BISOU: A balloon pathfinder for CMB spectral distortions studies

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ABSTRACT

The *BISOU* (Balloon Interferometer for Spectral Observations of the primordial Universe) project studies the viability and prospects of a balloon-borne spectrometer, pathfinder of a future space mission dedicated to the measurements of the CMB spectral distortions. A balloon concept based on a Fourier Transform Spectrometer, covering a spectral range from about 90 GHz to 2 THz, adapted from previous mission proposals such as *PIXIE* and *FOSSIL*, is being studied and modeled. Taking into account the requirements and conditions of balloon flights, we present here the instrument concept together with the results of a CNES Phase 0 study. We forecast a first detection of the CMB *Compton y-distortion* monopole with a signal-to-noise ratio of at least 5. We also present the future plan and work that will be the subject of a recently awarded two-year Phase A study.

Keywords: Balloon, Cosmic Microwave Background, CMB Spectral distortions, Cosmic Infrared Background

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1. INTRODUCTION

With the success of the ESA *Planck* mission, as well as subsequent results from balloon-borne and ground-based projects, the concordance cosmological model is established as the reference framework. However, outstanding questions about this model are still unanswered. The simplest inflationary model proposed as the origin of the initial matter perturbations is favoured by *Planck* measurement of the spectral index and low non-Gaussianity. Nevertheless, it still needs to be confirmed through the measurement of its smoking gun signature: the relic background of primordial gravitational waves. The latter can only be observed through the Cosmic Microwave Background (CMB) polarisation: namely B-modes, for which several dedicated instruments have been or are being developed, with notably the future space mission *LiteBIRD*[1] . The CMB frequency spectrum is another key observable to probe the cosmological model. Its intensity was precisely measured by *COBE/FIRAS*[2,3] almost three decades ago, with deviations limited to $\Delta I/I \approx 10^{-5}$. Since then, not much progress has been achieved in measuring its deviation from a true blackbody. However, while the space mission proposals *PIXIE*[4,5] (NASA), *PRISTINE* (to ESA F1 mission call) and *FOSSIL*[6] (to ESA M7-mission call) have not been successful, following a white paper[7] , the ESA Voyage 2050 programme has selected this topic amongst its three upmost priority themes.

BISOU[8,9] is a future balloon-borne spectrometer, pathfinder of a future space mission dedicated to the absolute measurement of the CMB spectrum. While *PIXIE* and *PRISTINE* were targeting measurements of both the CMB B-mode polarisation, and of the CMB spectral distortions, *BISOU*'s main goal is to perform a first measurement of the later. However, secondary science will also include a better measurement of the Cosmic Infrared Background (CIB) emission, a better determination of the CMB average temperature, together with Galactic emission lines such as CI, CII, NII and OI.

Taking into account the specificity of a balloon flight in term of requirements and conditions (i.e. residual atmosphere, observation strategy for instance), this CNES Phase 0 study evaluates *BISOU*'s sensitivity to measure at least the Compton y-distortion while consolidating the instrument concept. The first sections below give the status of this project together with its current instrument concept, while the last sections describe the future work that will take place during the upcoming follow-up Phase A.

2. SCIENCE OBJECTIVES

The *COBE* space mission has shown that the CMB has a nearly perfect blackbody emission spectrum at a temperature $T = 2.72548 \pm 0.00057$ K[10] . However, deviations from the Planck law, referred to as spectral distortions, are expected. They result from processes that affect the thermal equilibrium between matter and radiation. One of the standard distortions, known as the Compton y-distortion, is created in the regime of inefficient energy transfer (optically thin scattering) between electrons and photons, relevant at redshifts $z < 5 \times 10^4$. Processes creating this type of distortion are dominated by the inverse-Compton scattering of CMB photons off hot electrons during the epoch of reionization and structure formation, also known as the thermal Sunyaev-Zeldovich (tSZ) effect.

Moreover, chemical potential or μ-type distortions, on the other hand, are generated by energy release at earlier stages ($z > 5 \times 10^4$), when interactions are still extremely efficient (optically thick scattering) and able to establish kinetic equilibrium between electrons and photons under repeated Compton scattering and photon emission processes.

