT concept), while the technology had not been developed in the relevant wavelength range.

In this document we summarize the achievements of the activities engaged in addressing instrument-related technology issues for the Double-Fourier modulation and report briefly on the state-of-the-art technologies it relies on. We also mention the summary conclusions other valid alternative approaches to far-infrared interferometry in space which were not directly part of this activity but which are included for completeness and for their potential. We then briefly summarize the results of the technology activities relating to the payload while reporting on the current state-of-the-art at the time of writing of this document of the technology elements for the chosen payload concept where relevant scientific literature was available and through presentations and contributions at the three High-Angular Resolution in the Far-Infrared FISICA workshops held during the three years of the project in Rome, Maynooth and London.

Where reporting in summary the work performed we direct the reader to the Task-specific deliverables (Table 1) where these are public, and to the scientific literature referenced therein.

**Table 1. Workpackage 3 deliverable list.**

| Code | Deliverable | Type | Diss. |
|---|---|---|---|
| D3.1 | A cryogenic (4K) delay line and associated test-bed. | Prototype | Public |
| D3.2 | Broadband far-infrared combiners | Prototype | Public |
| D3.3 | Multiple-beam combining spectral-spatial interferometer test-bed. | Demonstrator | Public |
| D3.4 | Note on Interferometer techniques trade-off | Report | Public |
| D3.6 | Cryogenic delay-line optical performance and positioning tolerance algorithms | Other | Public |
| D3.7 | Report on spectral spatial reconstruction with results of linearity tests | Report | Public |
| D3.8 | Final Report on Instrument technology readiness for FIR interferometer (This document) | Report | Public |

In the case of “prototype”, where a specific piece of hardware was developed and built, or “demonstrator”, where a combination of hardware elements were assembled together to perform measurements and prove that a given technique yields certain results, we have compiled in each case accompanying reports including detailed description of such objects (with images), their performance and as much information as to allow the reader to have a clear idea of the object or assembly in order to fully comprehend the TRL estimation.

# 2 Spectral-spatial interferometry with direct detection: status, advancement and next steps.

First discussed in Ohta et al. [1], the use of multiple Fourier Transforms as a means to improve the efficiency yield of information from astronomy measurements, Mariotti and Ridgway [2] performed the first laboratory test adopting a specific configuration which employs said technique and has since become a reference case for the employment of Double Fourier modulation (DFm) or spectral-spatial interference for astronomy applications.
This experiment showed that the technique is indeed feasible (and surprisingly resilient to atmospheric variability – on relatively small baselines).
Hereafter we describe the advancement during this activity of the Far-IR case, the issues and next steps to be addressed.

## 2.1 The Far-IR testbed.

The original testbed and its operation described in Grainger et al (2012) has been upgraded to work in the mid-Infrared. The upgrades to the testbed are listed and detailed in D3.3 [3] while the performance and data analysis that results from it are given in D3.7 [4]. In the following short paragraphs we list potential advances and improvements to this testbed as well as notes for other potential testbeds following in the paths of [2] and [5].

### 2.1.1 Scanning technique

One of the key advancements in this FIR testbed was the move from the FTS step and integrate (which requires a chopped source and a lock-in demodulation technique to be performed within the single OPD step of the spectral modulation $\Delta x$ (which relates to the Nyquist wavenumber $k_{Nyq} = 1/2\Delta x$ ) to "fast scanning" which allows a much faster acquisition of the signal, decreasing substantially the overall duration time of the data acquisition with comparable signal to noise data. Note that this technique is already widely adopted and was also employed in the HSO (Herschel Space Observatory) SPIRE-FTS spectrometer.

### 2.1.2 Frequency or wavelength range of the laboratory testbed

For reasons obvious to the reader, the spectral coverage of the testbed is best arranged where the atmospheric transmission is maximum (if the testbed is in normal laboratory conditions). This allows for minimal impact from water vapour absorption and overall air turbulence.
Nevertheless, water vapour lines can be useful for overall calibration as is the case in both the original FIR and the subsequent MIR upgrade.
For laboratory testbeds only, water vapour lines can provide (in the case of point-like sources) independent verification of the basic angle of incidence from the sky-simulating collimator. In order to do so, the conversion of incident angle at the telescopes needs to be converted into the collimated propagation angle through the FTS delay stage of the double-Fourier dynamic arm, as the angled propagation within this stage is what introduces the 1/cos factor that modifies the recovered wavenumber axis post-FT.

Future testbeds which embark in demonstrating the entire bandwidth coverage in a range where atmospheric absorption does not normally allow it, would have to employ an entirely sealed environment (such as nitrogen flushed chamber) to allow sufficient optical transmission to detect power at all in-band wavelengths.
Such arrangement is non-trivial and introduces additional issues (turbulence and vibration) which have been successfully controlled in the optical testbed at Goddard [5].

