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Optical analysis of BISOU: a balloon project to measure the CMB spectral distortions

N Trappe¹, C O'Sullivan¹, B Maffei², N Aghanim², M Abitol³, E Battistelli⁴, J Chluba⁵, X Coulon⁶, P de Bernardis⁴, C Hill⁷, A Kogut⁸, S Masi⁴, L Pagano⁹, A Rotti¹⁰, G Savini¹¹, A Tartari¹²,

(1)National University of Ireland; Maynooth, Co Kildare. Ireland; (2)Institut d'Astrophysique Spatiale, CNRS (France), Univ. Paris-Saclay (France); (3) Univ. of Oxford (United Kingdom); (4) Sapienza Univ. di Roma (Italy); (5) The Univ. of Manchester (United Kingdom); (6) Institut d'Astrophysique Spatiale (France); (7) Columbia Univ. (United States); (8) NASA Goddard Space Flight Ctr. (United States); (9) Univ. degli Studi di Ferrara (Italy); (10) The Univ. of Manchester (United Kingdom); (11) Univ. College London (United Kingdom); (12) Univ. di Pisa (Italy).

ABSTRACT

BISOU (Balloon Interferometer for Spectral Observations of the Universe) is a CNES phase 0 study investigating the feasibility of observing spectral distortion in the CMB signal using a balloon-borne spectrometer, which also will act as a pathfinder for a future space mission dedicated to the measurements of the CMB spectral distortions. The CMB frequency spectrum is an important probe of the cosmological model. In this paper, we describe the optical layout and outline the initial optical analysis of the signal path and the reference beam path. The major challenge outlined is the inclusion of the required optical train in a confined volume of the cryostat. We include a multimoded description of the optical response of the system from the multimoded pyramidal horn through the optical path containing mirrors and wire grids and predict beam patterns on the sky.

Keywords: long wavelength optical analysis, CMB spectral distortion, instrument optics analysis

1. INTRODUCTION

1.1 Background Science

The CMB (Cosmic Microwave Background) is a rich resource to learn important parameters about properties of the early Universe and is being extensively analyzed currently particularly for its polarization properties and historically to measure the temperature anisotropies. In recent years, successful missions like ESA's Planck Surveyor have been central to firming up the cosmological concordance model, with seven precisely measured cosmological parameters. Currently many ground-based missions are starting to measure the polarization of the CMB to allow cosmologists constrain theories of inflation by measuring the B mode levels. BISOU (Balloon Interferometer for Spectral Observations of the Universe) with a proposed bandwidth from 90 to 2000 GHz will seek to observe the CMB for its spectral characteristics and measure any spectral distortion that may exist allowing a different insight to be gained. Low-level differences from the average CMB energy spectrum compared to a perfect blackbody provide a probe of the cosmic thermal history. This was first measured with the COBE mission in the 1990s. The sensitivity achievable with current technology can improve on the sensitivity of COBE/FIRAS's measurements by a factor of up to one thousand. The CMB spectrum is known to be close to a perfect blackbody but nonetheless has deviations from the ideal of about one part in 20,000. With this new sensitivity and precision, BISOU could measure new insights into the early Universe. The BISOU mission concept builds on the heritage of COBE/FIRAS and previous space-mission proposals (i.e., PIXIE [1,3] and PRISTINE [2]). BISOU is seen as a pathfinder and verification step towards a dedicated space spectral distortion space satellite mission, which can offer a unique opportunity to measure the CMB distortion to a level that can target novel science [3].

The CMB spectral distortions should arise because of two main processes - *Compton y distortion* from energy release at cosmological redshifts of z values greater than 5×10^4 , and chemical potential or *μ distortion* in the CMB signal at z values less than 5×10^4 . BISOU plans to utilize unique sensitivity and spectral coverage to measure this distortion at levels of three

orders of magnitude fainter than the original COBE/FIRAS measurements. BISOU should at least set the most stringent limits on distortions. Other interesting science on black hole formation, dark matter candidate particles, early Universe physics, thermal Galactic dust emission and determining the average CMB temperature T_0 to a few μK are all target science themes that can be studied through the planned measurements between 90 and 2000 GHz.