Therefore, these distortions encode information about the full thermal history of the Universe from the early stages (primordial distortions from inflation and cosmological recombination lines) until today (star formation and galaxy clusters). Many of these processes are part of our standard cosmological model and are detailed in several publications[7,11,12] . Combined with models of the CMB and foreground emissions, largely based on Planck data[13] , a full sky model[14,15] has been developed in order to estimate the received fluxes by our future instrument. As shown in Fig. 1, it can be seen that the *COBE-FIRAS* limit, $|y| < 1.5 \times 10^{-5}$ (95% C.L.), is roughly one order of magnitude larger than the expected signal[12] , $y \approx 2 \times 10^{-6}$. Signal from μ-type distortions will be even fainter.

It is therefore crucial to have reliable models of all the emissions but also experimental data across a broad spectral range (from tens to thousands of GHz) in order to properly subtract all these foreground signals.

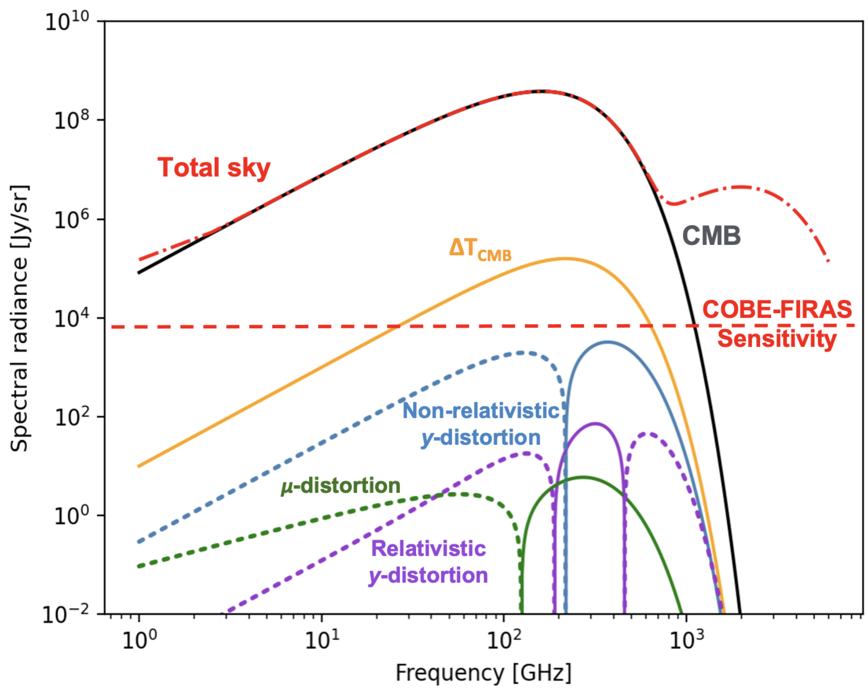


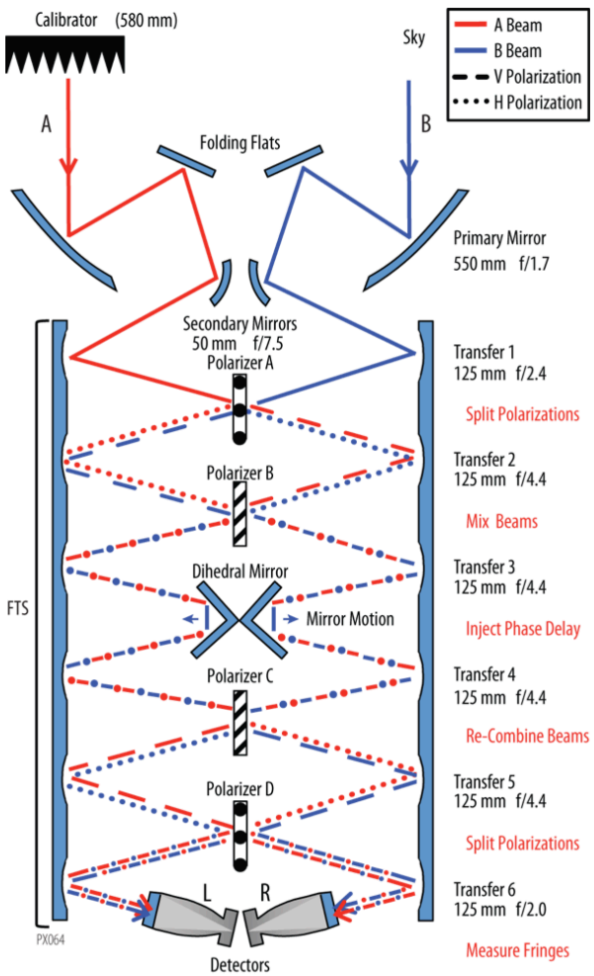
Figure 1. Models[15] of the spectral distortions emissions: Black body distortion ΔT_{CMB} (orange), non-relativistic y-distortion (blue), relativistic y-distortion (purple) and μ-distortion (green). To be compared with CMB emission (black) and the total sky signal - Foregrounds + CMB (dashed red).