### 2.1.3 One or Two dimensional spatial interferometry

All the DFm testbeds so far have been operated in a one-dimension baseline configuration due to the inherent operational difficulties of moving telescopes on a plane rather than on a single line, and the available advantage (which is being currently explored) of rotating the on-axis source to simulate (in the source reference frame) the rotation of the two-telescope baseline.
Future advancements will need to demonstrate the full maturity in transforming 2d-scenes with the two-dimensional baselines, which is expected analytically and shown in the results of the FIInS simulator.

## 2.2 The beam-combiner technology readiness.

In the first part of work-package 3 activities a key activity which allowed two others to come to fruition was the critical development of the broad-band beam-combiner which could work at relevant wavelengths.
A proven (TRL 9) technology, Far-Infrared beam-combiners (splitters) have been employed in the Herschel Space Observatory's instrument the SPIRE Fourier Transform Spectrometer. This device was operated at cryogenic temperatures performing well within the (13-53) $cm^{-1}$ band.
Sufficing for the original double-Fourier testbed operating up to 300 microns, a "replica" of this achieved component would not allow operation at the shorter end of the wavelength range needed for a FIRI-like concept (25 microns or 400$cm^{-1}$).
Deliverable 3.2 [6] summarizes the achieved developed beam-combiner manufactured through higher control of metal-mesh patterns and substrate thickness to achieve a final wavelength coverage from 20 to 100 microns, exceeding the initial prescription.
Two components were manufactured with the first prototype showing how design based on modified transmission line models allowed a first prototype to be built and measured in order to then modify the model and produce a more effective balance between the reflective and transmissive components.

The same technology as that adopted in the SPIRE-FTS combiners has been adopted, with the final physical device produced having very similar physical characteristics and thus allowing us to consider this TRL unaltered as that of its longer wavelength "cousin".

For future developments, even shorter wavelength could be attempted. This requires very high precision photo-lithography and approaches the limit when attempting to impress and etch structures which are sub-micron for wavelengths approaching 10 microns. At this stage, model prediction and measurement agreement become less matching and alternative technologies are sought. This however is not of particular relevance to the FIR technology, but rather of interest for future near- and mid-IR.

## 2.3 Cryogenic Metrology considerations

Deliverable 3.1 [7] details the development and implementation of a high-precision metrology system (Renishaw differential laser interferometer) within a 4K interferometer delay stage and the relevant challenges in accounting for thermo-mechanical issues.
Measurements of mechanical and thermal properties of materials employed in the build of a Fourier Spectrometer have been included as critical to the design of such an FTS system.
Predicted performance of the 4 K interferometer and associated cryogenic sub-Kelvin detector system are also presented with the final design of the 4K FTS mechanism.

The metrology associated with the control of the phase delay arm of the interferometer is of primary importance. An aspect which has been identified as critical and is not represented by a specific item of technology requiring development is the AIV and alignment of the instrument which is then cooled to cryogenic temperatures.
As in most cryogenic instruments, parts are designed according to the prior knowledge of their cryogenic properties at the temperature of operation, assuming that thermal modelling of the entire structure will predict accurately the final instrument configuration. Actual alignment at operating temperature is then very hard to perform unless the actual wavelength-relevant system is run in parallel, and this can often be extremely time consuming and expensive if the instrument requires sub-Kelvin temperatures for its correct operation.

The latter issue arises (mostly in the Far-IR) due to the need to block most wavelengths short of the bands of interest to limit the radiative input to the cryogenic stages.

A similar problem has been faced by other instruments in the past, with each instrument team suggesting different in-operation tests to verify metrology precisely.

In this activity (and detailed in D3.1) a new component (beam-splitter/combiner) has been devised to help achieve such alignment in a less complicated way, by creating the splitter/combiner (as described in 2.2) but by leaving a gap (where the FIR need not propagate) allowing a laser through to test the metrology of the system before and during operation.
The development of this facility at the University of Lethbridge will allow future detailed cryogenic metrology tests where required to characterize the performance of cryogenic filters and beam-splitters in their relevant environment with additional phase characterization.

## 2.4 The Mid-IR testbed.

In parallel to the upgrade of the FIR testbed to shorter wavelengths, an additional attempt was made in creating a spectral-spatial interferometry testbed (but imaging) by employing a medium-grade commercial IR camera as the focal plane detector array. A similar optical configuration was adopted (as that of the FIR testbed) and a preliminary pair of beam-combiners (one used as splitter) were adopted together with a linear stage to align the system as an imaging-FTS in the mid-IR (8-12 microns). This was achieved and the system (which is not directly part of the FISICA-funded programme) is described briefly in D3.5 [8] as it was used to validate the thermal spatial structure used as a potential spatial calibration source.

