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Quasi-optical analysis of a far-infrared spatio-spectral space interferometer concept

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ABSTRACT

FISICA (Far-Infrared Space Interferometer Critical Assessment) was a three year study of a far-infrared spatio-spectral double-Fourier interferometer concept. One of the aims of the FISICA study was to set-out a baseline optical design for such a system, and to use a model of the system to simulate realistic telescope beams for use with an end-to-end instrument simulator. This paper describes a two-telescope (and hub) baseline optical design that fulfils the requirements of the FISICA science case, while minimising the optical mass of the system. A number of different modelling techniques were required for the analysis: fast approximate simulation tools such as ray tracing and Gaussian beam methods were employed for initial analysis, with GRASP physical optics used for higher accuracy in the final analysis. Results are shown for the predicted far-field patterns of the telescope primary mirrors under illumination by smooth walled rectangular feed horns. Far-field patterns for both on-axis and off-axis detectors are presented and discussed.

1. Introduction

The FISICA project involved an international collaboration of researchers including leaders in the fields of far-infrared astronomy, cosmology, far-infrared instrumentation, optics, optical materials manufacture, and satellite positioning. FISICA aimed to identify the scientific questions related to high spatial resolution far-infrared observations, and to translate these questions into a technological definition of a far-infrared space-based mission, including a baseline telescope design. The work builds on previous far-infrared double-Fourier studies carried out by both European and US institutes, including the ESA Far-Infrared Interferometer (FIRI) Technology Reference Study (TRS) [1], the Space Infrared Interferometric Telescope (SPIRIT) study [2] (a candidate NASA Origins Probe mission), and the Balloon Experimental Twin Telescope for Infrared Interferometry (BETTII) [3]. For publications on the broader FISICA project see [4,5], for example.

It has been long known that radiation in the far-infrared waveband can be used to probe many important astrophysical processes occurring in both the local and distant Universe. However, limitations due to diffraction mean that if resolutions ($\theta_{min} = 1.22\ \lambda/D$) of less than 1 arcsecond are to be reached in the far-infrared, then a primary mirror on the order of 50–100 m must either be built or synthesised. Atmospheric attenuation of far-infrared radiation, and the difficulties involved in using large mirrors in space leads to the requirement of space-based interferometry. Furthermore, if we are to at least match the spectral resolution of single dish far-infrared observatories such as Herschel [6,7], Spitzer [8] and SPICA [9], then a high-resolution spectroscopic technique must be used in combination with the spatial interferometer. The technique selected for the FISICA study was Fourier transform spectroscopy (FTS), and when spatial and spectral methods are used together the technique is called double-Fourier spatio-spectral interferometry [10].

One of the main drivers for a baseline optical layout for a far-infrared interferometer was the production of realistic aperture fields for use with the recently developed PyFIInS (Python Far-infrared Interferometer Instrument Simulator) software [11,12]. The PyFIInS simulator has thus far been capable of modelling the

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double-Fourier interferometry process, and reproducing sample sky maps while accounting for realistic sources of error and noise. To date though, the input primary mirror beams on the sky were those of uniformly illuminated apertures, and thus did not take account of optical aberrations, beam structure and polarisation effects of realistic detector beams, etc. Furthermore, it was clear that at such long wavelengths and propagation distances, diffraction would cause difficulties.

The main body of this paper starts with a description of the predetermined design parameters for the optical system of the interferometer resulting from the FISICA science case. A trade-off study between two very different interferometer design concepts is then presented, with one of the designs subsequently selected for further study. Following a discussion of results from approximate modelling methods such as ray tracing and Gaussian beams, an accurate PO (physical optics) model of the system is described. The PO model is ultimately used to propagate detector horn beams through the optical system, including the hub condensing optics, the variable interferometric baseline, and the light collecting telescopes. As such, the optical aberrations, beam truncation, and field structure that would be expected in a real system are accounted for in the predicted beam patterns shown in Fig. 6. Finally, a discussion of conclusions is given at the end of the paper.