3. INSTRUMENT REQUIREMENTS AND INITIAL CONCEPT

New highly sensitive technologies able to perform spectroscopy in the millimetre / sub-mm regime are being developed (such as spectroscopy on a chip with bolometric detectors) and they might well be technologies that will be used for a distant future L-class space mission. However, due to the need of a very large spectral range the obvious spectrometer choice is a Fourier Transform Spectrometer (FTS), which has also the benefit for its spectral resolution and frequency coverage to be optimised even during the mission if necessary.

The starting point is based on the concept that had been proposed by the *PIXIE* team[4] (shown in Fig. 2a). The instrument is based on a FTS with two inputs and two outputs. Both inputs are going through separate telescopes, both sets of optics being identical in order to minimise the systematics. Because *PIXIE* has several observation modes, an external calibrator (cooled blackbody) could be located in front of one of the apertures at any one time.

In the "spectral distortion" mode, with which the absolute spectrum would be measured, one input is directed towards the sky, the second towards the blackbody calibrator whose temperature is set to the CMB one, 2.726 K. After going through a set of polarisers, each of the two outputs is focused on a dual-polarisation multimoded bolometric detector (L and R on Fig. 2a). Each of the four detectors measures an interference fringe pattern between orthogonal linear polarisations from the two input beams. Therefore the variable part of the interferogram signal will be the difference between the signal from the sky and the one from the calibrator at 2.726 K[4,5] thus a differential measurement. In order to limit the photon noise, the whole instrument is cooled to about 3 K, the detectors being at sub-K temperature. This original instrument concept has then evolved[5,16]. For the ESA M7 mission *FOSSIL* proposal[6], specifically dedicated to the spectral distortions measurements, the concept has been further modified. The main change was the addition of a dichroic at each output, allowing to split the signal into two sub-bands (low and high frequency bands) so that the sensitivity could be optimised (see Sec. 4.3).



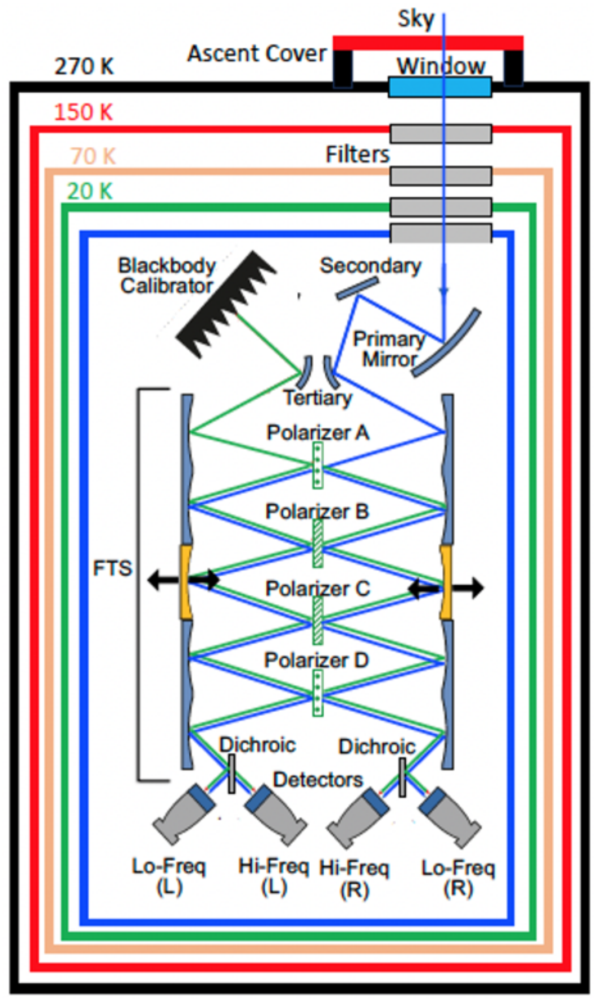


Figure 2. (a) Left: Original instrument concept from the *PIXIE* space mission proposal[4] . (b) Right: *BISOU* instrument concept adapted for a balloon platform. Differences include the addition of the dewar window and spectral filters, only one input telescope, and the addition of dichroics leading to 2 sub-bands and 4 focal planes.