The testbed development was interrupted by the lack of a large diameter and large focal length collimator necessary to act as Sky simulator for the double-Fourier imaging testbed. This has now been sourced (80cm diameter, 2.4m focal length) from existing unused hardware from a collaborator and will allow (with the removal of one of the splitters and the shift of one of the fold mirrors to perform spatial interference through the two input ports. The usefulness of this testbed will be primarily in the testing of off-axis effects (which are seen in the single pixel testbed but cannot be directly compared to another pixel) as well as the effect of self-emission from the optical components in the testbed (original aim of this particular add-on development).

In future developments, this testbed will hopefully allow us to constrain and estimate the effect of in-band self-emission (working in room-T laboratory conditions between 8 and 12 microns). So far this can only be performed through estimations and modelling (as in the case of the Sensitivity Spreadsheet).

## 2.5 Calibration Sources

In order to make use of the double-Fourier testbed, a sufficiently powered source has been used. A standard laboratory water-chilled Hg-arc lamp masked via a single or double slit aperture have been adopted.

For more sensitive satellite instruments and their on-board operations on the other hand, with ultra-sensitive cryogenic low-background detectors a smaller source with well-defined optical properties needed to be investigated.
There is a substantial volume of scientific literature on the topic of calibration sources and the optical and thermal properties of materials used. Initially, the focus of our calibration source activity was centred on the material properties with the goal of achieving as high an emissivity as possible (close to 1) in order to avoid having to account for additional unknown terms in the optical modelling due to non-zero reflectivity (with an emphasis on good temperature control).

Most high-emissivity paints, materials and coatings area based on materials which possess high thermal constants making these impractical for fast on-board calibrators, but more apt to be used as coating for references (such as was SCAL for the SPIRE-FTS).

For laboratory testbeds on the other hand, some degree of spatial nature was required and this has been explored successfully although not extensively with the use of mounted printed electronics. FTS imaging in the mid-IR of this source showed consistent behavior with the predicted properties and suggests that more complex scenes can be generated to be used for calibrator for similar testbeds, but also as references for thermal cameras at industrial level also.

Pulsed calibration sources with high speed of response have already been employed (PCAL on the HSO SPIRE instrument) effectively by using heated filaments and these can be employed in a similar manner with little to no increase in TRL needed given its maturity.

## 2.6 Testing a Double Fourier future instrument. Challenges and needs.

If we were to assume that all ingredients (detectors, optics, phase delay modules, …) can be sourced, a question arises on what aspects future testbeds, demonstrators or path-finder instruments willing to adopt this technique will need to tackle in order to raise the TRL level of this technique.

We have verified throughout this activity that spatial-spectral interferometry is easily recognisable through relatively simple data analysis when a clear known signal is involved. More complex scenes involving partially unknown sources will prove more challenging given the lack of phase closure (unlike the more common operation of ground-based radio-interferometers).

This however could in principle be addressed in this technique through the use of a 3-antenna system where each antenna's input power is split with the other two and 3 focal plane arrays are employed. All delayed with a single synchronous (i.e. mechanically connected) delay stage. (very low TRL concept)

Future development of a technique which could in principle act as a phase monitor alongside the double-Fourier modulation would increase confidence in its use for astronomical measurements.

In addition, the usage for "CLEAN"-equivalent data reduction techniques of single antenna (telescope) FTS data is invaluable as it helps provide a field-envelope of the power involved and would strongly constrain any model of the sources involved in the spatial interference. As such the built-in capability of allowing single dish data alongside the interferometric operation is something that future concept should consider strongly.

Finally, an interesting development which should be considered alongside the testbed concept built here and that we have not pursued due to the focus on shorter wavelength is that of a polarization defined multi-FT testbed [9]. This clever design concept, can allow in principle the recovery (in addition to spatial and spectral information) of the polarization degree of the observed source, providing the full and complete information package characterising the input radiation.

# 3 Far-infrared Interferometer potential architectures

## 3.1 The coherent approach

By far the most weathered technology to perform interferometry (mostly in the radio frequencies) is the heterodyne approach. With a history in excess of half a century, radio interferometry has paved the way for the community and demonstrated through many applications and discoveries the potential of the technique first suggested by Michelson.

Wavelengths at which heterodyne interferometry has been achieved have been steadily decreasing with ALMA (the Atacama Large Millimetre Array) now successfully observing below the millimeter.

We report here the four reasons listed in D3.4 for which a direct comparison between heterodyne and double Fourier cannot really be performed as they address distinct science cases. It is however this very reason that suggests that both approaches should be maintained and ways to combine their use (as was done for the HSO) explored in order to avoid an exercise in science field prioritization.

