

**Project title: Far Infra-red Space Interferometer Critical Assessment:
Scientific Definition and Technology Development for the Next
Generation THz Space Interferometer**

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PROJECT FINAL REPORT

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1. Final publishable summary report

Executive summary

The FISICA project has completed a three year journey through the development and refinement of the scientific cases which single out Interferometry as a necessary next step to bring our knowledge of astrophysics in the Far Infrared (FIR) with its wealth of information on the warm components of the Universe and a vast majority of common molecular tracers, in par with the rest of the electromagnetic spectrum. A discussion of such cases and details on the instrument capability required to perform such observations have been compiled and are available in report form together with the technical limitations and possible avenues to achieve this through a first pathfinder step.

A number of technologies which are relevant for a future far infrared interferometer have been explored. Technology advancements in carbon-fibre lightweight mirrors have been investigated, summarizing the benefits of their use as well as the adaptation of a space-qualified ultra-sensitive accelerometer as means to improve satellite attitude control. The latter has been adapted for validation on a cube-sat platform to demonstrate how cube-sats provide an excellent technology validation step. For the instrument a technique of choice (which can measure both the continuum and perform medium resolution spectroscopy), spectro-spatial interferometry, has been chosen for a case study demonstration at the relevant wavelengths. An optical test bench has been upgraded with detectors and optical elements working throughout the entire Far-Infrared range spanning the gap between the mid-infrared of the James Webb Space Telescope and the radio and mm-wavelengths of the Atacama Large Millimetre Array. The necessary element to recombine multiple beams (the beam-combiner) has been raised in Technology Readiness Level and a facility to perform detailed high-resolution cryogenic metrology built and tested during this period.

The baseline design of a space-based FIR Interferometer has been simulated with an end-to-end Instrument simulator code in Python which has been compiled as an open source and made available to the public through GitHub. This software allows the visualization of the performance of the virtual space interferometer given an input spectral-spatial dataset for the virtual observation. This tool will allow the user to introduce systematic effects and unplanned instrument defects to predict and assess how this would affect the retrieved data and therefore place requirements on the design of such an instrument.

The conclusions and final results of the project were presented at our final workshop held on December 15-17 in London in order to inform the community of the potential impact of a space-based interferometer and the critical elements in the path of its development. Assessing the range of technologies on which such a concept depends it is our conclusion that 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. Further detailed conclusions can be found on the topic-specific deliverables from the EC portal and the project website.

Summary description of project context and objectives

Context:

In the last 25 years, the Hubble Space Telescope has provided high resolution images which have guided the understanding and improved the inference in many fields of astrophysics. This highlighted how combining high-angular resolution with the unperturbed space-based environment (in terms of atmospheric contamination) yields results which are greater than the simple sum of the parts.

Visible light is, however, not the only light we can detect and with which we can study our Universe as there is a large amount of energy which is emitted at longer wavelengths from the near- to far-infrared (largely inaccessible from the ground) to the radio waves. At these wavelengths we can learn other physical properties of the building blocks of our Universe as well as, in some cases, observe objects which would otherwise be invisible in the optical due to the obscuring presence of dust. Combining all the observations together this multi-wavelength picture helps us to understand how astrophysical systems evolve, where the matter which constitutes everything that we know first originated, and to test our physical theories against observations in the biggest laboratory available – the Universe. In order to achieve this efficiently, all such pictures, across all wavelengths, should provide a comparable level of detail. Unfortunately, this places a constraint due to diffraction dictating that longer wavelengths produce coarser pictures and this can only be compensated by increasing the size of the mirror used as a telescope. It becomes apparent that to match visible wavelengths in Space (Hubble diameter is 2.4m) becomes quickly prohibitive in terms of launch availability and costs. The successor to Hubble, the James Webb Space Telescope, with its 6.5m deployable aperture, will help substantially working at near- to mid-infrared wavelengths covering the range up to 28 microns. From the radio end of the spectrum the technique of interferometry has already shown in the past century that combining coherently the output of two distant telescopes is the only way to increase angular resolution to a level comparable to that at shorter (optical and near-IR) wavelengths.

It is in the wavelength range between 30-300 microns where most cold objects (i.e. objects associated with, for example, forming stars) emit the majority of their light. In addition, the region allows the study of an abundance of spectral lines which are the ideal proxy for the detection of molecular species outside beyond our planet, which requires extending this ground-based solution to Space which is a non-trivial but necessary step to take.

Main Objectives: The Far-Infrared Space Interferometer Critical Assessment (FISICA) programme therefore aimed to:

-) Identify the most pressing Scientific Questions for each field of astrophysical study which such an instrument could help understand and characterize the data products required to improve our understanding of the current astrophysical paradigm;
-) Establish the optimum instrument design to address the scientific questions, including an assessment of the feasibility and maturity of key technologies. The main features will form a Strawman concept, which together with accompanying sensitivity models, will provide an initial estimate of capability, costs and risks.
-) Achieve several specific advances in technology activities related to the need of a space interferometer in order to reduce the risk factor involved in their usage

-) Design and make available an end-to-end simulator in an open source code to predict the typical performance and data products produced by such an instrument. This will be made freely available to the community at the end of the programme.

In the first period of the FISICA project, the early call for the ESA Large class missions' science White Paper and the planned definition of the key goals for high-angular resolution Far Infrared observations in the decades to come, allowed us to set the scene and produce some specific and yet demanding objectives. These have been subsequently transformed into well-defined instrument requirements. Our parallel investigation on alternative techniques available for Far-IR interferometry has produced a not so unexpected trade-off for the various techniques employed, the latter favouring one or the other science cases of interest depending on the respective instrument requirements.

The second Period of this activity has been characterized by the bulk of the technology-related activities. The investigation of the cube-sat platform as a useful potential technology validation test bench for Far-IR related technologies has shown how indeed this was achieved with the adaptation of a high-sensitivity accelerometer, capable of detecting very small accelerations aiding in the Attitude and Control of the platform orbit, to the cubesat format, power supply and communication protocols with the final tests of a fully functional unit in the lab subject to various forms of accelerations.

Carbon-fiber composites have also been explored in their thermomechanical properties with the purpose of assessing their usage for light-weight mirrors. These tests were performed in a dedicated cryogenic metrology facility at Lethbridge by one of the project partners developed in order to allow metrology intended for optical delay systems cooled at cryogenic temperatures to access the cooled regions.

The instrument-related activities progressed as expected after the production in the first 18 months of the new broad-band beam-combiners allowing in two separate instances the coverage with good phase uniformity across the desired spectral bands. The spectral-spatial interferometry testbed identified as a promising instrument to acquire medium spectral resolution of wide Field-of-View targets whilst performing interferometry was upgraded in its optics (as well as the beam combiner), the linear delay drives and detector system. After reproducing the already achieved data acquisition performed prior to this project with an improved Signal to Noise but in approximately one 10th of the time, the beam combiners were replaced and the band widened to confirm the expected excessive background loading of the detectors due to the large input radiation. To validate the testbed upgrade, the latter was pushed to (and exceeded) the limits of the wavelength requirements (initially set to 25 microns) from the instrument requirements document, by inserting a band-pass filter in one of the few atmospheric bands available in the FIR between ~21 and ~27 microns (where all metrology and phase issues are hardest to control)

New data was acquired with multiple configurations demonstrating spectral-spatial interferometry clearly and identifying a number of potential improvements to the system both optical and non which will allow the use of such a system concept on a ground-based demonstrator.

To achieve this a short study on the atmospheric properties of a few ground-based sites and the turbulence properties which would affect a path-finder instrument have been performed identifying two potential sites where a substantial baseline could be installed and produce meaningful scientific data again in the few atmospheric transmission bands accessible from these very remote sites (the Antarctic Dome A and the topmost sites of the Atacama desert in Chile).

Finally, the Instrument Simulator which was being developed during the first period of this activity has reached a further stage of maturity being ported in Python (free available software language) and in its final stages installed on GitHub (open access software repository) to allow the wider community to contribute to its development as well as being able to run the software.

A test of the software capabilities was done publicly at the 3rd and last dissemination workshop to the wider astrophysical and scientific community in London (Dec 2015) where the software was presented, its operation demonstrated and a few specific astrophysical cases (based on simulated “data-cubes” combining spatial and spectral information content) with the purpose of providing a useful tool to the astrophysical community as to what would be the capabilities of such a mission concept.

Core of the final report: main S&T results/foregrounds

Main S&T results/foregrounds for Work Package 1 - Scientific definition of Instrument Requirements

The far-infrared region, which encompasses the spectral range from 30 to 300 μm , contains a wealth of information about the optically-obscured 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* means that the study of some of the most critical astrophysical phenomena, which are often found on small size-scales, remains elusive. The Far Infrared Space Interferometer (“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 JamesWebb Space telescope (JWST) at shorter wavelengths (near IR) and the Atacama Large Millimeter/Submillimeter Array (ALMA) at longer (300 μm 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 probe the intrinsic physical scales of astrophysical phenomena, e.g. nuclei of galaxies, circumstellar disks, star-forming cores, young proto- and stellar clusters through photometric and spectroscopic imaging.

