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Telescope baffling for CMB Polarization experiment SWIPE/LSPE

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We present the design and optimization of the forebaffle for the SWIPE telescope, the balloon-borne bolometric instrument of the LSPE mission. LSPE–SWIPE is designed to measure the polarization of the Cosmic Microwave Background on large angular scales. The low amplitude of the target signal makes the experiment particularly sensitive to stray light contamination and other optical systematic effects. Several forebaffle geometries, dimensions, and surface treatments have been studied through electromagnetic simulations of the telescope beam. The resulting angular responses are analyzed with the *litebird_sim* framework, which allows the generation of synthetic sky signals and their convolution with the telescope beam. This preliminary approach enables us to create a pipeline to estimate the impact of forebaffle design and modeling choices on the reconstructed sky maps and angular power spectra.

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1. Scientific case

The Cosmic Microwave Background (CMB) is a fundamental probe of modern cosmological observations, providing unique insight into the physical conditions of the Universe during the epoch of recombination, when photons decoupled from matter and the Universe became transparent to radiation. Observed today as a nearly perfect blackbody, with a temperature of approximately $T = 2.725$ K [1], the CMB shows small temperature anisotropies at the level of 10^{-5} [2]. The CMB also exhibits a weak linear polarization produced by Thomson scattering between photons and free electrons. This polarization arises when free electrons scatter radiation that possesses local quadrupole anisotropies, generated by velocity gradients and inhomogeneities in the photon–baryon fluid at the time of recombination. The polarization pattern can be decomposed into two components based on their symmetry properties: E-modes, characterized by curl-free, parity-even morphologies, and B-modes, characterized by divergence-free, parity-odd morphologies [3]. CMB polarization is dominated by E-mode, which is primarily generated by scalar density perturbations in the primordial Universe. In contrast, B-mode polarization can arise either from tensor perturbations, in the form of primordial gravitational waves or from the gravitational lensing of E-modes from large-scale structure. The primordial B-mode signal is particularly interesting, since it would provide direct evidence for inflation, which is an early phase of accelerated expansion of the Universe that predicts a stochastic gravitational wave background whose amplitude is parameterized by the tensor-to-scalar ratio r. A measurement of this component would directly probe the inflationary energy scale. Current observations have placed upper limits on r, but no definitive detection has been achieved, as reported in [4]. At large angular scales, where the lensing B-mode signal is mostly subdominant to the primordial signal, the contamination is represented by polarized galactic foreground, which is primarily synchrotron emission at low frequencies and thermal dust emission at high frequencies. These signals are larger than the expected primordial signal by orders of magnitude. In addition, instrumental systematic effects represent a potentially critical limitation for B-mode measurements. Spurious polarization can arise from beam asymmetries, sidelobe pickup, stray light contamination, and imperfect calibration of the angular response of the telescope. For this reason, the detection of primordial B-modes requires high detector sensitivity and also an exceptional level of control over the optical response and related systematic effects.

2. The SWIPE experiment

The Short-Wavelength Instrument for the Polarization Explorer (SWIPE) [5] is the balloon-borne component of the Large-Scale Polarization Explorer (LSPE), which is a program dedicated to the measurement of the polarization of the CMB on large angular scales, with the primary goal of detecting primordial B-mode polarization. SWIPE is a bolometer-based polarimeter (Fig. 1) designed to achieve high sensitivity at large angular scales. The instrument employs a refractive optical system based on a single cryogenic lens with an aperture of 44 cm. The telescope provides a field of view of ±10°. The optical system is designed to illuminate two curved focal surfaces. These host a total of 330 multi-mode bolometric detectors operating in three frequency bands centered at 145, 210, and 240 GHz [5]. The use of multi-mode detectors allows each pixel to collect multiple spatial modes, increasing the per-pixel throughput and thus the sensitivity under

