Out-of-band rejection requirements for LiteBIRD Medium and High Frequency Telescopes.

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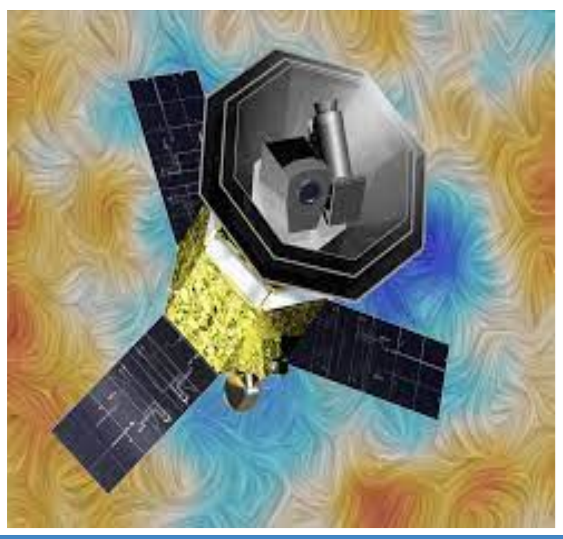

Scientific context:

LiteBIRD, the Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection is a JAXA-led Strategic Large-Class mission, selected by ISAS/JAXA in 2019 to be launched by the end of the 2020s, and aimed at mapping the cosmic microwave background (CMB) polarized emission over the full sky at large angular scales [1]. As the fourth generation of CMB space missions, after Planck, LiteBIRD is targeting the measurement of the CMB B-mode signals, which are known to be the best probe of the primordial gravitational waves generated during the first period of our Universe′s history, as predicted by the cosmological inflation theory. These B-modes are large-scale curl patterns imprinted in the CMB by the primordial gravitational waves, and characterized by a power spectrum whose amplitude is directly proportional to the tensor-to-scalar ratio (called r), which is related to the inflationary energy scale. Their detection would allow us to test major inflationary models and directly access the energy of inflation.

Project:

The development of the Medium- and High-Frequency Telescopes (MHFT), covering observational frequencies from 89 to 448 GHz, is taken in charge by Europe [2]. The challenging scientific requirements of LiteBIRD imply stringent technical requirements to reach a high sensitivity and an unprecedented control of the instrumental systematic effects. The objective of this work is to derive the requirements for the out-of-band rejection, and define the filtering strategy of the two telescopes.

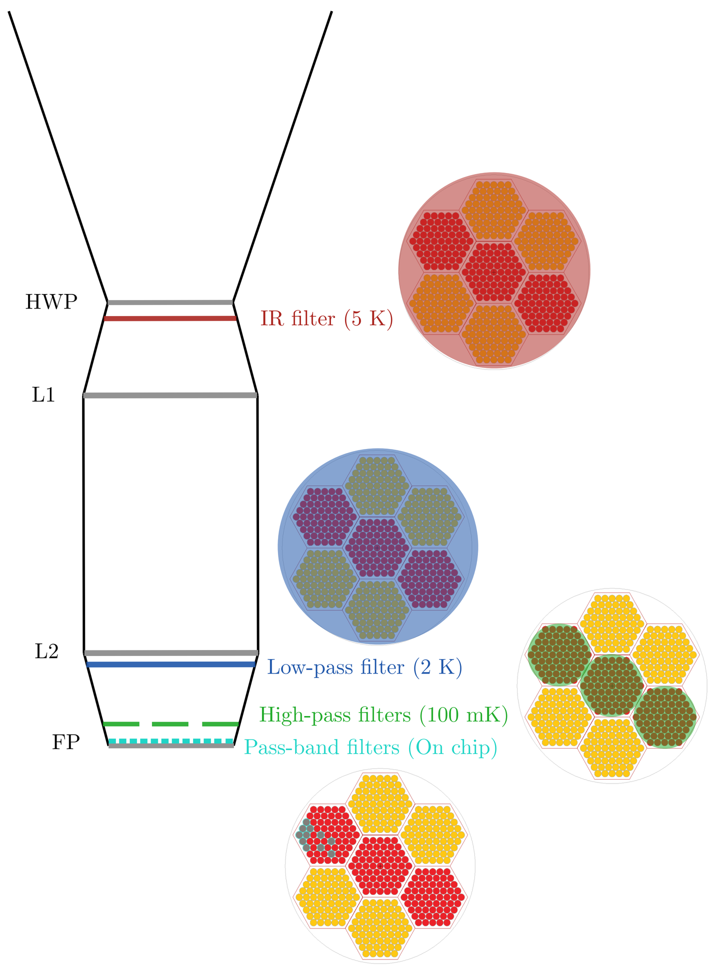

Figure 1: Available filters for MHFT.