The science requirements for a FIRI mission were studied in detail in the first year of the FISICA project.

It has been realized that to make a break-through advance in the knowledge of a few astrophysical fields, for which the mid-to-far infrared spectral window is essential, the primary need is to obtain astronomical observations at a high spatial resolution, using both direct imaging and imaging spectroscopy, obtainable only with interferometers from the space. The major astrophysical research areas for which an angular resolution of the order of 0.1-0.2 arcsec is needed in a spectral range of 30-200 μm include the study of star and planet formation, the study of the Galactic Center, the study of the emission regions in local active galactic nuclei (AGN) and the study of the evolution of the starburst structures as a function of cosmic time. The reason why a 0.1-0.2 arcsec angular resolution is needed is because the physical sizes of the astrophysical sources, together with their distances, put both severe constraints on the angular dimensions that need to be explored. To give an example, the outer radius of a protoplanetary disk is about 100 AU and the closest star forming region in our galaxy is at a distance of 140 parsec, resulting in an external angular dimension of 0.7 arcsec, while the so called “planet forming region”, where planets are expected to develop, is about 10 times smaller, of the order of 0.07-0.1 arcsec. This latter is the region that we need to explore in infrared imaging and spectroscopy if we want to understand how planets form. Similarly, if we want to study

what is the occurrence of multiple systems in star formation, we need to resolve 100 AU at the distance of 1kpc, because the separation between the stellar companions is of the order of few hundreds AU. Another example is the study of the line emitting regions excited by accretion onto supermassive black holes, in the nuclei of galaxies. If we want to sample the active galaxies in the local universe, at a distance of 50 Mpc, we need to explore the Narrow Line Regions, which have a typical extension of 100-500 pc, corresponding to a total angular size of 0.4 - 2 arcsecond: to resolve these regions and explore their structure, we need to sample at 0.1 - 0.2 arcseconds. The main instrument requirement driving the scientific assessment is a maximum inter-telescopes distance of the interferometer of 100 meters, which allows an angular resolution of 0.1 arcsec at 40 μm and one of 0.25 arcsec at 100 μm , needed to fulfil the science requirements. The other instrument requirements needed to allow the science cases to be fully explored include a minimum simultaneous spectral range of 30-200 μm , a spectral resolution of the order of $R=1000-5000$, a baseline sensitivity of $1 \times 10^{-19} \text{ W/m}^2$ (1 hr, 1σ), and a “goal” sensitivity 10 times better. The choice of an interferometer with a maximum inter-telescope baseline of 100 m, equipped with two 2m class telescopes, will result in observing times of the order of 20-30 hours to reach the indicated science goals.

This scientific assessment 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 D1.1 in terms of the requirements for medium resolution spectroscopy.

The science requirements dictate a number of **key top-level instruments requirements**, which were described in detail in D1.2. 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 previous 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 below table 1 summarises the top-level requirements from the FISICA study and Figure 1 shows a possible conceptual model for a FIRI mission.

Spectral coverage	Continuous from 25 to 400 μm
Configuration	2 element interferometer with imaging FTS
Primary diameter	2m off-axis, afocal
Baseline	3–100m
Angular resolution	Minimum of 0.2” at 100 μm
Field of view	1 arcmin in diameter
Spectral resolution	5–5000

Table 1: Summary of top-level requirements

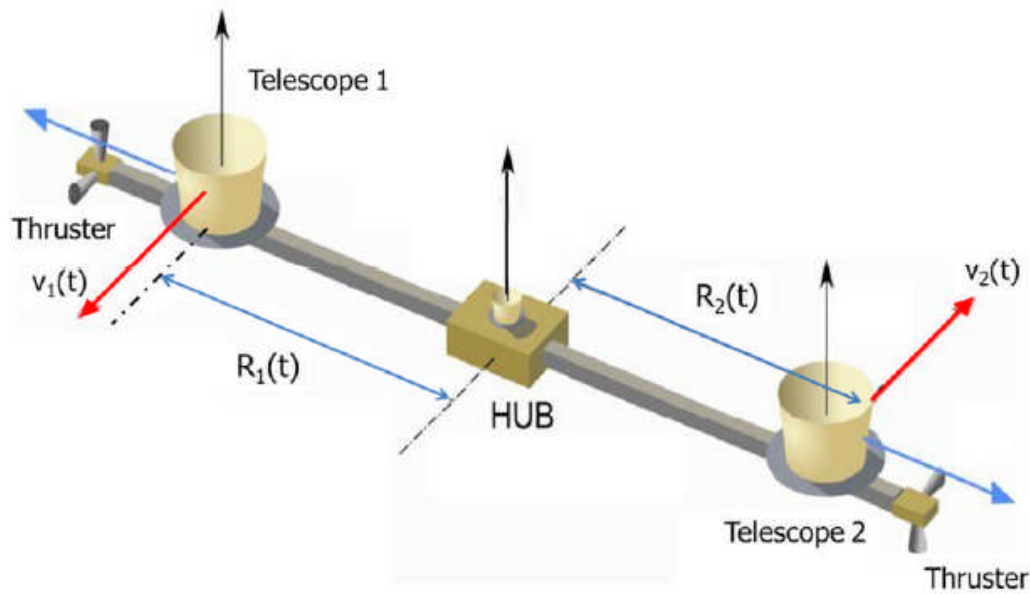


Figure 1: Possible concept for a FIRI mission outlined in the FISICA study.

The FISICA sensitivity model and predicted performance is outlined in D1.2 and was derived from previous 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 FISICA sensitivity model assumes:

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 throughput (“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 D1.2.
4. Stray light: Although a modest factor of 1% has been included for the internal optics it is possible that this is underestimated.

In addition to the Instrument Sensitivity model, which can be used to predict observing times to specific detection thresholds, the FISICA project has also developed an **Instrument Simulator FIInS**. In terms of setting up an observation the instrument simulator offers a realistic sequence of instrument configurations including selection of the wavelength band, baseline range, and u-v pattern to be traced out. Systematic errors are also included as part of the simulation such as background noise from the instrument, cosmic ray strikes, telescope pointing errors, baseline positional errors, FTS mirror positional error and glitches.

Another key element investigated in WP1 was the **identification of the requirements for the satellites** in terms of vibrational noise that can be tolerated, requirements on the AOCS in order to satisfy the science objective and identification of algorithms necessary to maintain satellite positions during scientific observations, which were described in detail in D1.3.

The **scientific capabilities of a ground based or balloon-borne instrument** were also analysed in D1.4, reviewing the conditions at a number of astronomical sites selected among the known best locations for mid-IR to far-IR astronomy. As pointed out by Matsuo, H. (2010), observations of important species become possible from the ground in selected atmospheric windows. However, this requires a site with exquisite atmospheric transmission properties, such as Dome A (Figures 4 to 6). OI (63 μm , 145 μm), OIII (52 μm , 88 μm), and NII (205 μm) are major coolants of photo-dissociation and ionized regions which are observable by a ground instrument, but do require exquisite atmospheric conditions to reach the line sensitivity between 10^{-16} – 10^{-17} W m⁻² in a reasonable integration time. CO is observable in several atmospheric windows, but in general atmospheric windows on the long-wavelength side of the band considered here are easier thanks to the increased coherence radius of the atmosphere and longer turbulent time constant. The number of sources observable, the integration time requires and the uv-coverage needed for each source requires a dedicated study, but it is clear that in order to maximise the scientific return from the investment made into a possible Antarctic interferometer, the instrument should be designed to observe simultaneously in multiple bands. A balloon interferometer is not limited by atmospheric windows and operates in an environment with much lower background, however these instruments are best used as single-baseline IR interferometers. Both the BETTI and FITE teams are close to their first flights from which we will learn in details the effectiveness and limitations of this class of instruments. Airborne instrumentation (e.g. SOFIA) were not considered in this analysis however. Although it would be in principle possible to fit two receiving antennae on an aircraft, the instrument will be limited to a relatively short baseline. As for a balloon interferometer, the uv-plane would be under-sampled but the quality of the atmosphere at 10km is not as good as at balloon altitude. Airborne instruments also suffer from very high costs (construction and operation), much higher than for ground or balloon instrumentation. Therefore it is unlikely that airborne interferometry can be made competitive with other non-space approaches.

