LiteBIRD

Hirokazu Ishino

*Department of Physics, Okayama University, 3-1-1
Tsushimanaka, Kita-ku, Okayama 700-8530, Japan
scishino@s.okayama-u.ac.jp*

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We present LiteBIRD, a satellite project dedicated for the detection of the CMB B-mode polarization. The purpose of LiteBIRD is to measure the tensor-to-scalar ratio r with a precision of $\sigma_r < 0.001$ to test large-single-field slow-roll inflation models by scanning all the sky area for three years at the sun-earth L2 with the sensitivity of $3.2\mu\text{K}\cdot\text{arcmin}$. We report an overview and the status of the project, including the ongoing detector and systematic studies.

Keywords: CMB; B-mode Polarization.

1. Introduction and LiteBIRD science goal

The gravitational waves generated during the inflation imprinted the B-mode polarization in the cosmic microwave background (CMB). Measuring the intensity of the primordial gravitational waves may reveal the mechanism why the inflation happened. The intensity is represented as a single parameter r , tensor-to-scalar ratio. Most of the large-single-field slow-roll inflation models predict $r > 0.002$ with the relation:

$$r \simeq 0.002 \left(\frac{60}{N} \right)^2 \left(\frac{\Delta\phi}{m_{\text{pl}}} \right)^2, \quad (1)$$

where N is the e-folding number of the inflation expansion, $\Delta\phi$ is the change of the inflaton, and m_{pl} is the Planck mass. The current most stringent upper limit of r is obtained to be $r < 0.07$ at the 95% confidence level.¹

LiteBIRD is a next generation satellite aiming to measure the ratio r with a precision of $\sigma_r < 0.001$ at the 1σ confidence level, providing a crucial test of the inflation models^{23,4}. The satellite will scan all the sky area for three years at the sun-earth L2 point with the sensitivity of $3.2\mu\text{K}\cdot\text{arcmin}$ to probe the B-mode power

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spectrum in the angular multi-pole range of $2 \leq \ell \leq 200$ that includes the large angular scales where the re-ionization bump is prominent. Figure 1 shows the anticipated LiteBIRD sensitivity as a function of the multipole moment with the B-mode power spectra of various inflation models. LiteBIRD will measure the frequency range of $40 \sim 400$ GHz with 15 bands using two telescopes consisting of the reflective and refractive optical systems with the focal planes that mount arrays of 2276 superconducting detectors. The wide band range is needed to remove the foreground components with a 99% level, which has been demonstrated by a template method⁵ and a parametric method.⁶ Systematics caused by the uncertainties of the differences in the beam pointing, the gain and the beam features are mitigated using a polarization modulator, i.e., a continuously rotating Half Wave Plate (HWP).

In this report, we describe details of the LiteBIRD mission components consisting of an optical system and superconducting detectors as well as the scan strategy and systematics.

2. LiteBIRD satellite system

2.1. Overview

Figure 2 shows an overview of the satellite. The satellite consists of the mission module and the bus module. The mission module contains the optical systems consisting

Fig. 1. Anticipated LiteBIRD sensitivity. The red curve is the LiteBIRD sensitivity. Colored lines are the predictions of various inflation models. The thick black line is a sum of the B-mode power spectra of the primordial gravitational waves with $r = 0.002$ and the lensing.

Fig. 2. Overview of the satellite system. Details are described in the text.

of telescopes, polarization modulators and focal plane detector arrays, refrigerators and readout systems. The bus module comprises of the satellite control systems of the attitude, the electric power and the data transfer between the satellite and the ground stations. The mission module revolves on the bus module with 0.1 Revolution Per Minute (RPM) using a slip ring to provide the spin rotation of the boresight slanted by 30 degrees with respect to the spin axis.