1.2 Instrument layout and requirements

BISOU (Balloon Interferometer for Spectral Observations of the Universe) is a CNES phase 0 study investigating the feasibility of observing spectral distortion in the CMB signal using a balloon-borne spectrometer, which also will act as a pathfinder for a future space mission dedicated to higher sensitivity measurements of the CMB spectral distortions. Its optical design is very much constrained by volume and mass requirements within a small cryostat and confined space and requires slightly different optical considerations to PIXIE [1] due to the limits imposed by the fairing volume and mass requirement of a balloon mission. The PIXIE concept is based on a two input and output Fourier Transform Spectrometer design. In this original concept both sky inputs go independently through identical off-axis telescopes as illustrated in figure 1a below. A mechanism to swap beams from the sky to a blackbody calibrator was proposed for PIXIE and Pristine allowing up to three observing modes to remove systemic effects and measure spectral distortion and possibly polarization. In the first two modes of operation (without all details here), one path sees the sky, the other the internal calibrator, so that the difference between the sky and the reference blackbody is recorded. The third mode, used only for optics calibration purpose, where both FTS beams look at the sky.

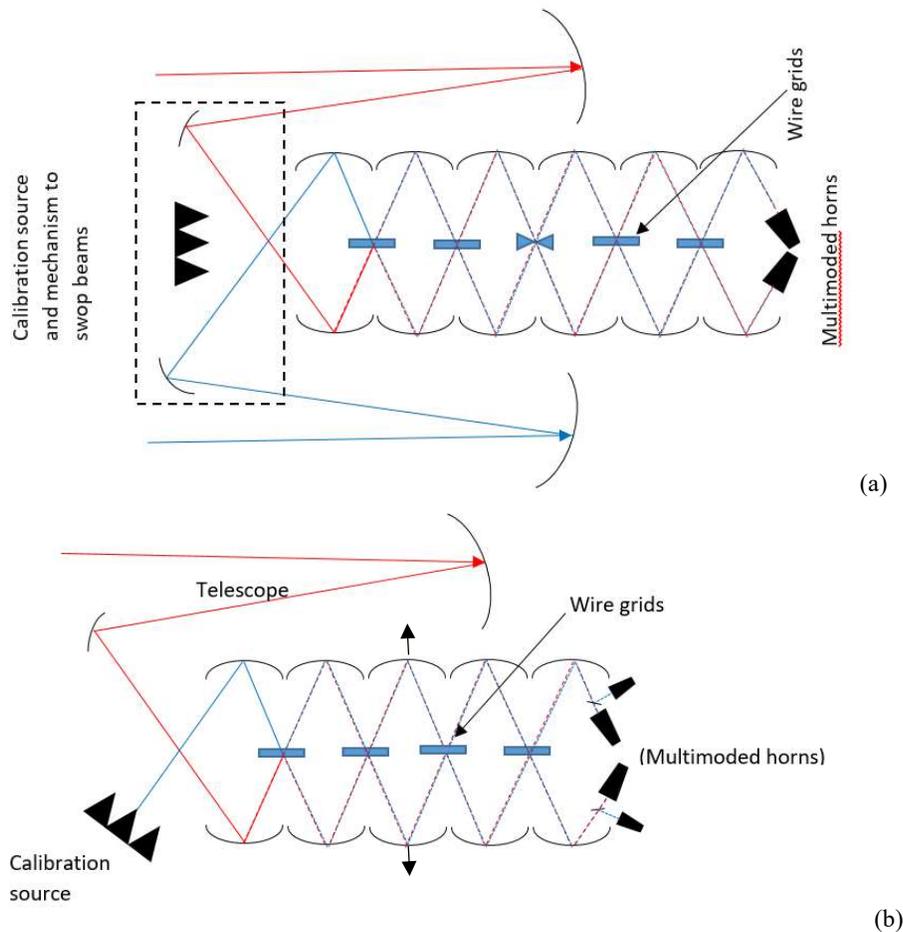


Figure 1: A sketch of the optical layout of BISOU compared to PIXIE [1]. Some variation of this design is required due to mechanical and volume constraints in BISOU.