Instrument model:

MFT and HFT share both the same optical and mechanical designs. They consist in refractive telescopes with two plastic lenses with assumed index of refraction n = 1.52. The diffraction-limited field of view is 28 deg. A continuously rotating half-wave plate (HWP) is placed at the entrance of the telescope, maintained at 20 K. Optical properties along the spectrum are simulated in terms of emissivity, reflectivity and efficiency which are related through:

$$E + R + \varepsilon = 1$$

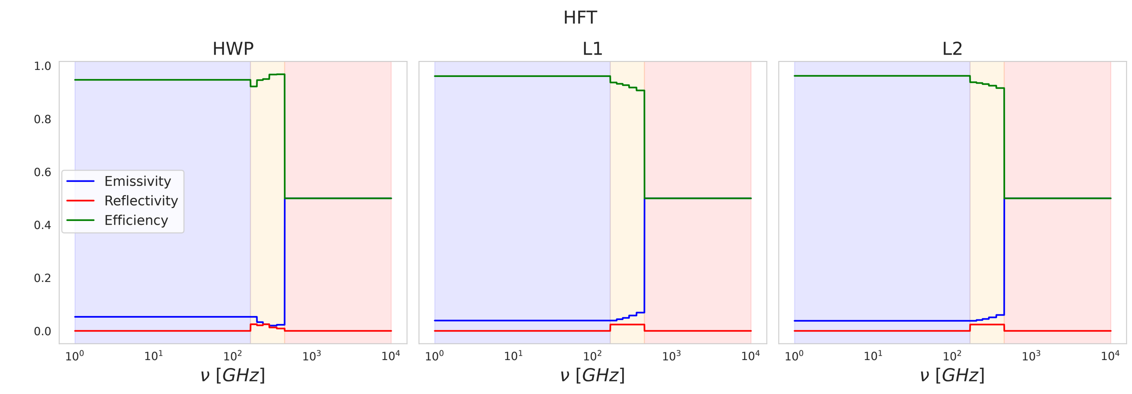

Figure 2: Optical model for the HFT half-wave plate and lenses.

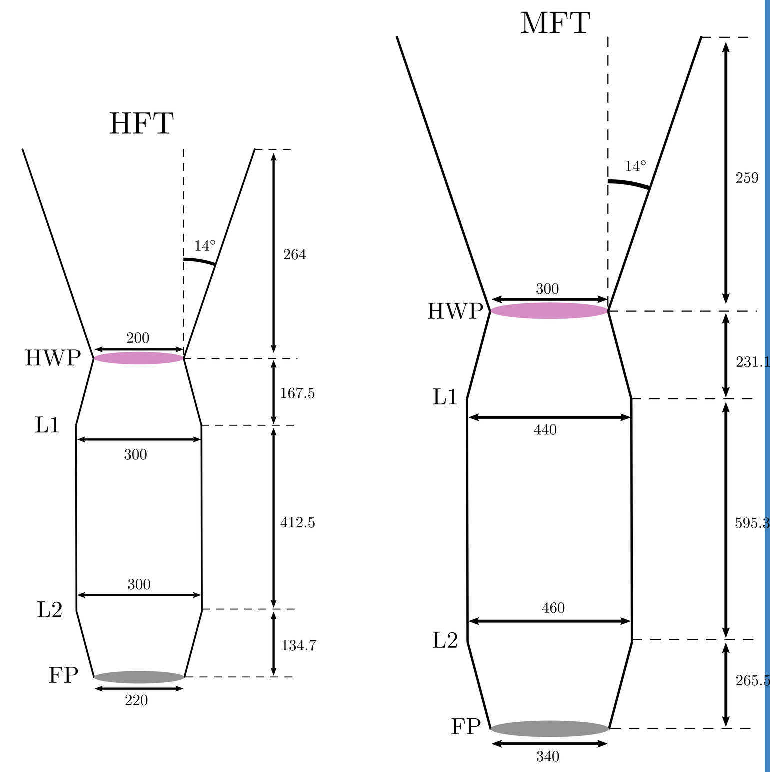

Figure 3: MHFT model and dimensions.