2. Light collecting telescopes

2.1. Broad optical design

In the context of the FISICA study, the demands on sensitivity, resolution, and FoV (field of view) were well defined by the science case, and these requirements drove the initial optical design parameters. Two-metre primary mirrors (flux collectors) are required if integration times are to be kept within practical timescales. For example, for an interferometer with two mirrors ($d = 2$ m), the average time needed per-pointing is 33 h. This corresponds to approximately 4000 u–v sample points with two FTS scans per pair of u–v points [13]. The most demanding science questions translate into the need to spatially resolve astrophysical objects of angular size ≈0.1–0.25 arcseconds at wavelengths ranging from 25 to 200 μm, with a desire to extend the range to 400 μm. This sharp resolution at such long wavelengths requires interferometric baselines up to $B = 100$ m [13,4]. The wide spectral coverage would likely be separated into three wavebands: (1) 25–50 μm, (2) 50–100 μm, (3) 100–200 μm, with a possible 4th band of 200–400 μm, if feasible. Finally, science questions relating to mapping of the galactic centre call for a 1 arcmin^2 FoV. One on-axis single-mode coherent detector/horn assembly illuminating a 2 m primary mirror will yield a beam size on the sky on the order of a few arc seconds squared. However, filling the relatively large arcmin^2 FoV with one such detector is not possible, and so a FPA (focal plane array) of single-mode or over-moded horns will be required. Thus, these values of $d = 2$ m, $B_{max} = 100$ m, FoV = $(\pm 0.5')^2$, and the need for a FPA provided a clear starting point for the optical design.

Unlike imaging telescopes which focus a collimated beam onto a focal plane, the purpose of the light collecting telescopes in this instance is to convert a collimated beam into a smaller (de-magnified) collimated beam. This de-magnification is required in order to keep the size of the cooled hub optics small. Also, the beams must be propagated over distances up to $B_{1/2} = 50$ m, before being combined in the hub craft. For each of the two beam paths a flat mirror oriented at 45° to both the sky and the hub spacecraft is used to steer the beam toward the hub. De-magnification of the beams can be performed either before or after propagation over the semi-baseline. Fig. 1 (left) shows a design where de-magnification is done before propagation over $B_{1/2}$. This was the option chosen by the FIRI study [15,1], where two on-axis afocal telescopes (pointed at the source) sample the u–v plane and de-magnify the aperture fields. Fig. 1 (right) illustrates how de-magnification can alternatively be done after propagation over $B_{1/2}$, as selected by the balloon-borne BETTII mission [3] (due for launch in 2016). In this case two large flat siderostats (oriented at 45° to the source) sample the u–v plane and propagate the large beams toward the hub. Two afocal telescopes (off-axis layout for

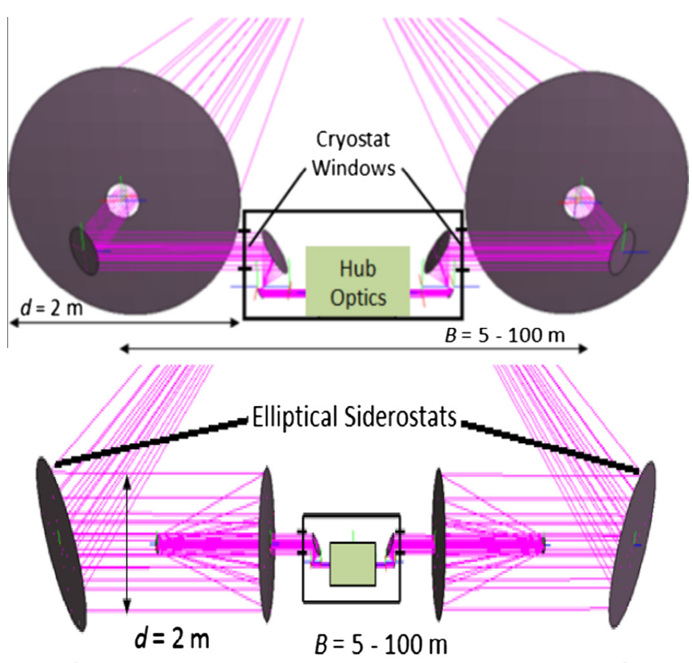

Fig. 1. Interferometer concept designs. *Left*: De-magnification carried out before propagation over the semi-baseline. *Right*: De-magnification carried out after propagation. The required dimensions of the flat siderostats in the right figure are $a = 2$ m and $b = 2.83$ m. (Pictures generated using GRASP software [14].)