With the limited volume available on the balloon fairing for BISOU, fitting the two identical telescopes is not feasible and so a more compact optical train is proposed and is currently being analyzed. BISOU requires about a 40 cm primary mirror to achieve the required optical resolution on the sky and fitting two identical telescopes in the cryostat is not feasible. Therefore, one side of the FTS looks towards the sky and one towards a calibration source that fills the beam along the other FTS path. The roof mirror or moveable mirror is also removed in an alternative FTS design proposed in a white paper 2020 [4]. Therefore, more calibration and simulation will be required to understand and remove systematic effects for BISOU. The Fourier Transforms of the time domain interferograms of the detector outputs provide a set of modulated spectra, the combination of which will yield spectra of the desired source. The FTS outputs are fed to detectors (bolometers) via multimoded feed horns. The detectors will require sub-K temperatures (typically 100 to 300 mK). What is outlined here is a primary optical analysis incorporating all the main components and also a preliminary analysis of the multimoded horn and how this influences the analysis programme.

1.3 Preliminary optical Analysis

To verify the optical performance of BISOU, an initial analysis was carried out using GRASP21 by Tiera [5]. Mirror sizes and spacing are limited by the available volume of the cryostat (roughly 1030 × 910mm). In addition, as this is a balloon experiment, the beam to the sky must look 20 degrees off the vertical to miss the balloon fittings of the housing. An optical design that fits within this volume and meets this criterion is illustrated in figure 2, showing one path through the dual path FTS (identical opposite path not shown). The FTS and telescope are not in plane and a slight aberration arises on a beam on the sky as illustrated in figure 2, using a frequency of 300 GHz.

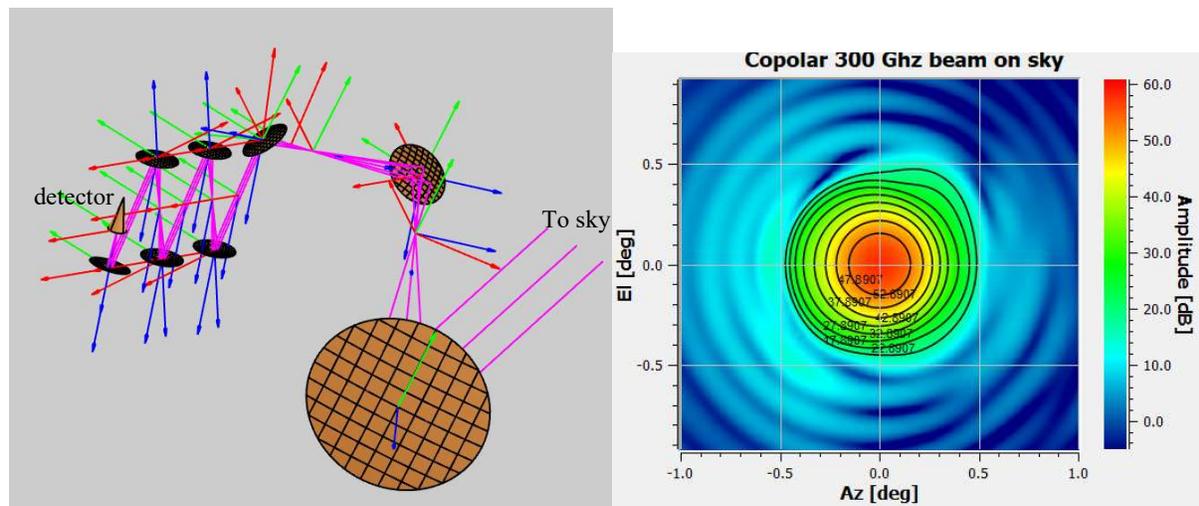


Figure 2: Preliminary optical design of BISOU showing one path of the FTS to the sky. Using a Gaussian input, a beam at 300GHz is propagated to the sky to validate optical quality of the system.