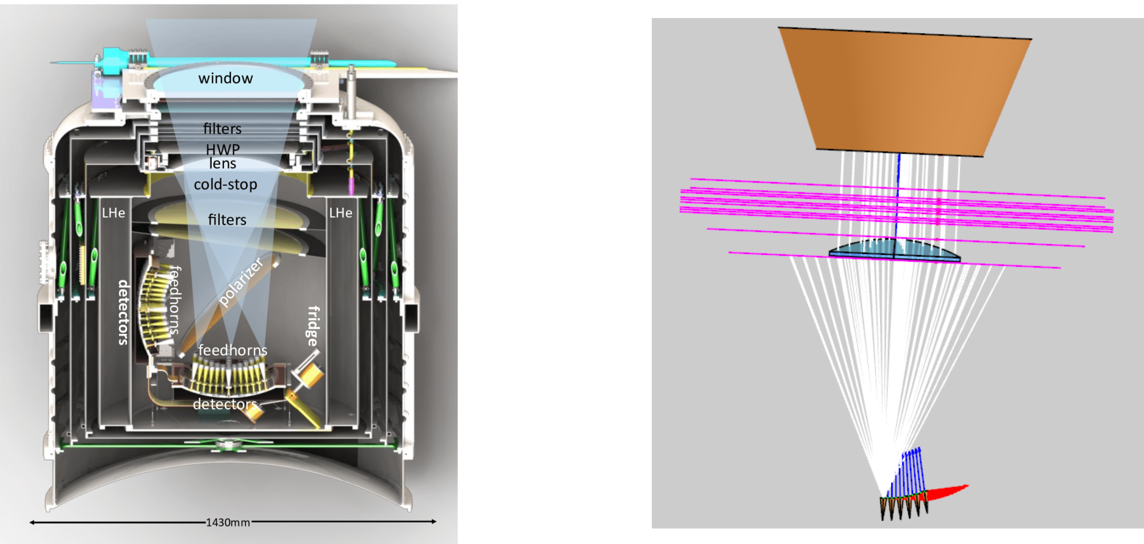

Figure 1: (left) Overview of the LSPE/SWIPE instrument [5].
(right) GRASP simulation of the optical system; the orange structure is the forebaffle, and the feed is placed in the center pixel of the focal surface.

photon-noise–limited conditions. The detectors are cooled to a base temperature of approximately 0.3 K [6]. Polarization modulation is achieved through a cryogenic Half-Wave Plate (HWP) placed ahead of the optical chain, operating at a temperature of 4 K [5]. The HWP is rotated continuously, modulating the incoming linear polarization signal. This modulation strategy shifts the polarized sky signal to higher temporal frequencies, mitigating the impact of low-frequency noise and instrumental systematics. The wide frequency coverage, polarization modulation, and multi-mode bolometric detectors make SWIPE suited for large-scale CMB studies and separating cosmological and polarized foreground signals. In particular, the experiment aims to reach a sensitivity sufficient to establish an upper limit of $r < 0.015$ [5].

3. Forebaffle design

We performed detailed electromagnetic simulations to study the optical system, with particular emphasis on beam response and stray light contamination. Stray light is defined as any unwanted radiation reaching the focal plane of an imaging system. It can originate from bright astrophysical or terrestrial sources. Even when these sources lie far outside the nominal field of view, their radiation can enter the instrument through sidelobes or diffraction effects, contaminating the measurements and potentially masking the faint cosmological signal. The first step in mitigating this effect is the accurate simulation of the propagation of radiation through the optical system. This has been performed using the GRASP software package [7]. It is based on the calculation of induced surface currents: starting from an incident electromagnetic field, placed on the focal surface, the software computes the currents induced on each surface and, from these, it derives the radiated or reflected field. To reduce computational complexity, several simplifying assumptions are adopted. The radiation is assumed to be monochromatic, at a reference frequency of 150 GHz, and some optical elements, such as the polarization modulator, the beam splitter, and the second focal plane are not