4. PHASE 0 STUDY OUTCOMES

The previous studies for the instrument concept were performed on the basis of a space mission. For the case of a balloon project, the conditions, the requirements and therefore the instrument concept will be different. Stratospheric balloon projects might be considered to be in near-space conditions, but there are still many differences, some having strong impacts on the payload concept.

BISOU being a pathfinder, its main scientific goal is to perform a first detection of the CMB spectral distortions within a reasonable time-frame. It will be limited to the Compton y-distortion monopole, as we cannot expect to be as sensitive as for a space mission. Therefore, the systematic effect levels requirements could be somehow relaxed, allowing for a simpler design, while relying on sub-systems with fairly high TRL, limiting the risks and complexity.

4.1 Typical stratospheric balloon requirements

The residual atmosphere at an altitude of about 40 km will be at a pressure of about 3 mbar with a temperature of the order of 250-270 K. This will not only lead to an additional photon noise contribution, but also to the necessity of hosting the overall instrument inside a cryostat in order to maintain it under vacuum and at a temperature below 5 K typically. Even with a small pressure difference, the cryostat will then need to have a window through which the telescope will point towards the sky (see Fig. 2b). The outside cryostat shell being at ambient temperature, intermediate thermal stages will be necessary with thermal filters in order to limit the thermal background load and potential straylight.

This is also preventing the calibrator to be outside the dewar and will then have to be located inside in order to keep it at a very steady temperature of about 2.7 K.

The balloon being located above the gondola, the payload will not be able to point at the zenith. Avoiding emissions from the ground or from the Sun has a direct impact on the observation strategy. We will have to limit the elevation to 50 ± 15 deg, and have the line of sight direction opposite to the Sun location.

4.2 CNES balloon flights

The balloon flight and infrastructure being provided by CNES, our study is based on the use of the standard CARMEN gondola[17] design in order to reduce the cost of developing a new one. It allows for a maximum payload mass of about 610 kg with a maximum footprint of 0.9 m$\times$1.8 m. The **payload** will need to include our science **instrument**, the elevation mechanism, the stellar sensor for the attitude control and reconstruction.

CNES had so far flown this type of payloads for a typical 35-hour flight duration. A first transatlantic test-flight between Kiruna (north of Sweden) and Canada took successfully place late June 2024 for a duration of 3.5 days. We will therefore base our sensitivity calculations on the assumption that a 5-day flight will be available in the future.

4.3 BISOU instrument concept

A preliminary *BISOU* instrument concept, adapted to the conditions and requirements of a balloon project and established towards the beginning of the Phase 0 study, has already been published.[8] It is clear from the previous sections that the overall dimensions and mass of the payload has to be limited. The fact that the whole instrument has to be within a vacuum-tight vessel surrounded by a 270 K ambient temperature with intermediate temperature stages, is already costly in term of envelope and mass. This also implies the necessity of using a cryostat entrance window and thermal filters on the temperature stages, thus increasing the background noise. The major drawback of the FTS is that for a null path difference the entire spectrum of the signal of interest, but also of any other emissions (foregrounds, instrument, etc..) are reaching the detectors, therefore leading to a large photon noise.

This is confirmed by the sky and instrument models leading to an overall photometric model[14,15] that has been developed in the workframe of spectral distortion projects. Applying this model to the specific case of *BISOU*, exploration of parameters such as telescope diameter, flight duration, observation efficiency, or again spectral resolution as well as parameters related to the observation strategy, has allowed for a first design optimisation.

As expected, the sensitivity is strongly dependant on three key parameters: the temperature and emissivity of the window, and the maximum frequency of observation as the photon noise is increasing with frequency.

These above considerations are leading to the following decisions, compromises and consequences.