The unique science “selling point” of a mission such as FIRI will be to provide sub-arcsecond angular resolution in the mid-far IR region for the first time. Table 3 lists a set of possible observations, based on the key scientific areas where FIRI could make significant advances that were presented and discussed at the FISICA workshops, the last of which was held in London in December 2015 and that could be undertaken during a mission lifetime of 3 years (goal of 5 years). Assuming overheads of 100% the operational time equates to about 2.1 years.

Topic	No of fields	F-o-v Diam (")	Spectral resolution	Wave range (μm)	Time per field (hrs)	5-σ flux limit (W/m ²)	5-σ source flux density limit (μJy)	5-σ line flux density limit (mJy)	Total time (days)
Mapping the water distribution on Titan (monitoring over 5 years?)	25	2	3000	25-50 50-100 100-200	14	1.8 × 10 ⁻¹³ 1.4 × 10 ⁻¹³ 2.0 × 10 ⁻¹³		6.6 10.3 30	15
Protoplanetary disk imaging	200	5	10	25-50 50-100 100-200	6.7		4.2 6.6 19		56
Protoplanetary disks: deep, high spectral resolution survey	200	5	3000	25-50 50-100 100-200	6.7	2.5 × 10 ⁻¹³ 2.0 × 10 ⁻¹³ 2.9 × 10 ⁻¹³		5.2 4.9 14	56
Debris disk imaging: searching for planet-induced structure	100	30	10	25-50 50-100	14		3 4.6		50
Debris disk mineralogy survey (smaller sample)	50	30	300	25-50 50-100 100-200	14	1.8 × 10 ⁻¹³ 1.4 × 10 ⁻¹³ 2.0 × 10 ⁻¹³		0.7 1.0 3.0	25
Isolated pre-stellar core	10	5	1000	50-100 100-200 200-400	100	6.6 × 10 ⁻²⁰ 5.0 × 10 ⁻²⁰ 7.5 × 10 ⁻²⁰		0.8 1.3 3.7	42
Embedded Class 0 protostar system: imaging	50	10	5	50-100 100-200 200-400	17		13.2 38.7 107		35
Embedded Class 0 protostar system: imaging	50	10	3000	50-100 100-200 200-400	17	4.0 × 10 ⁻¹³ 5.8 × 10 ⁻¹³ 8.0 × 10 ⁻¹³		30 87 240	35
Central star cluster at the GC	1	60	3000	50-100 100-200	106	5.0 × 10 ⁻²⁰ 7.3 × 10 ⁻²⁰		3.7 11	4.5
Spectroscopic survey of GMCs in nearby galaxies	100	20	3000	25-50 50-100 100-200 200-400	14	1.8 × 10 ⁻¹⁹ 1.4 × 10 ⁻¹⁹ 2.0 × 10 ⁻¹⁹ 2.8 × 10 ⁻¹⁹		6.7 10 30 82	58
AGN spectroscopy	50	20	3000	25-50 50-100 100-200	14	1.8 × 10 ⁻¹⁹ 1.4 × 10 ⁻¹⁹ 2.0 × 10 ⁻¹⁹		6.7 10 30	35
Deep AGN spectroscopy (3σ limits)	5	20	3000	25-50 50-100 100-200	140	3.3 × 10 ⁻²⁰ 2.6 × 10 ⁻²⁰ 3.8 × 10 ⁻²⁰		1.3 2.0 5.7	29
Resolving starburst structures at high redshift	10	30	3000	25-50 50-100 100-200	105	6.4 × 10 ⁻¹⁹ 5.0 × 10 ⁻²⁰ 7.3 × 10 ⁻²⁰		2.3 3.6 11	44

Table 3: A possible notional time allocation for a FISICA-based far-IR interferometer from the science case examples.

Main S&T results/foregrounds for Work Package 2 - Interferometer satellite Technology Development

Work Package 2 was focused on the overall technology development study of the key satellite and telescope aspects relevant to a Far-Infrared Interferometer and investigated the following particular aspects, retained as critical:

- Light-weight cryogenic materials and their employment through deployable systems.
- Investigation of the technical challenges in implementing closed loop accelerometer feedback for satellite position control to satisfy positional accuracy requirements.

- Identify and validate a key metrology technique for FIRI using a nano-satellite test bench.

The **low-mass cryogenic deployable telescope mirror study** has been performed by Glyndwr University under the coordination of Prof. David Walker. The work has been conducted under the collaboration between UCL, the Glyndwr Composites Centre, and the National Facility for Ultra Precision Surfaces. Establishment of this has been led by UCL under RCUK Basic Technology funding. The used Facility is hosted by Optic Technium which (itself now operated by Glyndwr) is located in the N.Wales Opto-Electronics Cluster.

The requirement for a lightweight, stiff and dimensionally stable material for future space astronomy and earth-observation missions is unquestionable. Large and precise mirrors with reduced mass are fundamental to support future scientific advances, within the envelopes imposed by project-cost and launch-vehicle capacity. Reducing mirror-mass for a defined overall mass also releases mass-budget for instrumentation. A technical report (D2.2) on tolerances and implications in the use of carbon composites for lightweight deployable telescope described the current state-of-the-art of CFC mirrors and the current knowledge of thermal implications of their usage at cryogenic temperatures for light-weight deployable mirrors and a prototype of a polished CFC mirror (D2.4) was manufactured and subjected to cryogenic testing to verify current polishing performances of these materials as light weight mirrors and the implications of thermal cycling.

A key finding of this study is that the low density of CFRP mirrors is unrivalled for space application. At present however, the technology readiness level is still low. As mentioned previously, form error and texture of the mirror after replication did not meet requirements, but present a basis for a future development programme, and are already within the scope of corrective polishing. Finite element analysis showed that dimensional stability of the specific composite samples manufactured and tested was significantly degraded during cooling to 4K. CFRP mirrors can be made extremely stable for short temperature excursions, but this technology has not yet been developed for space programmes. Ultimately, it is hysteresis on cool-down, rather than expansion coefficient that is the key area that requires addressing.

It was shown that the performance of the composite during cooling is another major concern, with large deformations in the mirror being predicted by FEA. It is expected, however, that an increase in the number of support points and optimised material selection could reduce this significantly. By engaging with material suppliers and manufacturers more suitable polymers could be used for this application. Budgetary constraints precluded a more extensive acquisition and characterisation of materials, especially any materials tailored for this application, or any advanced materials such as cyanate ester composites, given that these are manufactured only in large batch-sizes.

The technology to create a CFRP for a cryogenically cooled primary mirror is therefore at a very early stage. Significant development and, ultimately investment, is however required to improve the readiness level for a mission. The benefits of this development are clear, and a target areal density of less than 10kg/m² is not in question.

The **technical challenges in implementing closed loop accelerometer feedback for satellite position control to satisfy positional accuracy requirements** were investigated under the coordination of the team from AGI with experience of similar on board systems, using inputs from INAF-IAPS and substantial coordination with LAM, where development of a metrology test-bed using a nano-satellite has taken place.

The study is connected to the FIR interferometer in the conditions of satellites mechanically interconnected and took into account the particular manoeuvres that the interferometer must perform during the observation modes and its environmental conditions, particularly to the dynamical noise, both in the band, in which the satellite must be controlled, and out of this (to avoid accelerometer saturation and aliasing effects).

The possibility to use a high sensitivity accelerometer in a FIR Interferometer for space use, so to help satisfy the metrological requirements imposed to the mission has been studied, with particular attention to the precise positioning of the satellites and to control the dynamics of the interferometer during the observation modes.

Preliminary studies have been done in order to have a detailed knowledge of the kind of acceleration signals and noise present on a FIR space interferometer. In particular two classes of acceleration have been analysed:

- a) Acceleration and gravity gradient acceleration arising on the whole structure of the interferometer during its observation mode and connected to its dynamics.
- b) Acceleration noises present on the interferometer due to the appendices movements (RW, SA, HGA) and to the transient oscillation of the whole structure of the interferometer, when the thrusters are used.

The conclusion concerning these activities is related to the methodology to use for the choice of the frequency range where the spectroscopic signal can be translated by means of an appropriate sledge velocity, where its level is at the minimum. The same analysis can give the opportunity to set appropriate requirements for the level of acceleration noise that can be present on the FIR Interferometer.