It is well known that:

- Heterodyne systems are inherently spectrally narrow banded ($R \sim> 10^6$) and are therefore not suitable for many of the science cases identified in [10]. They are however the primary (and in some science cases – as in p202-229 of [11] - the only way to perform a comprehensive study of astrophysical chemistry and its dynamics. In some cases, with sufficient numbers of dishes, these have also been able to make images of dust emission [12].
- The ultimate sensitivity of heterodyne systems is limited by quantum fluctuations due to their high spectral resolution and use of lasers as local oscillators. This is especially true at optical and infrared wavelengths (the “quantum limit” – [13]. This limits their use for measurements requiring high sensitivity but at the same time allows them to have to avoid sub-Kelvin cryogenic temperatures for operating the receiver units.
- Direct amplification of input THz signals is not yet routinely available for any application. Although there has been progress in developing parametric amplifiers working at high frequencies, these are in their infancy and cannot be considered for studying an interferometer at the present time as too little is known about their possible performance characteristics (e.g. [14]).
- Finally, there are a few technical problems with implementing a heterodyne interferometer in space which are at least as challenging as those associated with a direct detection system. These deserve and require a full study and the development of a testbed (similar to the one at the centre of this study) where interference performed on the basis of exquisite time-keeping rather than metrology is performed in a wireless setup, the dynamics of a free-floating set of antennas simulated to understand the range of configurations (and hence baselines) allowed as well as the requirements for on-board computing or data volume downlink – see for instance the ESPRIT study [15].

### 3.1.1 Coherent receiver readiness

The status of current heterodyne receivers is a combination of considerations linked to the elements which it relies on. There are for example a number of different mixer options (SIS, Schottky and Hot-electron bolometer or HEB). With the SIS working best below 1.2 THz and HEBs best used at high frequencies (multi-THz).

One of the critical issues for a receiver is for the Local Oscillator to generate sufficient power in the mixing with the signal. Classical LO solutions include diodes for which power decreases rapidly as frequency increases making most diode types impractical past 1 to 1.5 THz. At the other end of the spectrum, lasers provide sufficient power for nominal operation, but this solution also fails to generate sufficient power this time below 10 THz [16].

A recent candidate to tackle this "THz power gap" are Quantum Cascade Lasers (or QCLs) [17] which have been proven (and flown on SOFIA) up to 4.7THz to observe the 63 μm Oxygen line. Noise measured for this setup is of the order of ~7 times the quantum limit and continuously improving.
For an ESPRIT type concept, this device is relatively close to the requirements set[1], and further tests on their performance will result from the upcoming Stratospheric THz Observatory (STO2), a US-led high-altitude balloon experiment in collaboration with SRON and TU-Delft.

## 3.2 Fizeau interferometry

Fizeau interferometry has been studied widely at other wavelengths and is still considered as a potential candidate for a future FIR interferometer.

The possibility of multiple telescopes collecting portion of the same wavefront and combining these at the detector focal plane has a number of advantages (large multi-segment adaptive optics telescopes are in a way the limit for minimal mirror separation), although this arrangement competes with the preferred "nulling interferometry" suggested for both the Darwin space interferometer (ESA cornerstone mission proposed and then abandoned in the last decade) as well as the NASA Terrestrial Planet Finder (cancelled in June 2011) interferometer concepts.

We have however in this activity, recognized that Fizeau interferometry presents a useful and practical opportunity to demonstrate the capabilities of interferometry in space. As such we linked the activity of Task 3.2 with the cube-sat technology validation activity and took forward the idea of developing the first small satellite concept that would perform interferometry in space, as well as working together with LAM on the development of the algorithms for image reconstruction of the small hyper-telescope demonstrator.

[1] These requirements are in Wild et al [15], and for the sensitivity, these are relatively reduced compared to those set in [10] for the direct-detection case.

# 4 Far-infrared Interferometer payload technologies: a baseline and its alternatives

## 4.1 Detector readiness

The detector technology required to achieve some of the sensitivities identified in D1.1 [10] is possibly the most challenging of tasks. With the wide applications of detector technology and the use of these in other FIR missions, the former does not imply that detectors have a low TRL in this case. On the contrary, continuous technology development is ongoing both funded at European level (SPACEKIDS [18], and by the European Space Agency) and in the US.

To make a synthetic but comprehensive picture of detector technology and its likely status in one or two decades, is no easy task, but by combining existing information in literature with the recent detector review by J.R.Gao [19] at the 3rd FISICA London workshop one can have an idea of the directions that the technology is taking and its potentials (whilst keeping in mind that every few years there have been new ideas and developments which have either accelerated or enhanced detector capabilities beyond the scale of linear improvements.

Three main techniques will be briefly mentioned as potential candidates for FIR direct detectors to be used for future far-IR interferometers: transition-edge sensors, Kinetic inductance devices and Quantum Capacitance detectors. The following are looked at in the chronological order of their appearance in instruments in the field (ground-based).