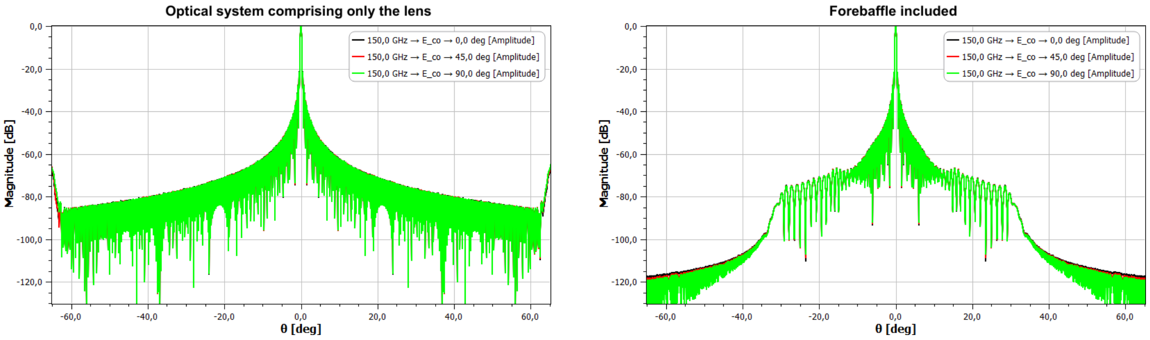

Figure 2: (left) Lens-only configuration. (right) Forebaffle included.
Simulated angular response of the center pixel of the field of view showing the effect of the forebaffle. The lines represent the beam in spherical coordinates (θ, φ), cut at $\varphi = 0°$ (black), $\varphi = 45°$ (red) and $\varphi = 90°$ (green).

included. Using this approach, the angular response of the telescope is studied as a function of the feed position on the focal plane. The results are represented as the magnitude of the power associated with the copolar field E: $dB = 20log|E|$, it is shown as a function of the angle. An external optical element is then introduced to suppress stray light contamination: the forebaffle. It is a shielding structure that surrounds the cryostat aperture and is placed ahead of the telescope window. Its function is to block radiation arriving from angles larger than a defined cut-off angle, while allowing radiation coming from the nominal field of view. Radiation incident at angles larger than the cut-off interacts with the inner surface of the forebaffle and is suppressed. The forebaffle is modeled as a metallic structure, shaped as a truncated cone, with a reflective exterior and an absorptive internal coating. The entire optical chain comprising the forebaffle, used for the GRASP simulation is shown in (Fig. 1). The effect of the forebaffle is clearly visible in the simulated angular response: the system response is suppressed beyond a characteristic angular scale, referred to as the cut-off angle. Radiation originating at angular scales larger than this cut-off does not contribute to the detected signal, as shown in (Fig. 2). The dependence of the cut-off angle on the forebaffle geometry is studied by varying its dimensions. To suppress diffraction from the outer edge of the forebaffle, a flared profile is introduced, with an outward curvature defined as a multiple of the wavelength. The most realistic simulation is performed using the actual multi-mode feed of the instrument at 150 GHz. The horns accept 26 electromagnetic modes, each of which is propagated independently through the optical system. For each mode, the electric field and the corresponding intensity are computed, and the total beam is obtained by incoherently summing the intensities of all modes. This procedure allows reconstruction of the full angular response as a function of θ and φ, providing the most accurate description of the instrument beam in the presence of a forebaffle with a cut-off angle of 35°. The cut-off was chosen to exclude bright sources at the specific angular scales they subtend relative to the instrument line of sight during observations. It will be refined based on materials, payload weight, and flight design. This result is presented in (Fig. 3). The rim dimensions are optimized for a single frequency, so diffraction mitigation may vary at other frequencies, and including internal reflections from the HWP, beam splitter, and second focal plane could raise sidelobe levels. These effects will be addressed in a future refined iteration of the simulation.