- While we are always aiming at using low-emissivity quasi-optical components (i.e. window and spectral filters), in order to limit the input background, only one entrance window will be used with an aperture diameter of 50 cm maximum. This limits the telescope aperture diameter to 40 cm maximum.
- In order to save mass, only one telescope aiming at the sky will be used. The second FTS input will always be looking directly at a fixed blackbody calibrator through a simple re-imaging optics. The rest of the FTS optics (mirrors, polarisers) will also have to be limited in size.
- Unlike *PIXIE* which could alternate the position of the calibrator over either telescope in order to cancel any asymmetry between both optical systems, for *BISOU*, the systematics arising from this asymmetry will have to be carefully studied, traded off by a thorough ground calibration campaign, the inclusion of a calibration source and a highly accurate temperature monitoring of the optical components;
- The size of the optical elements driving the spectral band lowest frequency, we converged towards a minimum frequency of 90 GHz. The compromise between the background noise for this balloon project and the science objectives, sets the high frequency limit to 1.5 - 2 THz.
- A fixed spectral resolution of 15 GHz across the frequency range is sufficient for the science goals while limiting the FTS mirror scan to less than 1 cm.
- During the first iterations of our photometric model, it became apparent that due to the high level of contribution of the high frequency part of the spectral band to the photon noise, the sensitivity of the instrument could be increased and optimised through the use of a dichroic splitting the overall detection into 2 sub-bands. The low frequency band tailored for spectral distortions measurements, and the high frequency band essentially used for foregrounds removal. The initial frequency split was set to 500 GHz, but more recent calculations[18] show that a frequency around 300 to 350 GHz would be best.

Our photometric model shows that the whole instrument needs to operate below 10 K typically, leading us to choose a dewar cooled with a liquid helium filled tank as proven technology. This will ensure a temperature ranging from 4 to 2 K depending on the bath pressure, using the natural low pressure at high altitude. Several intermediate thermal stages and shields cooled with the helium vapour retrieved from the bath will allow for heat load reduction on the successive temperature stages. Typical intermediate temperature stages are 150 K, 70 K and 20 K, where spectral filters will be located at the optical input of each shield to decrease the photon load on the detectors and avoid out-of-band spectral leakages.

These points led us to the overall *BISOU* instrument design shown in Fig. 3a hosted in a big dewar 1.5 m high, 1.4 m long and 0.8 m wide to fit within the CNES CARMEN gondola. A preliminary implantation of the instrument is shown in Fig. 3b, together with the ESTADIUS[19] stellar sensor. The overall payload mass is estimated to be 630 kg, without margin. It is slightly above the limit and mass reduction could be achieved with an optimisation of the mechanical structure, the present design being the first iteration.

We adopted a L-shape dewar to reduce the mass, where one vertical cylinder includes the telescope, the second horizontal cylinder hosts the liquid helium tank and the cold plate where the rest of the instrument (FTS, calibrator and detection chain) will be located for good thermal stability. The drawback of this arrangement might be the larger thermal gradient and poorer thermal stability of the telescope optics, that might lead to larger background fluctuations and therefore induced systematics.

While the instrument relies on a FTS, the key sub-systems that will require development and optimisation are listed afterwards.