### 4.1.1 Transition-edge Sensors (TES)

Making use of the very sharp variation in sensitivity to temperature, these superconductor-based detectors have been employed successfully in a number of ground-based and balloon instruments (Scuba-2 has 4 arrays of TESs for a total of ~10k pixels, Atacama Cosmology Telescope, the E and B Experiment and the SPIDER polarimeter are other instruments with such detectors). Their sensitivity is currently being pushed to a few x 10-19 $WHz^{-0.5}$ a year ago and recently below $2x10^{-19}$ with time constants in the range of a few hundreds of μsec. These latest developments have been very challenging but have also proven a continuous improvement of the sensitivity of these devices and promise to soon deliver the necessary detectors (already close to the requirements for 2 of 3 spectral bands of operation of the SAFARI instrument which given the technology is a necessary precursor to a direct-detection Far-IR interferometer.

### 4.1.2 Kinetic Inductance Devices (KID)

KIDs have been a late addition to the FIR detector family with instruments already fielded such as the NIKA camera (soon to be upgraded to NIKA-2) on the IRAM telescope and the MKID camera at the Caltech Sub-millimetre Observatory in Hawaii. This promising technology has the potential to create large format arrays with different

coupling methods (antenna, lens arrays, …) which are relatively easily manufactured and thanks to frequency multi-plexing architecture, easily read with few connections required, hence reducing heavily thermal parasitics on any cryogenic arrangement.
NEP levels for KIDs have the potential to be even smaller (possibly trading in time constant requirements), but while this technology is currently being pushed and invested in to achieve large format arrays with reduced complexity [18], NEP levels for these detectors have not yet matched that of TES devices.

### 4.1.3 Quantum Capacitance Detectors (QCD)

Finally, a more recent concept has been developed and has the potential to reach even lower NEP levels. A prototype has been measured [20] (~$1x10^{-18}$ $WHz^{-0.5}$) in sub-optimal cryogenic conditions with simulations showing the potential (if optimized) to reach (~$2x10^{-20}$ $WHz^{-0.5}$) but is yet to be demonstrated on a telescope.

## 4.2 Optical elements

Most optical elements related to the instrument throughput and the beam propagation are well developed (in some cases TRL 9). In more than one instance, the optical quality of the system relies heavily on the mechanical precision with which the structure (if connected) or the position of free-flyers is maintained. Transmissive optical elements in the far-IR would of course require tuning and an improvement in the control of the extra phase that they introduce (as is shown in [6] ) but are at a relatively advanced level overall. The same components benefit from the needs of other FIR mission concepts such as the SAFARI instrument on the SPICA satellite mission concept [21].

## 4.3 Metrology

Metrology is one of the key issues in interferometry, and one which has been at the forefront of the causes for not choosing interferometry as a medium of choice when metrology of sub-wavelength order is required in free-flying concepts such as Darwin or TPF.
Metrology is also the reason that places the Far-IR interferometer front and center in the first step to achieve interferometry in space, given the longer wavelength and hence the “relaxed” requirements compared to wavelengths ~100 times smaller.

As metrology pertains to the satellite platform technology, we won’t discuss details of the state-of-the-art of positional control for satellites which are either structurally connected or free flyers, and for that we direct to the summary contained in [22], as well as other more comprehensive reviews on the matter.

It helps to mention here that there have been recent investments in formation flying satellites (CANX4-5, PROBA 3) which are paving the way to improve the SotA. Additionally, it is expected that while the “coarse” metrology levels to achieve control of the satellite and telescope positioning are based on RF and optical metrology which feeds directly into the platform control, ultimately, the last stage of the metrology lies with the payload architecture and is thus specific to the instrument. The SPIRE-FTS data

showed how good quality data is sensitive to errors in metrology in the order of less than 1/100th of a wavelength. In our case, this would result in control of the order of sub-micron capabilities for the shorter range of wavelengths involved.
The latest PROBA3 concept promises to deliver sub-mm accuracy with the two metrology systems on board (which is a large improvement on the previous ~1cm sigma control obtained on PRISMA.

The demonstration of such a concept could allow to consider and design a first free-flying concept with an added optical delay compensator stage (as part of the payload) to compensate for the errors of such a platform. It is likely however that a first demonstrator will require more modest and connected baselines, for which the metrology is already available.

Payload metrology has been investigated in our activity and the inclusion of laser metrology in a cryogenic payload proven challenging but possible. The alteration of Far-IR optical components to allow this metrology to work fully through the optical delay stage and thus have direct monitoring of the phase delay introduced foes hand in hand with placing a requirement on metrology for the platform, so that the payload science instrument is not required to contribute (at least not other than during commissioning phase) to the routine metrology of the system.