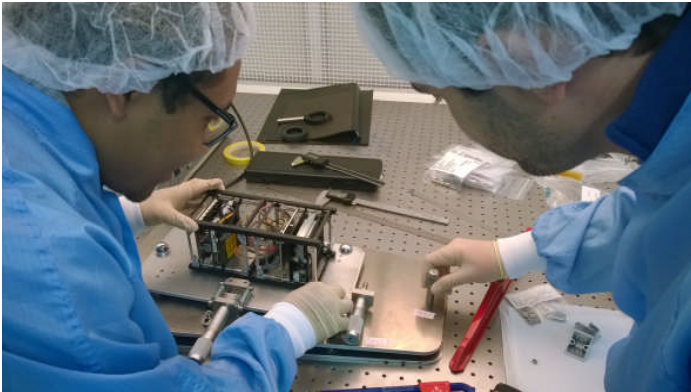
Using the information obtained by the activity described above, an activity concerning the implementation of a control loop has been performed; in the performed analysis the characteristics of a FIR Interferometer, with the two telescopes interconnected to a central Hub by means of two booms, respecting the baseline dimensions and weight have been considered. This theoretical activity has been accompanied with simulation of the system with an on-ground test bed. The conclusions are that it is possible to implement such kind of control loop using accelerometers, in a simple way also by means of a PID (Proportional, Integrative, and Derivative) control. The on ground test-bed activity has given a good idea on what happens during the control procedure.

The characteristics of an accelerometer as one of the main elements of a feed-back control loop for the FIR Interferometer have been defined and implemented; the performed tests demonstrate its perfect adherence to the requirements imposed by its use in a FIR Interferometer.

The study has finally been performed in close connection with the activity concerning the task 2.3 "Validation of key technologies with nano-satellite". In this contest and a prototype of accelerometer to be validated has been also defined and implemented. Space-born tests of key technologies, as offered by a nano-satellite mission, will be an important ingredient to improve the FIRI Technology Readiness Level (TRL) and the final activity in the context of this Work Package 2 has been dedicated to the **validation studies of the key technologies of FIRI with a nano-satellite**.

Preliminary parts of the study have focused on the definition of the concept of nano-satellite and resources (mass, volume, power, telemetry) typically available for the payload. The second part of the study has been

devoted to the selection of the FIRI key technology to be studied and implemented as first technological validation.



The performed activity demonstrates that a nanosatellite can be a suitable element to perform demonstration experiments capable to increase the technological readiness levels of elements useful for applications in FIR interferometer space missions. In particular, a single, 2-unit cube satellite was found appropriate to provide an optimal mission concept.

The on-ground experiments used a low-cost CubeSat platform for the technology validation in space. The experiments are based on a two-unit (2U, 10x10x20 cm³) CubeSat allowing the validation of a high-performance accelerometer and the implementation of the first ever space-borne imaging interferometer.

To validate the accelerometer, it is mounted at the extremity of a well-balanced 2U CubeSat for which the rotation can be controlled by a reaction wheel in such a way as to provide a controlled variation in centrifugal acceleration. The ground-based demonstration of this concept is achieved by hanging the CubeSat in a string, simulating weightlessness in a plane with negligible friction. The experiment allowed verification of the measurement concept and the dimensioning of the reaction wheel.

The interferometer is an aperture masking Fizeau interferometer simulating a future multi aperture space interferometer possibly based on formation flight technology. Preliminary dimensioning of this miniature interferometer allowing for measurement of solar radius and limb-darkening, for which an aperture size of 10 μ m and maximum baseline of 0.5mm is appropriate, shows that it can easily fit as a second payload within the 2U CubeSat. With pointing requirements of the order of 1 degree, navigation requirements are also within reach of off-the-shelf CubeSat technology. The ground-based demonstration experiment, based on the use of a CCD camera with a masked objective mounted on a sun-tracking telescope mount, has proven capable of producing high-quality interferometric images. It has also demonstrated the use of such a miniature interferometer for determination of solar parameters such as radius and limb-darkening function. Further study of this concept could lead to a proposal to its use as a high-quality solar monitoring instrument

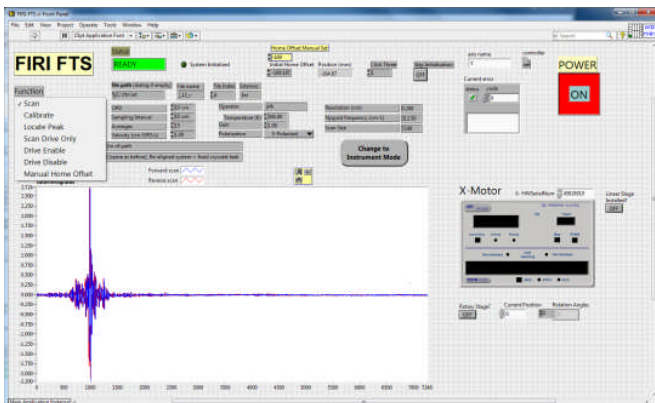
Main S&T results/foregrounds for Work Package 3 - Interferometer Instrument Technology Development

This workpackage comprises of 4 parts including the development and upgrade of the FIR spectral-spatial interferometry test-bed in Cardiff, the build of the far infrared beam combiners, the study of alternative concepts of interferometry, the development of a metrology test-bed applied to a 4K cryogenic stage, and the design of spectral spatial calibration sources.

While each of these activities was based in (and was the responsibility of) a given partner institute, all of them were closely followed by the Maynooth group which provided support with optical simulations of the test-bed optics.

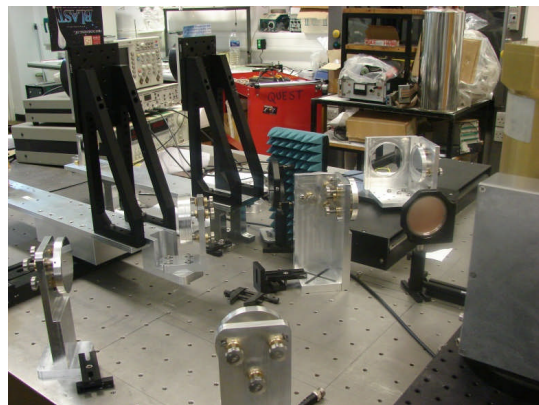
In the three years of this activity, tests have been performed and technology elements required for direct-detection interferometry in the Far-Infrared have been performed and raised in readiness. The experience from the SPIRE-FTS performance build and data analysis has highlighted the challenges which 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.

A fully functional interferometric test bed which operates from 25 to 350 μm and longer wavelength in selected band of the electromagnetic spectrum was developed. The test bed uses a telescope simulator to image custom made “astronomical scenes” (D3.4).



In D3.3 we have reported how the test-bed has been setup to test and validate the different beam combining geometries and associated optical components of the double Fourier technique in a spectral band covering the mid- to the far-IR. As discussed there, the test-bed was available at the start of this project but required optimisation in order to make it fully functional at the wavelengths required.

This has been achieved acquiring or manufacturing in house the relevant hardware components, and through a careful activity of alignment and verification. Using the quasi-optical modelling expertise and manufacturing capabilities, a beam-combiner efficient for the 35 - 350 μm bands has been designed. A second beam combiner covering the 20-120 μm band has also been manufactured and tested at 300K and 80K. A full report of the beam-combiner is given in Deliverable 3.2 submitted, and these optical elements have been used on the test-bed.



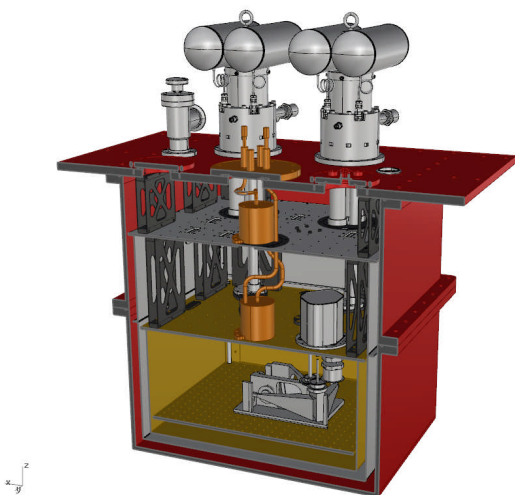
The test-bed has been extensively validated comparing the data acquired with advanced optical modelling of all major aspects of the instrument, from optical components (filters and beam combiners) and reflective surfaces (collimator, mirrors) to the focal plane (feed horn and detector). This is reported in D3.7. Modelling also include a tolerance and aberration analysis. While one of the aim of this WP was to assess the effects of detector non-linearity would impact the information recovery, it became apparent during this programme of work that this was not a significant issue, and that other instrumental effects or component non-ideal

behaviour impacted the data. D3.7 provides an account of the findings in the data analysis of the data runs and the effects which are potentially a cause of limitation for this technique.