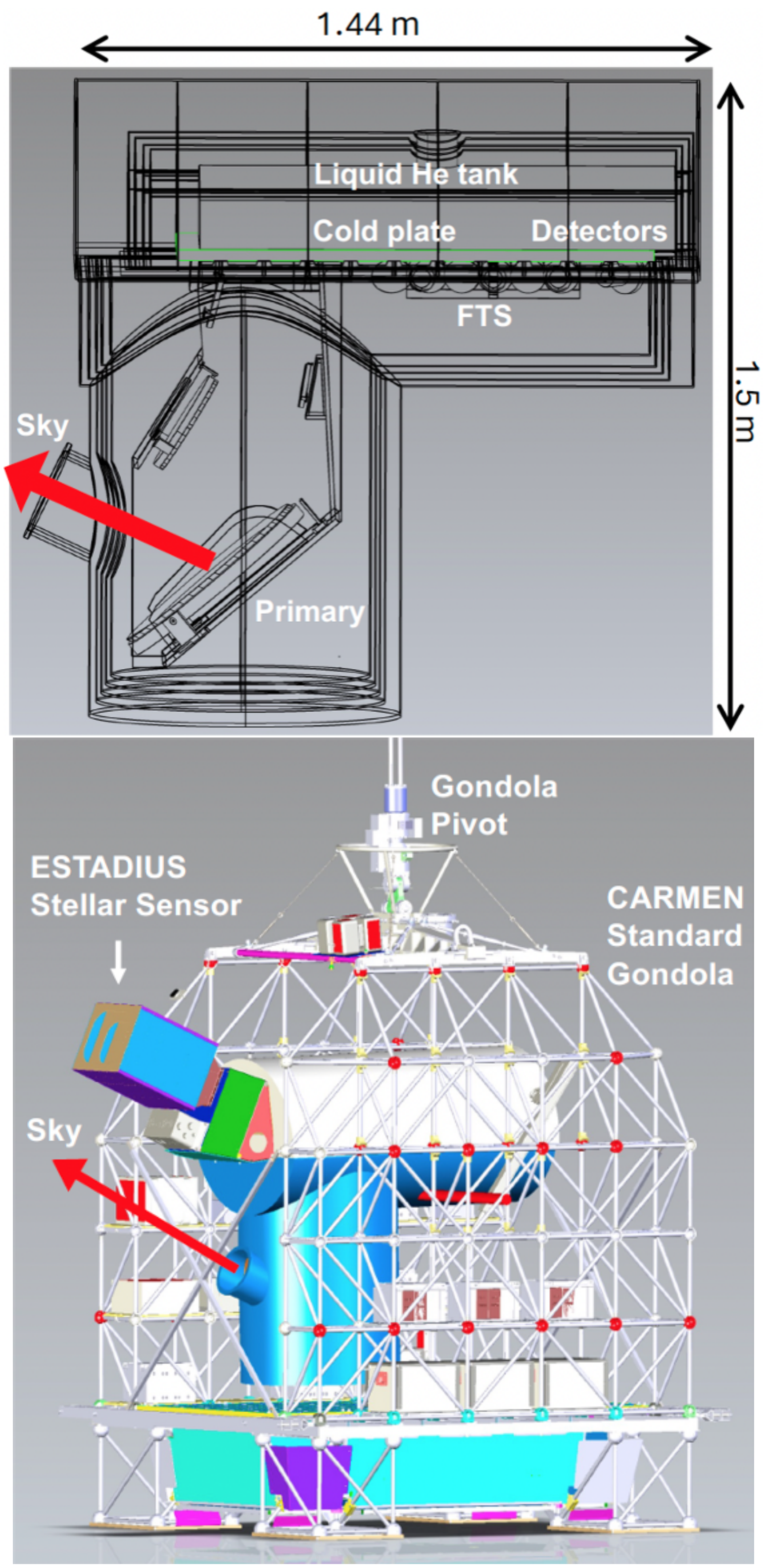


Figure 3. (a) Top: CAD drawing of *BISOU* L-shaped dewar including the whole instrument. (b) Bottom: preliminary integration of *BISOU* within CNES CARMEN gondola[4] .

4.3.1 The optical system

This system is multi-moded from the lowest frequency (about 10 modes at 90 GHz), the number of modes then increasing with frequency and therefore keeping a beam width almost constant across the whole spectrum. With a 40 cm diameter primary telescope to start with, the equivalent FWHM is of the order of 1.5 deg. However, the size of the optics dictates the overall dimensions of the instrument, as well as the size of the entrance window. This diameter could be reduced to 30 cm as the spatial resolution is not a driver for the targeted science, helping to reduce the overall payload mass.

In addition, this dewar window being the warmest optical element, it needs to have a very low emissivity and a stable temperature, therefore be as thin as possible to minimise the systematics. A current R&D programme is looking into the selection and characterisation of low emissivity materials.

In order to use a very thin window, a valve at the entrance of the dewar, opening only when the pressure difference is small (at a certain altitude), will be developed based on heritage from the previous Archeops[20] balloon project. Again, having a smaller diameter window would make such a mechanism lighter and easier to develop.

4.3.2 Focal planes and detectors

Due to the use of a dichroic at each of the FTS ouptut, we will have four focal planes (Fig. 2b), each with a minimum of one dual-polarisation detector. Depending on the assumptions and instrument parameters, our photometric model shows that a detector NEP of the order of a few 10^{-16} W Hz$^{-1/2}$ is enough to be photon noise limited, leading to the use of various possible detector technologies.

Taking advantage of previous developments, resistive detectors developed by NASA-GSFC for *PIXIE* can be adapted and optimised for *BISOU* and are therefore the baseline choice. They have a high TRL already and can be adapted to various photon noise background. Indeed, balloon operating conditions being different from a space environment, an operating detector temperature of 300 mK would be sufficient and easier to implement than a 100 mK sub-K cooler.