Sky model:

Five components are considered: CMB, thermal Galactic dust, synchrotron, Inter-Planetary Dust (IPD) and brilliant stars (OB). The spectral densities are shown in Figure 4, considering frequencies from 1 GHz to 100 THz. The amplitude of each component is scaled using available measurements, considering the maximum intensity in order to be conservative when setting requirements. To detect the maximum intensity, we first smooth the map at the LiteBIRD resolution. Depending on the study, we consider the total field of view which is 28 deg for MHFT (dash lines) or the beam FWHM which is specific to each frequency channel (solid lines).

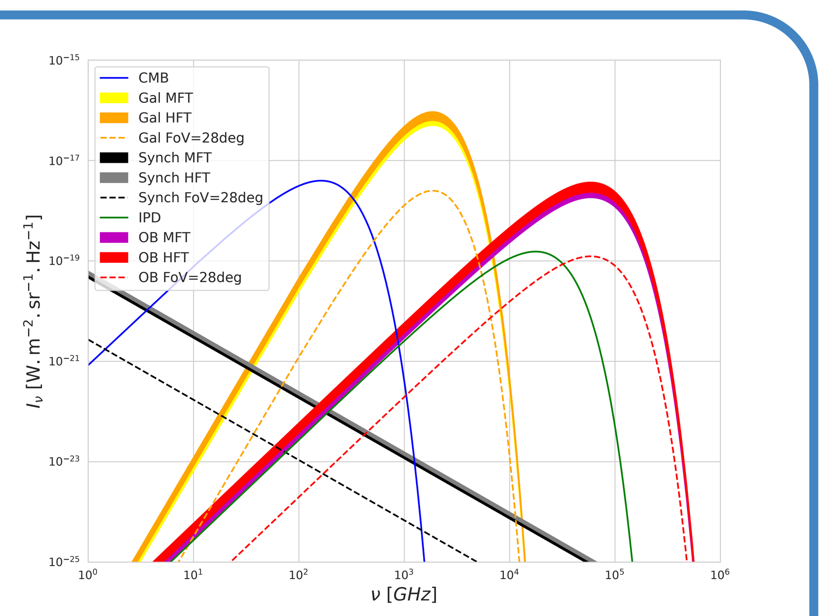

Figure 4: Spectral densities of the five sky components.

Requirements from detector contraints:

We first compute an estimation of the optical power arriving on the detectors in the four frequency domains defined in Figure 5: lower-frequencies, detector-band, complementary-band and higher-frequencies. We consider the five sky contributions and the power from optical components (HWP and the two lenses L1 and L2) and from the mechanical structure (the aperture and the tubes at 5 K and 2 K), modeled as black-bodies. Then, the power in Watt falling on detectors from a given component c, in one of the fourth frequency domains d, for one detector channel i, is equal to:

$$P_{c,d,i} = S\Omega_i \int_{\nu_{\mathrm{min,d}}}^{\nu_{\mathrm{max,d}}} E_c(\nu)\varepsilon_{c\to\mathrm{det}}(\nu) I_{c,i}(\nu)\mathrm{d}\nu$$

where S is the collector area, taken as the HWP surface, Ω_i is the solid angle, $I(\nu)$ is the spectral density, $E_c(\nu)$ is the emissivity of component c and $\varepsilon_{c\to\mathrm{det}}(\nu)$ is the efficiency of optical elements along the optical path between component c and the detector.