4. Map simulation

Once the angular response of the telescope has been characterized, it can be used to simulate the maps that would be observed and to derive the corresponding measurable angular power spectra. This procedure has been implemented using the $litebird\_sim$ framework [8], which was originally developed for the LiteBIRD satellite mission [4] and is well suited for CMB polarization studies. The framework allows the generation of synthetic sky signals and their convolution with the telescope beam. The simulation starts from the angular response obtained from GRASP simulations. The beam is first expanded in spherical harmonics by computing its harmonic coefficients. Independently, a synthetic sky signal is generated, producing a realization of the CMB temperature and polarization fields. The sky signal is then transformed into harmonic space by computing its spherical harmonic coefficients. For each multipole, the harmonic coefficients of the sky are weighted by those of the beam, introducing the filtering effect of the instrumental response. After the harmonic-space convolution, the filtered coefficients are transformed back into real space to obtain simulated observed maps. From these maps, the angular power spectra are computed by decomposing the signal into spherical harmonics and separating the temperature and polarization components. To estimate the statistical properties of the reconstructed spectra, the simulation is repeated using multiple independent realizations of the CMB sky. In this work, 10 different sky realizations have been generated, and the corresponding temperature power spectra have been extracted. For each multipole, the mean value and the standard deviation of the spectra are computed, providing an estimate of the expected variance. Limited set of realizations only gives a preliminary estimate that may underestimate low-multipole variance. Simulations have been performed using the multi-mode feed presented, including a forebaffle with a cut-off angle of 35°. The result (Fig. 3) is consistent with theoretical expectations, within the limitations imposed by the simplifications. The multi-mode feed combines feeds incoherently, which destroys the phase information needed to compute reliable polarization spherical harmonic coefficients. A new convolution approach is being developed to address this limitation. The software architecture also allows the simulation of the sky signal to be extended to include noise and astrophysical foregrounds, as well as CMB realizations generated for different values of the tensor-to-scalar ratio r. This framework therefore provides a flexible and powerful tool for quantifying how optical design choices and stray light suppression strategies affect the measurement of CMB temperature and polarization power spectra.

5. Conclusions and future work

The forebaffle is a key element in controlling beam sidelobes and the angular response of the instrument. The presence of the forebaffle does not affect the polarization properties of the signal for the center pixel, as its axially symmetric design and polarization-independent materials do not introduce differential effects between orthogonal polarization states. The optimal configuration identified is a truncated-cone geometry with a curved outer edge, a reflective exterior, and an absorbing interior, effectively suppresses off-axis radiation while preserving the main beam. The adopted pipeline allows optical design modifications to be propagated up to the reconstructed spectra, enabling validation of design choices before the payload construction. Future work will focus on optimizing the forebaffle geometry and materials to achieve the required sensitivity and

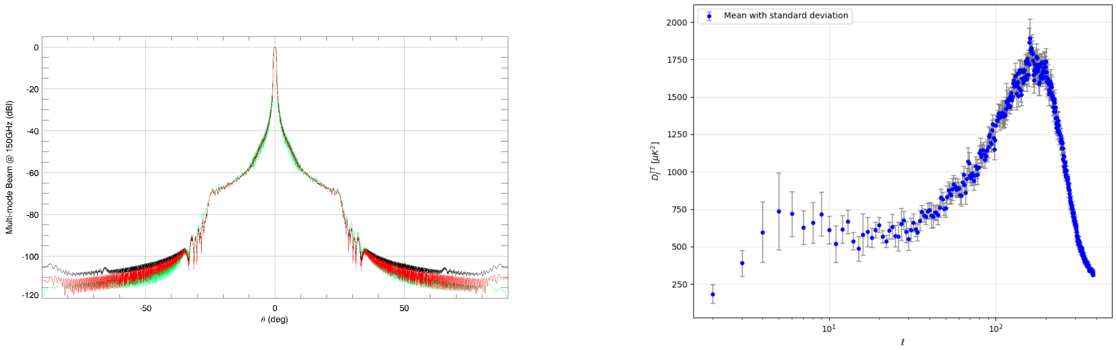

Figure 3: (left) Multi-mode angular response of the center pixel with forebaffle. The lines represent the beam in spherical coordinates (θ, φ), cut at $\varphi = 0°$ (black), $\varphi = 45°$ (red) and $\varphi = 90°$ (green).
(right) Simulated temperature angular power spectrum.

systematic control, as well as on implementing a time-domain convolution that incorporates the scanning strategy, taking into account the beam orientation on the sky and allowing the effects of beam rotation and polarization modulation to be evaluated.

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