On the other hand, *BISOU* could also serve as a pathfinder for new technologies such as Kinetic Inductance Detectors (KIDs) with high potential or even Thermal KIDs (TKIDs). Each of these technologies would be best optimised for different frequency ranges, and would require further development within the time frame of *BISOU*, but the use of two different spectral bands could allow for a mix of technologies. A recent R&D programme has started in France to develop this technology for *BISOU*.

The detectors will be coupled to the optics through the use of multi-moded feedhorns defining the beam shape and allowing for a control of straylight without the use of a cold stop. The instrument sensitivity has been computed assuming the use of only one detector. However the focal planes will probably contain several pixels (trade off under study still) in order to improve the sensitivity and the redundancy.

4.3.3 Calibrator

The reference blackbody (referred to as Calibrator) against which the relative measurement will be performed, will define the accuracy with which the CMB temperature and spectrum will be known. Its emission is the combination of its emissivity and its temperature. In order to radiate like a perfect blackbody, the emissivity needs to be equal to 1 (or as close to 1), meaning a very low reflectivity. In addition, its temperature, together with the temperature gradient across its surface, needs to be known and controlled to better than to a few mK. The ARCADE II experiment has reported[21] the development of a such broadband microwave calibrator operating up to 90 GHz. Improvement of such component has been achieved for *PIXIE*, but a specific development for *BISOU* based on this heritage will be needed.

5. SENSITIVITY ESTIMATES

Thanks to our photometric model that is allowing for the instrument optimisation, various cases with various instrument and mission parameters have been considered and already reported[18,15] . These can be summarised with one case below, with the following assumptions.

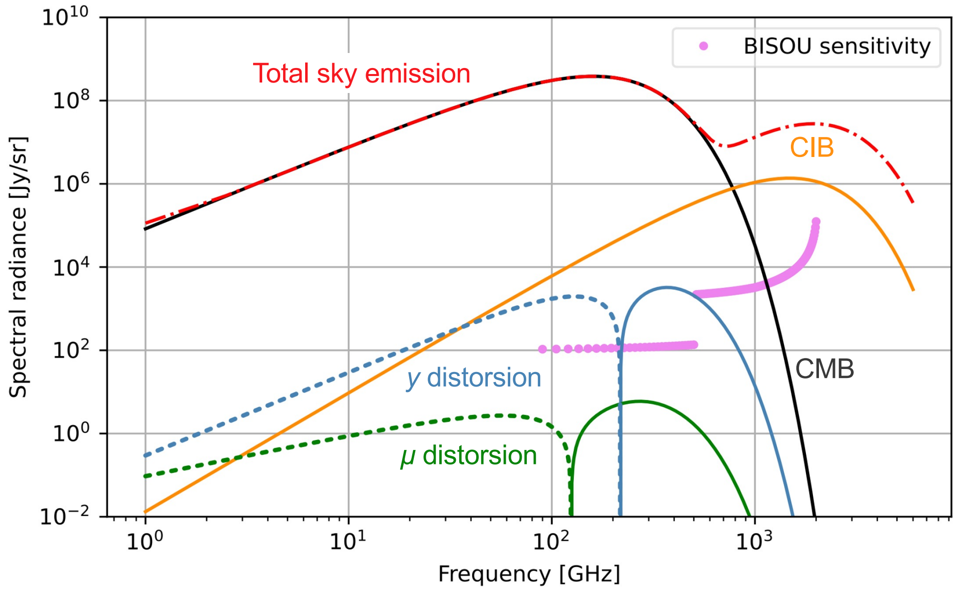


Figure 4. Estimated sensitivity for one configuration, compared to astrophysical signals of interest for *BISOU*. All calculations are assuming a 5-day flight assuming only one detector and no atmosphere.

- FTS spectral resolution $\Delta\nu = 15$ GHz across the whole spectral range;
- Overall spectral band : $\nu_{min} = 90$ GHz; $\nu_{max} = 2000$ GHz;
- Filters on the different temperature stages have an emissivity of 0.1%;
- Calculations are performed assuming only one detector;
- Two spectral sub-bands separated by a dichroic with a split frequency at 500 GHz;
- The atmospheric emission is not taken into account;
- Transatlantic flight of 5 days with 75% observation efficiency.