# 5 An overview of the Technology Readiness Levels (TRLs)

In order to appreciate the current status of the technology development of the single elements of a Far IR Interferometer, we should refer to an existing and published set of values quoted in the same context of a far-IR space interferometer. Such a table of TRL values was published in 2009 in the SPIRIT White Paper for the 2010 Decadal Survey and presented in [23] also shown here below for reference.

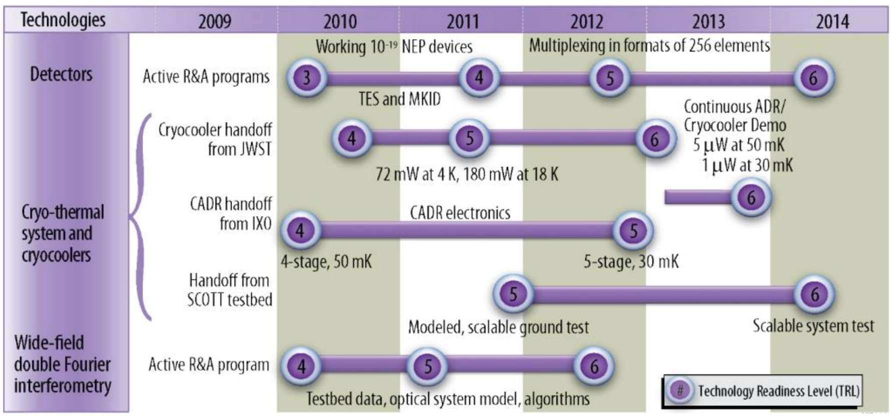


**Figure 1. TRL Progression identified in 2009 for some of the critical technology elements by NASA.**

While the 2012 paper highlights some of the progresses in the enabling technologies in the previous 3 years, there are other aspects which have not been considered and we shall attempt to integrate the information presented on this table to provide a more complete picture. It is important to point out that the TRL levels have been defined in

NASA, ESA and the European Commission. These definitions are mostly overlapping and generally consistent, but we refer to [24] for comparison. Hereafter we will refer to the ESA/NASA definitions as the EC ones are overarching and do not refer solely to Space technology but also manufacturing etc.
These definitions are briefly stated here:

| TRL | Description |
|---|---|
| 1 | Basic principles observed and reported |
| 2 | Technology concept and/or application formulated |
| 3 | Analytical and experimental critical function and/or characteristic proof-of-concept |
| 4 | Component and/or breadboard functional verification in laboratory environment |
| 5 | Component and/or breadboard critical function verification in relevant environment |
| 6 | Model demonstrating the critical functions of the element in a relevant environment |
| 7 | Model demonstrating the element performance for the operational environment |
| 8 | Actual system completed and accepted for flight ("flight qualified") |
| 9 | Actual system "flight proven" through successful mission operations |

An additional necessary consideration is the fact that TRL descriptions such as these are a “flat” projection of the suitability of a given element of technology with respect to a set of requirements. There is little room for the implications on the performance of a given element that satisfy pre-set criteria when combined with other hardware.
To clarify this statement, a detector can be functionally verified to have the required NEP, responsivity in the laboratory at the right temperature and even with a sufficiently high speed of response.

The table that follows is our concluding assessment on the TRL levels of the relevant subsystems. It has been compiled with all the information in our possession at the time of writing of this document and while we have attempted to source the most up-to-date information on subsystems (both relevant to the work of FISICA and those which complement it) it is possible that other work is ongoing which could effectively raise the TRL levels further.

**Table 2. Table of TRL values. If the TRL was increased by the FISICA program, this is identified in the Current TRL column in bold and with background colored cell.**

| Technology | Description and Relevance | Current TRL | Projected TRL (2020) |
|---|---|---|---|
| Deployable Booms | See Note 1 (5.1.1) | 6 / 3 | 6 / 4 |
| Free-flight Formation | See Note 2 (5.1.2) | 6 / 2 | 7 / 3 |
| Pointing stability | See Note 3 | 9 / 3 | 9 / 5 |
| CFRP Telescopes | See Note 4 | 9 | 9 |

| | | | |
|---|---|---|---|
| Deployable telescopes | See Note 5 | 9 | 9 |
| Cryogenic Telescopes | See Note 6 | 3 | 4→9 (2030) |
| Space cryo-coolers for science payload | See Note 7 | 4-6 | 5-7 |
| Detectors | See Note 8 | 4 | 6 |
| Optical components (filters) | Thermal filters, Band defining edge filters, Low-pass filters. Metal-mesh polymer technology | 9 | 9 |
| Optical components (Beam Combiners) | Thin film metal-mesh polymer grids. See Note 9 | 8 / 4 | 8 / 6 |
| Cryogenic Metrology | See Note 10 | **5** | 6 |
| Wide-field Imaging Interferometry | See Note 11 | **4** | 5 |