The left figure in Fig. 3 shows details of the mission module. In the figure, we only show the Low Frequency Telescope (LFT) that consists of a modified Crossed-Dragnone (CD) system offering a telecentric optics with a large Field Of View (FOV) of 20×10 degree square. At the aperture of the optical system, we locate a HWP to have the polarization modulation that mitigates the $1/f$ noise and systematics. On the focal plane an array of superconducting detectors is mounted at the temperature of 0.1 K provided by an Adiabatic Demagnetization Refrigerator (ADR). The two mirrors in the LFT and the HWP are cooled down to 4 K to reduce the thermal photon shot noise. The right figure in Fig. 3 shows a conceptual design of the LFT and the High Frequency Telescope (HFT). The cryogenic system consisting of Joule-Thomson and Stirling cooler systems as well as the ADR generates the low temperature environment in the mission module.

2.2. Telescopes

The LFT is a reflective telescope using two mirrors. The original CD system employs a parabolic (hyperbola) shape for a primary (secondary) mirror. In the modified CD system, the shapes of the mirrors are optimized to be 5th order polynomial

Fig. 3. (Left) The mission module. (Right) Two telescopes with the focal planes. Details are given in the text.

to provide a large FOV and a degree scale beam size in the frequency range of $40 \sim 235$ GHz with a compact size of $\phi 1.8 \text{ m} \times t 1.8 \text{ m}$. The CD system is known to be susceptible to the stray light caused by multiple reflections. We place a baffle at the aperture to remove the stray light. A simulation using GRASP10 with the baffle proves that the side-lobes caused by the stray light are reduced down to -60 dB. The HFT is a refractive telescope using two lenses to cover the higher frequency range of $280 \sim 402$ GHz with the FOV of 10×10 degree square. Both telescopes have a continuously rotating HWP that modulates the polarization.

2.3. Focal plane detector

Two options are being considered as a candidate of the focal plane detector array: Transition Edge Sensor (TES) bolometers and Microwave Kinetic Inductance Detectors (MKID). TES bolometer arrays are used in the ground CMB experiments that have detected lensing B-mode polarization. While MKID is a relatively new technology, the R&D of the MKID is rapidly progressing.⁷ At the current stage, we consider TES bolometer arrays as a baseline design.

On the focal plane of the LFT, tri-chroic 337 detector pixels are placed^{8,9}. Each detector pixel is covered with a lenslet made of silicon with anti-reflection coating.¹⁰ Light focused by the lenslet is translated to the electric signal power with a sinuous antenna that has a sensitivity to two orthogonal polarizations. The power of one polarization signal is divided into three through band path filters and detected by three TES bolometers. The bandwidth each TES bolometer can cover is 23% to 30%, depending on the frequency band. Hence, the LFT focal plane is composed of $337 \times 6 = 2022$ TES bolometers. The HFT has a focal plane containing 127 detector pixels (254 TES bolometers). Each detector pixel measures a single frequency band and two polarizations, and each polarization signal is detected by a single TES bolometer. The incoming light to the HFT focal plane is coupled to the corrugated

Low Frequency Telescope (LFT)

High Frequency Telescope (HFT)

Fig. 4. Low frequency telescope detector array.

Fig. 5. High frequency telescope detector array.

feed-horn design developed for the ABS, ACTpol and SPTpol^{11,12} Figures 4 and 5 show pictures of the detector arrays of the LFT and the HFT.

In total 2276 TES bolometers are used to provide a sensitivity of $3.2\mu\text{K}\cdot\text{arcmin}$ with three margins: the operation time efficiency (0.72), detector yield (0.8) and $1.25\times\text{NET}$ (Noise Equivalent Temperature). Figure 6 shows the sensitivity of the 15 frequency bands as well as the bandwidths.¹³

The TES bolometer signals are read out using a combination of the cold and warm electronics with the frequency domain multiplexing with a factor of 64. The

Fig. 6. Frequency bands for LiteBIRD. The colored bands show the bandwidths of individual bands. The vertical height indicates the sensitivity.

Fig. 7. Scan strategy of the LiteBIRD satellite.

digital active nulling technology allows us to measure the signal with a wide dynamic range^{14, 15}.