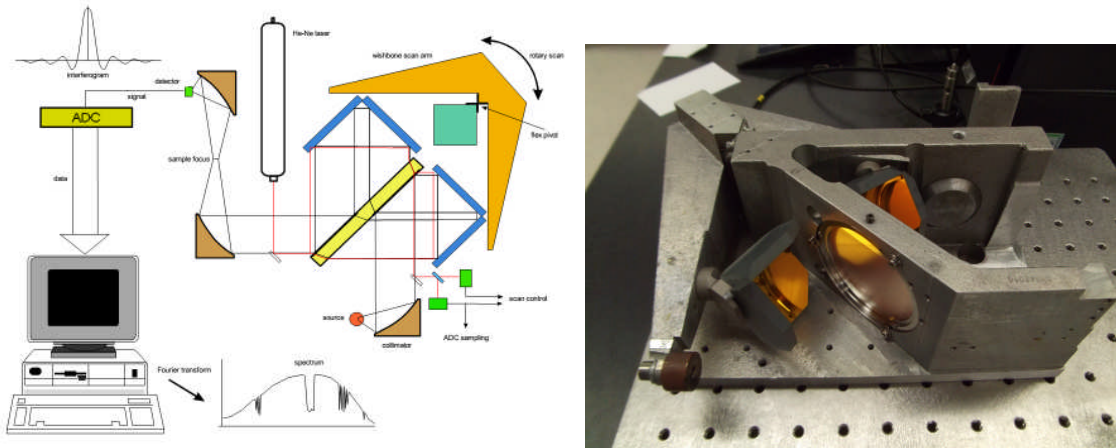
Data analysis algorithms have been developed to study the dataset obtained with this instrument and are detailed in D3.7. Implications of findings have been considered in order to outline subsequent steps which will be investigated following the end of this activity. The reports produced contain sufficient detail to serve as a reference for any groups engaging with this technique on problems to avoid and possibly methods to employ.

The development of a Fizeau aperture interferometer testbed as described in the DoW, has been set up at UCL and investigated with the potential of implementing IR optic fibres to propagate the Fizeau cells. Absence of white light fringes after considerable amount of effort prompted the activity to focus on the laboratory demonstrator set up at LAM and the data-analysis algorithms to optimize image reconstruction.

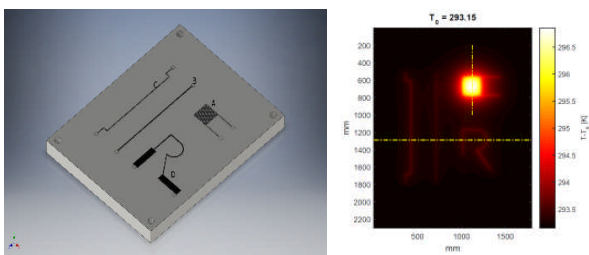
As pointed out in Period 1, early in Year 1 a choice was made to study in detail a technique that would be suitable (as was later identified by WP2 activities) as the best option for a cubesat validation instrument to be flown as the first space-based interferometer. The focal plane recombination with a limited set of aperture was identified and the results obtained in the lab testbed have helped design an initial concept for a small satellite mission to be proposed at the next 4S Symposium for small satellites.



The development of a large cryogenic test facility cryostat designed to cool an interferometer delay line to 4 K has been completed, partly with external funding which was secured in early 2014 and allowed construction of a much larger test facility cryostat which was better suited to housing a cryogenic FTS testbed. The plan was therefore changed to focus on the component and material tests that could be easily achieved using the smaller 4 K cryostats, and postpone the 4 K FTS tests until the large test facility cryostat is delivered early in 2015. A report detailing the development and testing of the cryogenic test facility and 4 K interferometer delay line was submitted at M36 (D3.1).



The combination of the large volume test facility cryostat, 4 K interferometer mechanism, laser metrology system and 0.3 K detector system provides a unique capability in Canada for testing materials, optical components and mechanisms at 4 K. We are actively pursuing collaborations to continue with low temperature CFRP testing for aerospace applications, as well as low temperature mechanism testing for future space astronomy instruments.



The calibration scene activity involved performing detailed measurements on properties of available known infrared black materials/paints. This task focused on two aspects, a passive and active source development. Some attempts to achieve passive sources did not suit the power requirements of the testbeds but ultimately a mask sourced was provided for the FIR testbed and an active circuit source was designed and modelled for the MIR testbed. The additional work performed on the thermal infra-red (8-13 micron) spectral-spatial imaging interferometry testbed progressed greatly thanks to the continued effort of Dr Juanola-Parramon to achieve an imaging-FTS in the same wavelength band. Measurements of a preliminary active source were performed to verify the FTS scanning optical delay. The final step to progress to spatial interferometry is still to be performed due to the unavailability of a large diameter collimator needed to produce the far-field collimated beam which presents itself with the same phase orientation after re-combination.

Main S&T results/foregrounds for Work Package 4 - An end-to-end simulator of FIRI: the Far Infrared Simulator (FInS)

WP 4 had the objective to produce an Instrument Simulator software based on basic existing predecessors (photometer and spectrometer simulators for SPIRE-Herschel).

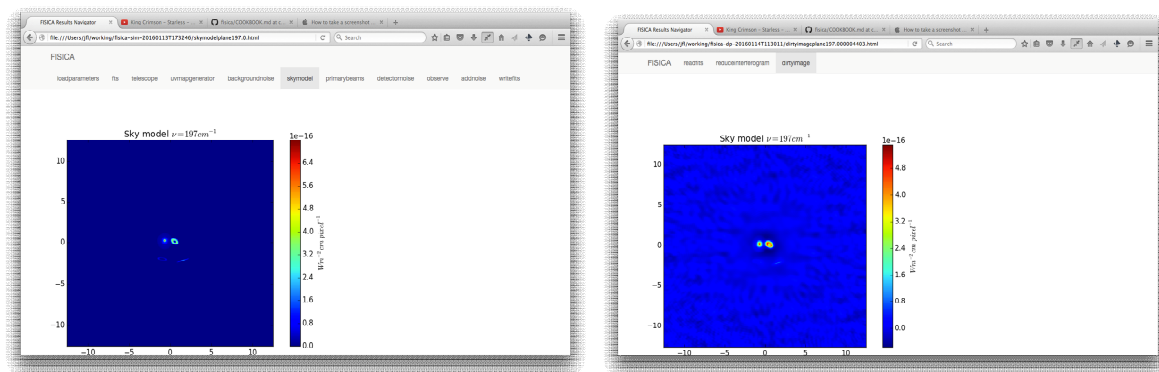
The FInS software builds on the work of Dr. Roser Juanola-Parramon at UCL who graduated with a thesis on “A Far Infrared Spectral Spatial Interferometer. Instrument Simulator and Test-bed Implementation”. This formed the starting point of an activity which is central to the program. The Instrument Simulator activity therefore commenced in the year preceding the FISICA activities and initially focused on the modelling of the Cardiff-RAL-UCL FIR test-bed in order to reproduce and validate the results obtained with the test-bed (published in 2012) but also in the attempt to explain a variety of second order effects which were seen to affect the test-bed setup in the sub-mm.

The FInS software was then successfully ported in Python by John Lightfoot (RoE-STFC) who has taken charge of the coding in Python of the simulator.

Substantial work was undertaken for the Instrument Simulator to work without glitches in all its parts and to also be placed in an open access repository (GitHub) with a sufficiently clear document tree to allow anyone with interest to contribute to this effort.

Furthermore, this work was complemented by the validation of this software in the final exercise (which required intense efforts from a number of partners) of running the software on a few datacubes (astrophysical simulations more or less simplistic) of a given spatial-spectral scene demonstrating in practice but most importantly in a clear and visual manner the capabilities of the baseline design of the FIRI satellite concept.

The software is currently of public access.



In support to this activity, the team in Maynooth carried out a series of investigations into a baseline optical design for light-collecting telescopes and interferometers arms for use in the PyFInS code and presented a trade-off analysis of these designs. For these initial simulations we chose a FIRI-type design, that is large condensing ($m=1/10$) optics at the end of the interferometer arms. An on-axis Cassegrain (F/1.5) design was used for these collecting telescopes. The optical stop of the system (2-m diameter) was placed at the primary mirror. A smaller set of condensing optics ($m=1/5$, off-axis Gregorian) was placed just in front of the

hub aperture. The narrow beams then propagate over a distance of 3 m (to account for the OPL required for the various hub optical components: beam splitters, dichroics, FTS, etc.), to a focussing mirror and on to a detector plane. An efficient Gaussian beam mode code was developed for beam propagation through the telescope at this design phase. Designs were verified for four wavelength bands. Finally, using full vector physical optics, we propagated beams from the detector plane to the aperture plane of the primary mirror and used this as input to the PyFIInS code. The simulator was adapted so that two different fields (also co- and cross-polar) could be used if required. We found that the primary mirror field changed significantly across the wavelength bands but not with baseline length. This informed the number of beam patterns that should be generated for a full simulation.

We used the PyFIInS code to model the off-axis pixels used in wide field-of-view instrument as well as proposing the use of a single (or a small number of) multimode feed horn(s) to achieve a wide field-of-view. An example set of sources was observed in a simulation of both types of instrument to illustrate how well sources are recovered. The use of a deliberately over-moded horn in this way is novel but over a wide band (e.g. the FIRI instrument) horns are likely become few-moded at high frequencies and so this analysis is relevant to far-infrared instrumentation in general.