## 5.1 Technical TRL Notes and Comments

### *5.1.1 Note 1 – Deployable Booms.*

The TRL level of a deployable boom should be expressed as a function of the length of the boom itself. There are substantial ongoing activities in the field of deployables with some relevant to extended booms. An example of the current state of the art functioning extended boom with active parts of the payload is NuStar [25] with a boom length of 10m and a 10μm lateral displacement laser metrology system.
The fact that such a boom is TRL 9 does not imply that a system which includes 2 of 18m (SPIRIT) or 2 of 40m (FISICA) deployable would have a similar TRL given that the stresses and metrology conditions would be substantially more complex. In Europe there is ongoing research on deployable booms in a number of companies but a similar length of boom is currently at TRL 6.
Given the discrepancy in size, and existing modelling of the boom mechanical stresses and dynamical behavior, a TRL of 3 is more appropriate for the FISICA baseline.
With no specific project in mind, an advance to TRL 4 through R&D and dedicated programs is foreseeable. TRL 5 however would require substantial investments (also a function of the length of the boom in question).

### *5.1.2 Note 2 – Free formation flying.*

Largely from considerations which occurred in . There are two main categories of 3F satellites. Those for which knowledge of the position is required but no actual high precision control is required (ESPRIT) and those for which the high precision is required in actual relative positioning of the satellite. For the latter category of interest here, and similarly to a length dependence of the TRL for the booms, free-formation flying TRL can be argued to decrease almost proportionally to the tolerance with which the inter-

satellite distance must be kept. At present, PRISMA results obtained cm-accuracy on large scale distances. Whilst current work on PROBA3 (to be launched in 2018) is aiming at mm-accuracy for most positioning tolerances. In addition, mass and overall size of the satellite is likely to also impact statements of TRL. As such FFF TRL is arguably at the lowest given that for 3 satellites (2 telescope and 1 hub) of masses ~ 5 to 10x that of PROBA3, a control requirement along the satellite axis of the order of a fraction ($1/10^{th}$) of the shortest wavelengths brings this to 3 order of magnitudes smaller than what can be achieved with the launch of PROBA3.
One alternative is to consider dynamic compensation of such a distance through accurate and redundant metrology, with a fast variable delay stage which compensates most axial displacements in real time. This would allow requirements to relax to the order of mm while introducing an additional subsystem, the TRL of which is much less complex to advance. With these considerations a TRL of 6 (7 post PROBA3) could be assumed, otherwise the gap between 2 (current), 3 with lessons learned from PROBA3 to increment model accuracy and 4 is too wide to expect to be bridged during the rest of this decade.

### *5.1.3 Pointing stability.*

Often considered a more platform-specific issue, pointing errors have been included in the developments of subsequent versions of FIInS and show minimal impact mostly with very small amplitude modulations of the source observed.
Pinning a TRL number on this specific aspect is not a rigorous exercise given again the sizes involved. In principle, state-of-the art pointing accuracy is already at TRL 9 as we do not require to push this performance further than it already is.
With the added constraint that the pointing stability would be that of a structure the size of which has only been assembled into something like the ISS and is likely to present vibrations which are not found in other satellites flown so far, this TRL level could be argued as far down as 3, to be raised up to 5 after the experience on JWST which will be a significantly larger structure.

### *5.1.4 Carbon-Fibre Reinforced Polymer Telescopes.*

CFRP mirrors have already been used (Planck is such a mirror) so TRL can be considered as 9 to begin with. It is also true that the Planck probe had relaxed requirements on surface form given that the wavelengths involved are even at the highest frequency channel ~300μm compared to the ~30μm of a FIRI or SPIRIT-like mission. The baseline considered in FISICA had 2 m telescopes although other studies (SPIRIT) have considered 1m primaries (comparable to Planck). This difference could be sufficient to reduce the TRL level, but for now we will consider this at level 9.

### *5.1.5 Deployable Telescopes.*

With the close advent of JWST, and even though the structure and mirror materials are completely different, we can assume that whichever study is championed in the FIRI design park, these will be trumped by the JWST primary deployable system which can then allow us to consider again a TRL of 7 currently, and 9 from 2020.

#### *5.1.6 Large aperture Dry Cryogenic Telescopes.*

Cryogenic telescopes have been flown (wet) and have always been of modest sizes (mostly due to the weight of cryogens required – IRAS, ISO). Studies have been proposed for a new satellite to push the limits of cooled primary mirrors in size and temperature (and furthermore without wet cryogens).
The most prominent example of this case is the proposed ESA/JAXA SPICA space telescope which is the natural successor to ESA's Herschel Space Observatory, and that as this document is written, will be put forward in the next call for Medium class missions.
This mission would be scheduled (if successful in being selected) to launch towards the end of the 2020 decade. The TRL for this technology is hence placed at 3 currently with a steady progression up to 9 with the launch of this important mission by 2030.