Results on this configuration are shown in Figure 4. They lead to S/N ratios of 5.6 for the y-distortion monopole, and about 2.3 for A_{CIB}, the amplitude of the CIB monopole, representing an improvement factor of more than 20 in comparison to the *COBE-FIRAS* mission. Future work (see following section) will address the issue of taking into account the emission of the residual atmosphere in these sensitivity estimates.

6. PHASE A PLANS AND FUTURE WORK

Following a successful Phase 0 study that ended in summer 2023, CNES has officially announced that a two-year Phase A is starting in June 2024. The aims are to fully define the instrument design, as well as its integration within the CNES gondola, to consolidate the mission parameters, the observation strategy and the sensitivity estimate through a more complete instrument model. Moreover, a first analysis of the instrument systematic effects will be carried out thanks to the development of a BreadBoard Model.

One of the main remaining points that will have to be solved, is the subtraction of the residual atmosphere emission. At an altitude of 40 km, the atmospheric pressure is of the order of 3 mbar. Its emission will create a large photon noise contribution with respect to the extremely faint signal that we are trying to observe[22] , 2 to 3 orders of magnitude higher that the non-relativistic y-distortion signal, depending on the frequency. In theory, assuming a perfectly reliable model, this contribution could be removed.

More importantly, will be the variations of the atmosphere with altitude, observation elevation and time. This cannot be easily modelled and will therefore need a way to modulate/monitor the atmosphere at a high enough frequency to be compatible with the variation timescale. Such potential solutions will be investigated during Phase A. One possibility might rely on the advantage of having two sub-bands. This will allow us to increase the number of the smaller high frequency detectors, therefore giving us an information (monitoring) of the atmosphere emission variation across a larger field of view.

Furthermore, the effect of various observation strategies have started to be implemented as these will have a direct impact on the mission concept. Example results are also given in a separate contribution to these proceedings[18] .

6.1 Cryogenic BreadBoard

Thanks to a successful funding application to the DIM-ORIGINES programme from Région Ile de France[23] , a cryogenic BreadBoard Model (BBM) of *BISOU* will be developed in parallel to the Phase A work. This laboratory BBM, representative of the instrument concept, will include prototypes of key sub-systems in order to tests their performance. Once validated, some of these will be directly transferred and integrated to the future real instrument. This system is being defined, and will rely on a fairly large cryogenic system with a 2 to 4 K plate of about 1 m×0.6 m dimensions.

In addition, its entrance optical port will be used to tests filters and windows properties. The system containing the cryogenic BBM will also be coupled to a second chamber where the atmospheric pressure can be regulated, and including single frequency / broadband sources to test the BBM in flight-like conditions. The variability of the residual atmospheric emission, and its effects on the measure, will also be studied.

Unlike imaging polarimeters aiming at measuring B-mode polarisation of the CMB that have been studied for many years, systematic effects of a spectrometer for spectral distortions detection, mainly from a balloon platform, are not well-known. Beyond the effects of the residual atmosphere, we suspect that the main sources of systematics will come from the emission of the warmest components in the optical path (Dewar window and spectral filters), and the temperature/emission stability of the calibrator to which the measurement will be compared to. The BBM will allow for instrument systematics studies ahead of the development of the *BISOU* payload.

6.2 Calibration

Once this project goes through the final selection at the end of the Phase A, it is clear that a thorough calibration plan needs to be in place. The study of an in-flight calibration strategy (additional source that could be included in the optical path) will be performed during Phase A. With respect to the ground-calibration, one major advantage of a balloon project is that the performance characterisations of *BISOU* can be perform in near-operational conditions. Here, the idea would be to re-use the cryogenic system developed for the BBM as a Ground Segment Equipment (GSE) in which sources to simulate the sky signals will be located, in order to couple it in front of the *BISOU* entrance window to illuminate the future instrument.

7. CONCLUSION

Assuming that the atmospheric emission subtraction for the signal can implemented for *BISOU*, no show-stoppers have been identified in order to develop a first pathfinder balloon experiment for the first observations of the CMB spectral distortions. This experiment will not be limited to a technological demonstrator for future space missions, but will be able to perform measurements of the CMB y-distortion monopole for the first time, with at least a 5 to 6 σ detection, as well as a better characterisation of the CIB emission.

Providing that all the remaining points are solved during the two-year Phase A study, and that the project is selected for development, a first test (short) flight could happen in summer 2029, with a first longer transatlantic science flight between Kiruna and Canada in summer 2030 or 2031.

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