Whereas early work and results reported in the literature allows us to investigate e.g. the effect of aberrations on the fringe visibility of a single observation, with PyFIInS we can see the effect on the recovered spectra and images of complex objects observed over an extended period. This ability to model a real system observing realistic objects is a significant improvement on previous optical modelling capabilities and can be applied to future interferometer designs for space and non-space applications. PyFIInS code was adapted to accommodate the optical modelling work throughout this reporting period and this code is now available to the community to use.

Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

In order to maximise the impact of the project, the FISICA team intended the **involvement of the wider far-infrared astronomy community** which is not involved in this study and technology development activity, but which will benefit from these results and from which useful input can be obtained during the course of the project that will be of value to the project itself.

To this end an External Advisory Panel was set up as initially planned in the first two months of the program in the persons identified in the DoW (Dr. Leisawitz and Prof. Matsuo) with the addition of a third, Prof. Shi from the Chinese Academy of Science (Purple Mountain Observatory) as an expert in THz receivers who in the past had shown interest in the installation of a large dish or interferometer pathfinder at the South Pole in the Chinese Dome.

We have regularly provided our quarterly reports on the ongoing activities to the EAP members and invited them (paid expenses) to attend the remaining two workshops (with the yearly Project Reviews occurring after each workshop).

Their attendance was fruitful in all instances with feedback provided by them regarding both our work and the expectation of their communities with respect to the ongoing efforts.

A full report on their findings after our first 18 months was submitted. As mentioned at the end of Period 1, FISICA was brought in the spotlight of a “twin” workshop organized in the US at NASA-Goddard by Dr Leisawitz where similar themes were raised to a mainly US community to assess the intention and feasibility of proposing such a mission concept in the near future. In addition FISICA was also mentioned (albeit briefly) in the IAU Commission 54 on Interferometry in a meeting held in Montreal Canada following the SPIE conference on Astronomical Telescopes and Instrumentation where a number of FISICA-related papers were presented.

Subsequent to the submission of the report, the EAP was approached (after the 2nd Maynooth workshop) to understand potential opportunities of collaboration from members of the FISICA Consortium. This has so far only proven successful with the Goddard group where information has been initially exchanged on algorithms and data analysis due to the close resemblance of the double-Fourier modulation testbeds. Ultimately, the value of this activity and the expertise reflects in Dr. Juanola-Parramon who was at the forefront of the FInS simulator and worked for FISICA during Year 3 moved to the US with a NASA Postdoctoral Fellowship further cementing the collaborative nature of the groups involved.

The collaboration with the BETTII team (Principal Investigator Dr. Stephen Reinhart) was pursued on three different fronts.

The first involves the design, production, testing and delivery of quasi optical components for BETTII. In particular the beam divider developed for the Fisica test bed under WP-3 and there validated by demonstrating reconstruction of spatial-spectral information, has been adapted and optimised for the BETTII bands and delivered to the project.

A second element is in the test-bed itself. BETTII (as discussed in D1.4) will detect visibilities and in order to extract scientific information from an under-sampled uv-space advanced data analysis techniques are needed. As the test bed can be operated in a configuration that very closely reflects this limitation, it is envisioned that it will be used in aiding the data analysis effort of the BETTII data from the 2016 flight. The simulator developed in WP4 will also play a major role here. It is envisioned that the combination of the test bed and simulator (and with the capabilities of using complex scenes in both, e.g. D3.5) will enable an effective analysis of the BETTII dataset enabling to optimise the pursuit of science investigations as well as an analysis of instrumental systematics.

A third aspect of contribution which took place was the provision of a component of the pointing system (star tracker software) for the BETTII payload. This activity was not directly related with the FISICA programme and did not make use of FISICA resources, however was generally enabled by FISICA as part of the overall collaboration with Goddard.

As a result, we expect to be fully involved in the flight preparation, and in the data analysis, as well as contributing to the publications that will result from this activity.

Members of the FISICA team have also been very active in disseminating the results of the project in both a focussed way by organizing a small yearly workshop on the back of a project review, and a wider way by participating at general technical meetings and astronomy forums to present the work performed and that intended.

On the 17th-18th February 2014, the First FISICA Workshop “Science Goals of a Sub-arcsecond Far-infrared Space Observatory” has been held in Rome, at the National Research Council, Piazzale Aldo Moro 7. The meeting has been fully organized by the Institute of Space Astrophysics and Planetology (IAPS) of INAF. The meeting has been successful, with a participation of 85 scientists from all over the world, with 23 invited talks. All the material, including the abstracts and the full presentations is online at the web-site: <http://fisica.iaps.inaf.it/wp/>

The 2nd FISICA Critical Assessment Workshop: “Instrument Simulation and Preliminary Technology Development Activities” was organized by MU with the help of the FISICA consortium, and was held on 28th-29th January 2015 (M25) on the MU campus, Co. Kildare, Ireland. There were 38 registered participants from 10 different countries. Nineteen talks were given over the two-day workshop and these were split into 7 sessions: FISICA and Sensitivity Models, Testbeds, Optical Modelling & Mirrors, Far-IR Projects & Concepts, Components, Posters and Software Simulators. There was time scheduled at the end of each session to allow discussion of all the talks just given.

Finally, the third FISICA workshop “Bringing Far Infrared Interferometry Into Vision” was organised on 15th – 17th December 2015 at the Royal Astronomical Society in Burlington House, Piccadilly, London. There were 51 participants registered from 12 different countries representing 26 organisations. 38 talks were given over the three days, organised around the following topics: Science and observing simulation, Mission concepts and Technology status.

Knowledge-based results accumulated during the first period of the project were presented at a variety of conferences in the field of optics and astronomical instrumentation attended by the members of the FISICA team, as attested by the 36 proceedings of attended conferences reported in Periods 1 and 2.

A number of FISICA-related papers were notably presented at the SPIE Astronomical Telescopes & Instrumentation bi-annual Conference and at the biennial OSA FTS conference held in Lake Arrowhead, California in March 2015. Results from the project will also be presented at the SPIE Astronomical Telescopes + Instrumentation 2016 conference, to be held in Edinburgh, UK.

Project website

The FISICA project web page can be found at the following link: www.fp7-fisica.eu/

2. Use and dissemination of foreground

All knowledge-based results accumulated during the different phases of this project are shared in a collaborative academic environment and have been presented both at the intended workshop milestones for discussion and subsequently at a variety of conferences in the field of optics and astronomical instrumentation to which participants to this project are regular attendants.

Major conferences where dissemination of our results is planned are listed in Section A below.

The main instrument for dissemination has been a planned yearly workshop. The central theme of which evolved from scientific drivers to instrument simulation and technology to reflect the Milestones of the project.

The aim of such workshops was not only to convene all members in one location to review the key milestones of the project, but also to expose the wider community interested in the idea of a Far Infrared Space Interferometer to our findings and stimulate discussion on the necessary steps to achieve it.

The first workshop at the end of the first year of activities was themed on the scientific capabilities and requirements, as well as the science that ultimately the scientific community intends to perform in this astronomical window. The workshop took place in Rome and was largely attended by close to 100 people who helped provide additional scientific context to the current science drivers of Far Infrared Astrophysics.

The second event at the end of year 2 was held at the National University of Ireland in Maynooth. The theme, in line with the major activity in which the Maynooth group was charged with was modelling and simulation of instrument specifics with updates on the ongoing work and a discussion of necessary steps to complete the FISICA activities.

The final workshop in the PI Institute in London was held at the Royal Astronomical Society and attracted a number of key external members of the Far Infrared Science community involved in most of the ongoing projects as well as future candidate FIR missions on both sides of the Atlantic. The theme of this last workshop included discussion on technical developments and possible roadmaps for the future with an eye at the upcoming calls for opportunity from both ESA and NASA as well as the potential for future pioneering measurements from Balloon platforms as well as in key atmospheric bands for niche science cases from the ground.