A separate mention requires the possibility of having the last 3 combined.
A 2K-cooled deployable CFRP telescope would significantly improve the mass and volume budget of a mission, but a TRL for a similar concept is at the bottom level of 1.

#### *5.1.7 Space cryo-coolers for Science Payloads*

Mechanical cryo-coolers have been employed in a large number of missions to this date. TRL levels depend on the technology adopted, the power required to be lifted and the temperature of the stage from which the power is taken. In Figure 1 a good overview of the current technologies and their rate of progress. We do not deviate from the values suggested there.

#### *5.1.8 Detectors*

Detectors, are in most contexts the subsystem where most of the R&D effort and costs go. Better detectors imply reduced complexity and cost of the ancillary apparatus for detection. As such placing a single number on Detectors is futile. But one can take example of the list in Figure 1 and argue that some aspects of the detectors in question cannot be ignored. In some cases,(KIDs) the relevant requirements (NEP and speed of response) are conflicting/competing and so a "best-case" configuration can be used as a reference for an assessment of the current TRL levels.

#### 5.1.9 Optical Components (Beam Combiners)

The beam-combiners developed within the FISICA programme are extremely broadband and are in principle able to cover between them the entire range of the FISICA baseline concept (or SPIRIT). Having tested it, we can easily claim a 4. These have not yet been tested cryogenically but they make use of a technology (metal-mesh filters technology) which has been flown successfully on many missions. The difference in parameter space and so by extension can be considered pretty high : 8.

#### 5.1.10 Cryogenic metrology

Metrology is a key enabling technology to achieve interferometry and its smooth operation at cryogenic temperatures is a requirement that narrows the groups operating in this field to very few.

The activity undertaken by the University of Lethbridge (AIG) help carry forward the drive for metrology operating at cryogenic temperatures by focusing on the range of lengths and delays typical of our application (Fourier Transform Spectroscopy). TRL levels here can be considered in rapid increase given the desirable inclusion of such systems.

### 5.1.11 Wide-field Imaging Interferometry

This particular element has already been advanced by the NASA-Goddard group with the WIITT testbed [5]. TRL levels of 4 or 5 could be claimed for the control algorithms and acquisition of such a system with its metrology, but with the detectors and all the components working in the optical (for lower costs and ease of replacement even if it implies a much more challenging metrology requirements).
The work carried out in WP3 of FISICA complemented this by operating at relevant frequencies and highlighting a few critical effects and points (beam modelling, multi-mode optics,…) which can now be included in instrument modelling raising the TRL level (or justifying it as operating in the relevant wavelength range).

# 6 Conclusions on readiness and challenges.

In the three years of this activity, tests have been performed and technology elements required for direct-detection interferometry in the Far-Infrared have been performed and raised in readiness. The experience from the SPIRE-FTS performance build and data analysis has highlighted the challenges which this technique will have to deal with, the scientific power benefits of astronomical FTS spectroscopy, and the importance of detailed attention to instrument modelling and careful data processing.

While a full space-based Far-Infrared interferometer is not ready to be built in this or the first half of the next decade, the single TRL levels of the key hardware elements required lie within the range that would allow Earth-based demonstrator concepts to be implemented as well as the fielding of a path-finder satellite.

The US community has already made steps (with NASA-Goddard leading this effort) to test in the lab [24] and demonstrate on a high-altitude balloon, BETTII [25] the potential of spectral-spatial interferometry at different levels of complexity. A Probe-class mission, SHARP-IR [26], presently in concept development, could allow a first direct detection interferometer (Michelson-type) alongside spectral capabilities to be demonstrated in space. The more mature SPIRIT mission concept [27] would offer more powerful measurement capabilities at a higher price point. There is a clear opportunity for the European scientific and instrumentation community to support and participate in these ongoing efforts by providing elements of the technology required as well as contributing to the design and data-analysis. An example of such contribution is provision of broadband beam dividers of the kind developed during this activity and described in [6]. At the same time the planning and development of a potential ground-based demonstrator (within the narrow atmospheric band and the priors discussed in

D1.4 [28]) could raise awareness of the capabilities of this technique through a scaled concept.

The activities initiated on the payload side require constant support in order for the technology to progress. In the best cases (see diagram in section 1) the technologies can be broadly applied to other mission concepts (such as the detectors for the SPICA mission) which indeed facilitates their development and readiness while others which are more specific to spectral-spatial interferometry require dedicated support with a long term vision. Efforts have been made and are underway (albeit at low TRL) in applying this technique to other fields (remote sensing, near-field imaging and thermal detection) in order to diversify the routes to technology maturity.

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