3. Scan strategy

The LiteBIRD satellite scans all the sky area with a combination of the spin rotation and the precession at the halo orbit around the sun-earth L2 point. The precession axis rotates around the anti-sun direction with an angle of α , and the spin rotates around the precession axis with an angle of β . Figure 7 shows the scan condition. In order to cover all the sky area while keeping the sun direction out of the main lobe beam, the scan needs to have a condition of $\alpha + \beta \sim 95$ degrees. The spin rate and the precession rate are also the parameters to be optimized. The four parameters are tuned so as to have a uniform hit map in all the sky and small cross link values for all the sky pixels, where the cross link is defined as $\langle \cos 2\theta \rangle^2 + \langle \sin 2\theta \rangle^2$, and θ is the angle between the scan direction and an axis fixed in the sky. With a simulation study, we have found the α in the range of $65 \sim 75$ degrees has the smallest mean value of the cross link. The spin rate is set to 0.1 RPM, equal to 10 minutes per revolution, by taking into account the data transfer rate, reaction wheel capability, star tracker pointing accuracy and satellite mass and power. With the anticipated f_{knee} value of 20 mHz in the $1/f$ noise, we need a continuous rotating HWP to modulate the polarization signal with the rate faster than the $1/f_{\text{knee}}$ time scale. At the present stage, we use the scan parameters as $\alpha = 65$ deg., $\beta = 30$ deg., the spin rate of 10 min. and the precession rate of 90 min. per revolution.

4. Systematics

Table 1 shows the systematics taken into account in the present requirements without the HWP. We obtain the systematic requirements by imposing that each effect causes B-mode power spectrum with an amplitude of 1/100 of that of the lensing effect. Individual systematics are estimated in an analytical manner with the scan

Table 1. Systematics without HWP.

Effects	Types	Requirement (biased)	Requirement (random)	Notes
Diff. beam width	False polarization	0.8% @ $\ell=2$ 0.2% @ $\ell=200$	2%	Instantaneous
Diff. beam pointing		2 arcsec.	20 arcsec.	
Diff. gain ellipticity		7% @ $\ell=2$ 0.04% @ $\ell=300$	3%	Focal plane average eases them by (up to) one order of magnitude
Diff. gain calibration		0.002%	0.04%	
Abs. gain calibration	Pattern modulation	Parity preserved	10%	Calibration in every 10 min.
Beam size stability		Parity preserved	$\mathcal{O}(10\%)$	
Angle calibration		1 arcmin.	10 deg.	
Pointing		3 arcmin.	5 arcmin.	knowledge

Table 2. Systematics comparing with and without HWP.

Effects	Requirement w/o HWP	Requirement w/ HWP
Diff. beam width	0.8 % @ $\ell=2$ 0.2 % @ $\ell=200$	10 %
Diff. beam pointing	2 arcsec.	2 arcmin.
Diff. beam ellipticity	7 % @ $\ell=2$ 0.04 % @ $\ell=300$	10 %
Diff. gain calibration	0.002 %	3%

strategy described in the previous section. The first four items originate from the systematics related with the differential effects, causing a leakage from the temperature to the B-mode polarization. The latter four cause the leakage from the E-mode to the B-mode.

Table 2 compares systematics with and without the HWP. The HWP can relax the requirements imposed by the system specification, as the HWP can modulate the polarization. The temperature to B polarization leakage is different for different HWP modulation angles, while the real polarization signal remains the same independent of the HWP angle, so that the leakage can be canceled out.

5. Status

LiteBIRD is down-selected as one of the strategic large mission candidates by JAXA/ISAS in 2015 for further studies. LiteBIRD proposal by the US group is also down-selected for NASA's missions of opportunity in 2015. The science importance of LiteBIRD is recognized by the Japanese science community; LiteBIRD is selected as one of the prioritized projects in the master plan 2014 by Science Council of

Japan. We continue intensive studies on foregrounds and systematics, as well as thorough studies on technical details of the detector and satellite itself, aiming for the target launch in 2024-2025.

6. Summary

LiteBIRD is a next generation satellite aiming to measure the CMB B-mode polarization with an unprecedented accuracy. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio r with an accuracy of $\sigma_r < 0.001$ at 1σ in the angular multipole range of $2 \leq \ell \leq 200$, providing a crucial test of the single-field slow-roll inflation models. The conceptual design of the LiteBIRD satellite is being studied with respect to the foreground removal and systematic mitigation as well as the satellite specifications.

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