Section A (public)

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers ¹ (if available)	Is/Will open access ² provided to this publication?
1	Herschel-ATLAS: a binary HyLIRG pin pointing a cluster of starbursting proto-ellipticals	R. J. Ivison et al.	Astrophysical Journal	Vol. 772/Issue 2	Institute of Physics Publishing	United Kingdom	01/08/2013	137 pages		Yes
2	Astronomical imaging Fourier spectroscopy at far-infrared wavelengths	David A. Naylor, Brad G. Gom, Mathijs H.D. van der Wiel, Gibion Makiwa	Canadian Journal of Physics	Vol. 91/Issue 11	National Research Council of Canada	Canada	01/11/2013	870-878		Yes
3	Demonstrating Spectro-Spatial Interferometry in the Thermal Infrared: Recent progress	Roser Juanola-Parramon and Giogio Savini	Fourier Transform Spectroscopy and Hyperspectral Imaging and Sounding of the	Paper JM3A.3.	OSA Technical Digest (online) (Optical Society of	California, USA	March 2015	3 pages		Yes (fees)

¹ A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

² Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

			Environment		America)					
4	Herschel SPIRE FTS data processing of partially extended sources	Edward Polehampton	Fourier Transform Spectroscopy and Hyperspectral Imaging and Sounding of the Environment	Paper JM3A.4.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
5	A Cryogenic FTS Translation Mechanism: Test-Bed design and Anticipated Challenges	Ian Veenendaal	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper JM3A.6.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
6	The <i>Herschell</i> SPIRE Spectrometer Phase Correction Data Processing Tasks	Trevor Fulton	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper JM3A.7	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
7	FIInS – A Python Simulator for a Far-infrared Double Fourier Interferometer in Space	John F. Lightfoot,	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper JM3A.9	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
8	Performance Requirements for a Spectral-Spatial Calibration Source for DFM Interferometers	Nicola Baccinet	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding	Paper JM3A.10.	OSA Technical Digest (online)	California, USA	March 2015	4 pages		Yes (fees)

			of the Environment		(Optical Society of America)					
9	Astronomical Far-infrared Imaging Fourier Transform Spectroscopy: the Challenge and the Potential	David Naylor	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper FT4A.2.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
10	Progress in the Critical Assessment for a Far-Infrared Space Interferometer with Double Fourier Modulation	Giorgio Savini	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper FT4A.3.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	4 pages		Yes (fees)
11	Astrophysical Capabilities of a Double Fourier Modulation Interferometer in Space	Roser Juanola-Parramon	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper FT4A.4.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	4 pages		Yes (fees)
12	Diffraction Issues for Far-Infrared Space Interferometry	J. Anthony Murphy	Fourier Transform Spectroscopy and Hyperspectral Imaging and Souding of the Environment	Paper FT4A.5.	OSA Technical Digest (online) (Optical Society of America)	California, USA	March 2015	3 pages		Yes (fees)
13	Development of a Far-Infrared	Locke D.	Fourier Transform	Paper FT4A.6.	OSA	California,	March 2015	3 pages		Yes (fees)

	Double Fourier Spatial/Spectral Interferometry Laboratory Testbed Instrument	Spencer	Spectroscopy and Hyperspectral Imaging and Souding of the Environment		Technical Digest (online) (Optical Society of America)	USA				
14	Optical and Quasi-Optical Analysis of System Components for a Far-Infrared Space Interferometer	C. Bracken	Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VIII	Vol. 9362, 93620N-1, 2015	Proc. Of SPIE		March 2015	12 pages		Yes (fees)
15	Design of a nano-satellite demonstrator of an infrared imaging space interferometer: the HyperCube	Kjetil Dohlen	Optical and Infrared Interferometry IV	Vol. 9146 914603-1, 2014	Proc. Of SPIE		July 2014	10 pages		Yes (fees)
16	The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII): Interferometry at the Edge of the Atmosphere	S. Rinehart	Optical and Infrared Interferometry IV	Vol. 9146 914602-1, 2014	Proc. Of SPIE		July 2014	10 pages		Yes (fees)
17	Design of a cryogenic test facility for evaluating the performance of interferometric components of the SPICA/SAFARI instrument	Ian T. Veenendaal	Space Telescope and Instrumentation 2014: Optical, Infrared and Millimeter Wave	Vol. 9143 914345-1, 2014	Proc. Of SPIE		August 2014	7 pages		Yes (fees)
18	The Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII): an Experiment for High Angular Resolution in the Far-Infrared	S.A. Rinehart	Publications of the Astronomical Society of the Pacific	Vol. 126, No. 941, July 2014	Astronomical Society of the Pacific	USA	10 July 2014	pp. 660-673		Yes (fees)
19	A Thermal Spectral-Spatial	Giorgio Savini	Optical and Infrared	Vol. 9146 91462N-1	Proc. Of SPIE	Montréal, Quebec,	June 2014	6 pages		Yes (fees)

	Interferometric Testbed		Interferometry IV	2014		Canada				
20	Heating of polymer-based filters in sub-mm space optics	Nicola Baccinet and Savini Giorgio	Space Telescopes and Instrumentation 2014: Optical, Infrared and Millimeter Wave	Vol. 9143 91434K-1, 2014	Proc. Of SPIE	Montréal, Quebec, Canada	June 2014	12 pages		Yes (fees)
21	An end-to end Far-infrared Interferometer Instrument Simulator (FIInS)	Roser Juanola-Parramon	Space Telescopes and Instrumentation 2014: Optical, Infrared and Millimeter Wave	Vol. 9143 914341-1, 2014	Proc. Of SPIE		August 2014	14 pages		Yes (fees)
22	Space-based Far-Infrared interferometry technology development through a laboratory-cased spatial/spectral interferometry testbed instrument	Locke D. Spencer	Space Telescopes and Instrumentation 2014: Optical, Infrared and Millimeter Wave	Vol. 9143 91434G-1	Proc. Of SPIE	Montréal, Quebec, Canada	June 2014	14 pages		Yes (fees)
23	FISICA (Far Infrared Space Interferometer Critical Assessment) Metrological problems and system requirements for interferometric observations from space	Valerio lafolla	Metrology for Aerospace (MetroAeroSpace)	2014	IEEE	Rome, Italy	May 2014	pp. 161-166		Yes (fees)

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities ³	Main leader	Title	Date/Period	Place	Type of audience ⁴	Size of audience	Countries addressed
1	Posters	NATIONAL UNIVERSITY OF IRELAND MAYNOOTH	“Optical design and analysis of a space-borne far-IR interferometer”	22/03/2013	Galway, Ireland	Scientific community (higher education, Research)	90	Ireland
2	Oral presentation to a scientific event	CARDIFF UNIVERSITY	“Double Fourier Modulation for ATeraHertz Space Interferometer”	06/09/2013	Meinz, Germany	Scientific community (higher education, Research)		The IRMMW-THz 2013 Conference
3	Oral presentation to a scientific event	UNIVERSITY COLLEGE LONDON	“Detailed Characterization of the Optical Constants of Polymers as a Function of Temperature”	10/09/2013	European Space Research and Technology Centre (ESTEC) in Noordwijk,	Scientific community (higher education, Research)		35 th ESA Antenna Workshop on Antenna and Free Space RF Measurements

³ A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

⁴ A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

					The Netherlands			
4	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	“Hypercube, un Hypertélescope spatial”, Atelier “Quels débouchés pour les nanosates?”	25/11/2013	Meudon, France	Scientific community (higher education, Research)	100	France
5	Oral presentation to a scientific event	SCIENCE AND TECHNOLOGY FACILITIES COUNCIL	“Debris disks: now and the future”	17/02/2014	Rome, Italy	Scientific community (higher education, Research)	85	International workshop – First FISICA Workshop “Science Goals of a Sub-arcsecond Far-infrared Space
6	Oral presentation to a scientific event	ASSIST IN GRAVITATION AND INSTRUMENTATION (AGI) SRL	“FISICA: engineering problems and system requirements for interferometric observations from the space”	18/02/2014	National Council of Research, Rome, Italy	Scientific community (higher education, Research)	85	International workshop – First FISICA Workshop “Science Goals of a Sub-arcsecond Far-infrared Space
7	Oral presentation to a scientific event	ASSIST IN GRAVITATION AND INSTRUMENTATION (AGI) SRL	“FISICA (Far Infrared Space Interferometer Critical Assessment) Metrological problems and system requirements for	29/05/2014	Benevento, Italy	Scientific community (higher education, Research)		IEEE International Workshop on Metrology for Aerospace

			interferometric observations from space”					
8	Oral presentation to a scientific event	University of Lethbridge	“Design of a cryogenic test facility for evaluating the performance of interferometric components of the SPICA/SAFARI instrument”	22/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research)		2014 SPIE Astronomical Telescopes and Instrumentation conference
9	Oral presentation to a scientific event	UNIVERSITY COLLEGE LONDON	“Heating of polymer-based filters in sub-mm space optics”	22/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research)		2014 SPIE Astronomical Telescopes and Instrumentation conference
10	Oral presentation to a scientific event	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	“Design of a nano-satellite demonstrator of an infrared imaging space interferometer: the HyperCube”	22/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research) - Industry		2014 SPIE Astronomical Telescopes and Instrumentation conference
11	Oral presentation to a scientific event	University of Lethbridge	“SCUBA-2 Fourier transform spectrometer (FTS-2) commissioning results”	25/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research) - Industry		2014 SPIE Astronomical Telescopes and Instrumentation conference

12	Oral presentation to a scientific event	University of Lethbridge	"The spectral response of the SCUBA-2850 and 450 micron photometric bands"	25/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research)		2014 SPIE Astronomical Telescopes and Instrumentation conference
13	Oral presentation to a scientific event	UNIVERSITY COLLEGE LONDON	"A Thermal Spectral-Spatial Interferometric Test-bed"	26/06/2014	SPIE, Montreal, Quebec, Canada	Scientific community (higher education, Research)		2014 SPIE Astronomical Telescopes and Instrumentation conference

Section B (Confidential⁵ or public: confidential information to be marked clearly)

Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights ⁶ :	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
n.a.					