1.4 Multimoded horn analysis and the optical response.

Multimoded horns are used to couple the signals to the detectors. Analyzing multimoded horns is computationally intensive if a full waveguide mode matching analysis is completed and using a ray tracing approximation may only be accurate at the higher frequency end of the band. In spectral distortion projects like BISOU the very wide frequency bandwidth means that only a few modes propagate above cutoff at the low frequency end of the band (10s) and thousands of modes at the upper end of the band satisfying the etendue criteria. If a full optical model of the system is to be developed, then we would like to use physical optics tools to analyze the optics but also including input horn fields that represent the horn accurately. At single mode operation, (typical of traditional radio systems), a single dominant waveguide mode (TE_{11} in circular and TE_{10} in pyramidal geometries) can be read into the physical optics code as a planar electric/magnetic field and propagated through the optics as a single input field. In a system like BISOU this becomes very computationally significant as each modal field must be treated as a separate input and then summed on the sky to create the composite incoherent response of the multimoded horn. This is of course is completely accurate but at the short wavelength end of the band becomes

unfeasible with thousands of inputs. Therefore, we seek the lowest frequency point where the horn field pattern is consistent in shape with enough modes propagating but not too many modes that it becomes computationally challenging. It has been shown [6] that ray tracing analysis can be successfully applied to characterize the optical response of the specially adapted pyramidal horns for PIXIE and this is an alternative approach but is known to miss some detail in the response especially at the low frequency end of the band. To achieve a certain etendue typically 10s of modes propagate at 90 GHz and thousands of modes at 2 THz. We expect that when enough modes propagate the beam pattern of the horn is consistent and shape representative of the overall field over the band. Here we would like to investigate when a full modal description of the multimoded horn works accurately but using the minimum number of modes possible to get a good indication of the behavior at higher frequencies.

Our research group have developed a horn analysis software called SCATTER that can be applied to the analysis of horn antennas using waveguide modes. Originally it was developed for cylindrical geometries and was applied in the optical design and analysis of several systems, including ESA missions such as Planck, Herschel Observatory (HIFI) and ALMA band 5 & 9 [7]. A complete overview of the code can be found in the online thesis [8]. We also then adapted the code to pyramidal horns structures such as the multimoded horns developed for the proposed SAFARI instrument for SPICA.

Within a waveguide structure a finite number of TE and TM modes can propagate and contribute field distributions. Each waveguide mode propagates above its cut-off frequency. The mode matching technique assumes that the field distributions can be described as the sum in quadrature of all waveguide TE and TM modes. This can be used to propagate a field through a uniform section of guide with constant volume by considering the propagation of the supported component modes individually, before recombining the modes to provide the overall field. So all horn geometries can be represented as waveguide structures in a finite series of continuous sections (typically 10-20 sections per wavelength) which can be cascaded together to work out the overall fields propagating. At each section junction we perform an overlap integral between each modal component of the incident field and allowable modal component of the transmitted field so power propagating in both directions is conserved. Essentially mode matching can be summarized as a technique which propagates a waveguide modal basis set, appropriate to the geometry, through successive junctions while conserving power [8]. Most waveguide geometries can be analyzed using this framework.

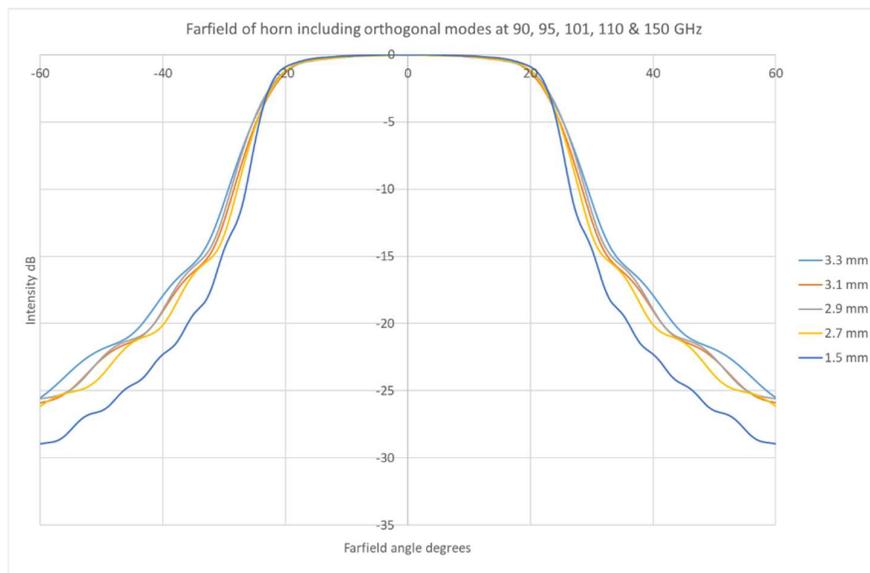


Figure 3: Showing the farfield of the detector horn beam on the sky at a number of frequencies near the low frequency end of the band. The beam pattern profile is very similar over this range proving that modeling the beam with a low number of modes is feasible and representative of higher frequency beam profiles.