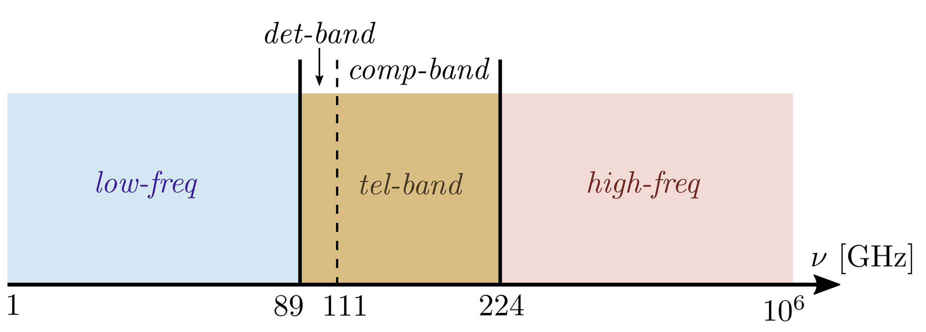

Figure 5: Sketch showing the four frequency domains.

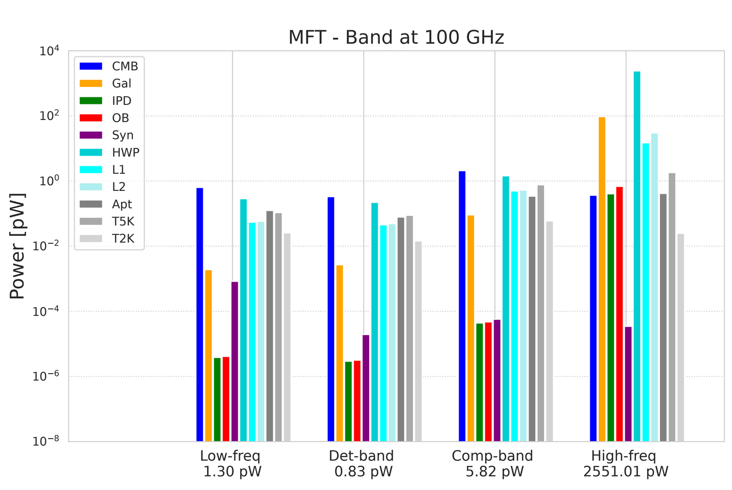

Figure 6: Powers falling on one MFT 100 GHz detector.

In order to derive requirements from the power estimation, we consider:

- the impact of out-of-band power on the detector Noise Equivalent Power (NEP) which defines the instrument sensitivity,
- the impact on component separation.

In this way, we derive attenuation factors needed for each frequency domain in order to achieve the precision required on the tensor-to-scalar ratio.

Requirements from thermal heat-load constraints:

The evaluation and the control of radiative heat-load in the instrument is important for two reasons. First, the total heat-load will increase the instrument temperature and so its radiative power. This is something we want to avoid to minimize the power arriving on the focal plane and so the needed cool down capacity. Secondly, the measurement is highly sensitive to thermal fluctuations because it will generate 1/f noise.

The radiative power on each optical element (HWP, L1, L2 and the focal plane), is calculated through:

$$P_{c_1\to c_2,d} = S_{c_2}\Omega_{c_1\to c_2} \int_{\nu_{\mathrm{min,d}}}^{\nu_{\mathrm{max,d}}} E_{c_1}(\nu)\varepsilon_{c_1\to c_2}(\nu) A_{c_2}(\nu) I_{c_1}(\nu)\mathrm{d}\nu$$

where c_1 is the emiting component, c_2 is the receiver element and d is the frequency domain. The spectral density $I_{c_1}(\nu)$ is integrated over the domain frequency range. $S\Omega$ is the optical extent. The spectral density is multiplied by the emissivity $E_{c_1}(\nu)$ of the emitting component, the efficiency $\varepsilon_{c_1\to c_2}(\nu)$ of optical elements along the light path, and the absorption $A_{c_2}(\nu)$ of the receiver (equal to its emissivity).

Figure [7] shows the powers received by the HWP, from sky components and radiated by the instrument itself. We distinguish three frequency domains: the telescope band, higher frequencies and lower frequencies (see Figure [5]). Optical extents are derived for each pair of emitting/receiving components, as illustrated in Figure [8].