No patents, trademarks or registered designs were produced during this activity.

⁵ Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

⁶ A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground ⁷	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application ⁸	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
n.a.								

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

¹⁹ A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

⁸ A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

3. Report on societal implications

A General Information (completed automatically when *Grant Agreement number* is entered.

Grant Agreement Number:

312818

Title of Project:

Far Infra-red Space Interferometer Critical Assessment: Scientific Definition and Technology Development for the Next Generation THz Space Interferometer

Name and Title of Coordinator:

Dr. Giorgio Savini

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)?

- If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports?

No

Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 'Work Progress and Achievements'

2. Please indicate whether your project involved any of the following issues (tick box) :

RESEARCH ON HUMANS

- | | |
|---|---|
| • Did the project involve children? | N |
| • Did the project involve patients? | N |
| • Did the project involve persons not able to give consent? | N |
| • Did the project involve adult healthy volunteers? | N |
| • Did the project involve Human genetic material? | N |
| • Did the project involve Human biological samples? | N |
| • Did the project involve Human data collection? | N |

RESEARCH ON HUMAN EMBRYO/FOETUS

- | | |
|--|---|
| • Did the project involve Human Embryos? | N |
|--|---|

• Did the project involve Human Foetal Tissue / Cells?	N
• Did the project involve Human Embryonic Stem Cells (hESCs)?	N
• Did the project on human Embryonic Stem Cells involve cells in culture?	N
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	N
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	N
• Did the project involve tracking the location or observation of people?	N
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	N
• Were those animals transgenic small laboratory animals?	N
• Were those animals transgenic farm animals?	N
• Were those animals cloned farm animals?	N
• Were those animals non-human primates?	N
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	N
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	N
DUAL USE	
• Research having direct military use	N
• Research having the potential for terrorist abuse	N

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator		1
Work package leaders	1	6
Experienced researchers (i.e. PhD holders)	4	24
PhD Students	0	4

Other	2	2
4. How many additional researchers (in companies and universities) were recruited specifically for this project?		2
Of which, indicate the number of men:		2

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? Yes
 No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective	Very effective
<input type="checkbox"/> Design and implement an equal opportunity policy	○ ○ ○ ○	√
<input type="checkbox"/> Set targets to achieve a gender balance in the workforce	○ ○	√ ○ ○
<input type="checkbox"/> Organise conferences and workshops on gender	√ ○ ○ ○ ○	
<input type="checkbox"/> Actions to improve work-life balance	○ ○	√ ○ ○
<input type="radio"/> Other: 		

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

Yes- please specify

No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

Yes- please specify

A number of Under-graduate students performed projects related to the activities involved.

No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

Yes- please specify

No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?		
<input checked="" type="checkbox"/>	Main discipline ⁹ : 1.2	
<input checked="" type="checkbox"/>	Associated discipline ⁹ : 2.3	<input type="checkbox"/> Associated discipline ⁹ :
G Engaging with Civil society and policy makers		
11a	Did your project engage with societal actors beyond the research community? (if 'No', go to Question 14)	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
11b	If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?	
	<input type="checkbox"/> No <input type="checkbox"/> Yes- in determining what research should be performed <input type="checkbox"/> Yes - in implementing the research <input type="checkbox"/> Yes, in communicating /disseminating / using the results of the project	
11c	In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	<input type="checkbox"/> Yes <input type="checkbox"/> No
12.	Did you engage with government / public bodies or policy makers (including international organisations)	
	<input type="checkbox"/> No <input type="checkbox"/> Yes- in framing the research agenda <input type="checkbox"/> Yes - in implementing the research agenda <input checked="" type="checkbox"/> Yes, in communicating /disseminating / using the results of the project	
13a	Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	
	<input checked="" type="checkbox"/> Yes – as a primary objective (please indicate areas below- multiple answers possible) <input type="checkbox"/> Yes – as a secondary objective (please indicate areas below - multiple answer possible) <input type="checkbox"/> No	

⁹ Insert number from list below (Frascati Manual).

13b If Yes, in which fields?

Agriculture	Energy	Human rights	
Audiovisual and Media	Enlargement	Information Society	
Budget	Enterprise	Institutional affairs	
Competition	Environment	Internal Market	
Consumers	External Relations	Justice, freedom and security	
Culture	External Trade	Public Health	
Customs	Fisheries and Maritime Affairs	Regional Policy	
Development Economic and Monetary Affairs	Food Safety	Research and Innovation	√
Education, Training, Youth	Foreign and Security Policy	Space	√
Employment and Social Affairs	Fraud	Taxation	
	Humanitarian aid	Transport	

13c If Yes, at which level?		
<input type="radio"/> Local / regional levels <input type="radio"/> National level <input type="radio"/> European level <input checked="" type="radio"/> International level		
H Use and dissemination		
14. How many Articles were published/accepted for publication in peer-reviewed journals?		2
To how many of these is open access¹⁰ provided?		0
How many of these are published in open access journals?		0
How many of these are published in open repositories?		0
To how many of these is open access not provided?		2
Please check all applicable reasons for not providing open access:		Lead and Corresponding author is US-based.
<input checked="" type="checkbox"/> publisher's licensing agreement would not permit publishing in a repository <input type="checkbox"/> no suitable repository available <input type="checkbox"/> no suitable open access journal available <input type="checkbox"/> no funds available to publish in an open access journal <input type="checkbox"/> lack of time and resources <input type="checkbox"/> lack of information on open access <input type="checkbox"/> other ¹¹ :		
15. How many new patent applications ('priority filings') have been made? <i>("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).</i>		0
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	0
	Registered design	0
	Other	0

¹⁰ Open Access is defined as free of charge access for anyone via Internet.

¹¹ For instance: classification for security project.

17. How many spin-off companies were created / are planned as a direct result of the project?	0
<i>Indicate the approximate number of additional jobs in these companies:</i>	
18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:	
<input type="checkbox"/> Increase in employment, or <input type="checkbox"/> Safeguard employment, or <input type="checkbox"/> Decrease in employment, <input type="checkbox"/> Difficult to estimate / not possible to quantify	<input type="checkbox"/> In small & medium-sized enterprises <input type="checkbox"/> In large companies <input type="checkbox"/> None of the above / not relevant to the project
19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs: Difficult to estimate / not possible to quantify	<i>Indicate figure:</i> <input type="checkbox"/>

I Media and Communication to the general public	
20. As part of the project, were any of the beneficiaries professionals in communication or media relations?	
<input type="radio"/> Yes	<input checked="" type="checkbox"/> No
21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?	
<input type="radio"/> Yes	<input checked="" type="checkbox"/> No
22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?	
<input type="checkbox"/> Press Release <input type="checkbox"/> Media briefing <input type="checkbox"/> TV coverage / report <input type="checkbox"/> Radio coverage / report <input type="checkbox"/> Brochures /posters / flyers <input type="checkbox"/> DVD /Film /Multimedia	<input type="checkbox"/> Coverage in specialist press <input type="checkbox"/> Coverage in general (non-specialist) press <input type="checkbox"/> Coverage in national press <input type="checkbox"/> Coverage in international press <input checked="" type="checkbox"/> Website for the general public / internet <input checked="" type="checkbox"/> Event targeting general public (festival, conference, exhibition, science café)
23 In which languages are the information products for the general public produced?	
<input type="checkbox"/> Language of the coordinator <input type="checkbox"/> Other language(s)	<input checked="" type="checkbox"/> English

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

- 1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
- 1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
- 1.3 Chemical sciences (chemistry, other allied subjects)
- 1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
- 1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2. ENGINEERING AND TECHNOLOGY

- 2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
- 2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
- 2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

- 3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
- 3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
- 3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

- 4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
- 4.2 Veterinary medicine

5. SOCIAL SCIENCES

- 5.1 Psychology

- 5.2 Economics
- 5.3 Educational sciences (education and training and other allied subjects)
- 5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary, methodological and historical SIT activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

- 6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
- 6.2 Languages and literature (ancient and modern)
- 6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other SIT activities relating to the subjects in this group]