In initial analysis a cylindrical horn with a waveguide exit radius of 4mm, 16 waveguide modes propagate at 90 GHz giving the correct order of etendue for the BISO system. At 100 GHz the number of modes increases to 19 modes (not counting their orthogonal counterpart modes) while at 200 GHz the mode number rises to 66 modes. If one was to carry out a full vector analysis of the horn fields from 66 waveguide modes it would require the inclusion of 132 electric fields

at the horn aperture into a physical optics propagator like TICRA's GRASP 20, which is becoming a significant computational project.

As an example of running a multimoded PO analysis a simple horn (dimensions entrance aperture = 4 mm, exit aperture = 10 mm and length = 80mm) is analyzed using the SCATTER code. At 100 GHz 18 modes propagate. So 36 aperture electric fields are calculated at 100GHz (including the orthogonal mode set) and all fields are then propagated independently through the BISOU optical path to the sky as illustrated in figure 3 below. The resultant beam on the sky is calculated illustrating an indicative beam pattern on the sky in terms of beam profile. This pattern is illustrated in figure 4 below. The mirror size requirements of the FTS and telescope can be verified using this multimoded approach to ensure all propagating modes (higher off-axis modes) can propagate through the optics without significant truncation.

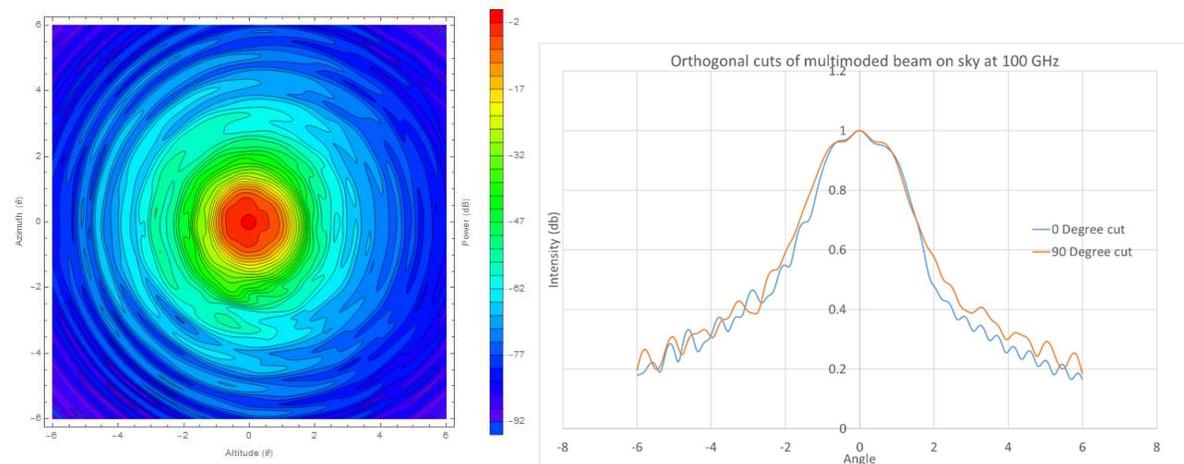


Figure 4: At 100GHz the multimoded horn response of the BISOU optics can be verified propagating all model fields independently through the optics.

CONCLUSION

In this phase 0 study, a detailed optical design analysis of the BISOU optics is being carried out. A detailed model of the multimoded horn response is required and using PO analysis representative horn beams can be created for the system. Over this wide bandwidth the number of modes propagating is very different and the use of ray tracing analysis and modematching for the horn antennas will be required. Low-level systematic effects will need to be understood and accounted for and so a detailed optical model for the full system is an important aspect of the mission success.

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