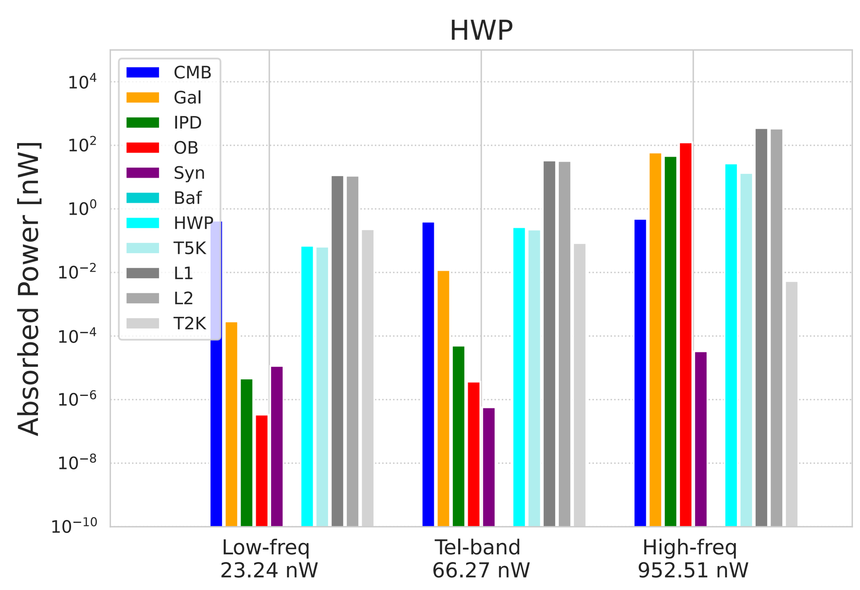

Figure 7: Powers received by the HWP.

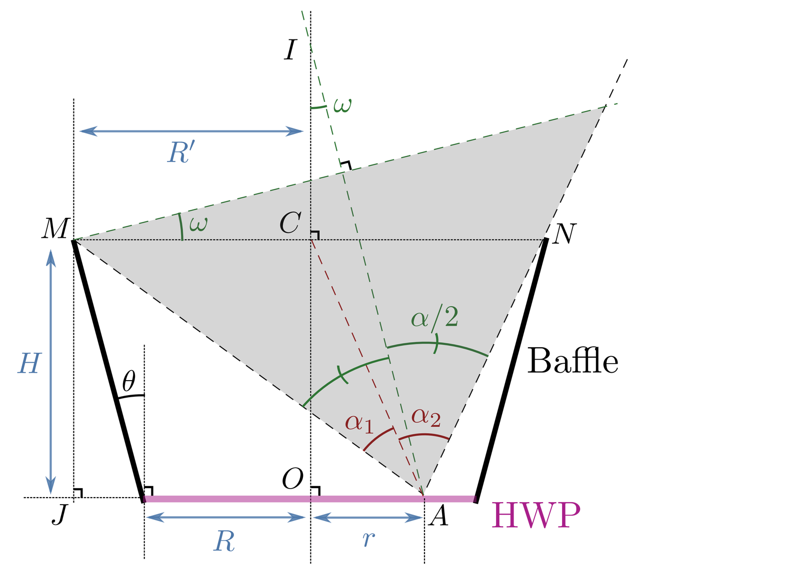

Figure 8: Solid angle under which point A on the HWP sees the sky.

$$\Omega(r) = \int_0^{2\pi}\int_0^{\alpha(r)/2} \cos(\omega(r))\sin\theta\,\mathrm{d}\theta\mathrm{d}\varphi$$
$$= 2\pi\sin\left[\arctan\left(\frac{H}{R'+r}\right) + \frac{\alpha(r)}{2}\right]\left(1-\cos\left(\frac{\alpha(r)}{2}\right)\right)$$

References:

[1] LiteBIRD Collaboration, *Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey*, Feb. 6, 2022. ArXiv: 2202.02773.

[2] L. Montier, B. Mot, et al., *Overview of the Medium and High Frequency Telescopes of the LiteBIRD satellite mission*, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, p. 250, Dec. 15, 2020. DOI: 10.1117/12.2562243.