Design of the On-Board Data Compression for the Bolometer Data of LiteBIRD

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Abstract
LiteBIRD is a space-borne experiment dedicated to detecting large-scale $B$-mode anisotropies in the linear polarization of the Cosmic Microwave Background (CMB) predicted by the theory of inflation. It is planned to be launched in the late 2020s to the second Lagrange point (L2) of the Sun-Earth system. LiteBIRD will map the sky in 15 frequency bands. In comparison with Planck HFI, the previous low-temperature bolometer-based satellite for CMB observations, the number of detector has increased by two orders of magnitude, up to $\sim 5000$ detectors in total. The data rate is 19 Hz from each detector. The bandpass to the ground is limited to 10 Mbps using the X-band for a few hours per day. These require the data to be compressed by more than 50%. The exact value depends on how much information entropy is contained in the real data. We have thus evaluated the compression by simulating the time-ordered data of polarization-sensitive bolometers. The foreground emission, detector noise, cosmic ray glitches, leakage from the CMB intensity to polarization, etc., are simulated. We investigated several algorithms and demonstrated that the required compression ratio can be achieved by some of them. We describe the details of this evaluation and propose algorithms that can be employed in the on-board digital electronics of LiteBIRD.

Keywords  TES · Digital signal processing · Space applications

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1 Introduction

LiteBIRD is a satellite dedicated to observing the anisotropy of the linear polarization of the Cosmic Microwave Background (CMB). It aims to detect the $B$-mode pattern at a large angular scales ($\ell < 200$) to constrain the theory of inflation. The mission is expected to achieve the sensitivity of the tensor-to-scalar ratio $\delta r \leq 0.001$ in order to discriminate physically well-motivated models. The satellite is planned to be launched in the late 2020s by JAXA and is designed by a collaboration of many institutions worldwide [6].

LiteBIRD has three telescopes (LFT [12], MFT, and HFT [10]) covering 15 frequency bands over 34–448 GHz. They have in total $\sim 5000$ Transition Edge Sensor (TES) bolometers cooled at 100 mK. Increasing the number of bolometers is essential in modern CMB experiments dominated by photon noise. In spaceborne experiments, the downlink rate from the spacecraft to the ground stations limits the entire data rate. The data compression is thus one of the major functional requirements for onboard data processing units. The algorithm should be developed for each experiment to exploit the features of the bolometer data. Significant efforts were made in Planck HFI [2] and LFI [4, 7, 8] with the trade-off between the cosmological information and the available telemetry rate. This article presents a study on the onboard data compression algorithm for LiteBIRD.

2 Bolometer Data

LiteBIRD has $\sim 5000$ TES bolometers. The TES detectors are operated at a bath temperature ($\sim 100$ mK) under the constant photon loading by the 2.7 K CMB. The differential power is cancelled via thermo-electric feedback with a 3.3 ms time constant [5]. The detectors are read out using SQUIDs by digital frequency-domain multiplexing [3, 9], using an anti-aliasing filter at $\sim 7.5$ MHz followed by sampling at 20 MHz (= 20 M samples/s). The rate is decimated by a factor of $2^{20}$ on board using a series of digital filters consisting of a poly-phase filter bank (PFB), two cascaded integrated comb (CIC) filters, and finite impulse response (FIR) filter using two hardware units at room temperature (Fig. 1 left). The warm readout electronics (WRE) is mainly responsible for fast data processing down to $20M/2^{17} = 153$ Hz using an FPGA, while the payload module data processing unit (PLM-DPU) is for slow and LiteBIRD-specific processing down to $20M/2^{20} \approx 19$ Hz using an FPGA and a CPU. A further downsampling would cause an unacceptable level of systematics in the modulated signal. The data compression algorithm is implemented in the PLM-DPU.

The ADC has a 13-bit resolution (bipolar, 14 bit). The effective bit length increases by 10 bits after a $2^{20}$ decimation. The downlinked data thus have 24 bits of information. The approximate total rate is $5000$ detectors $\times$ 24-bit depth $\times 19$ Hz rate $\times 24$ hours $= 25.9$ GB day$^{-1}$. The available downlink rate is 10 MHz (X-band communication) $\times$ a few (3) hours of contact $= 13.5$ GB day$^{-1}$. We thus
need to achieve a 50% data compression ratio. We prefer to compress the data losslessly, so as not to produce uncontrolled systematic terms.

The incoming signal is modulated by the continuously rotating half wave plate (HWP) at $f_{\text{HWP}} = 46, 39, \text{ and } 61 \text{ rpm} = 0.77, 0.65, \text{ and } 1.02 \text{ Hz (LFT, MHT, and HFT, respectively)}. \text{ The Stokes } U \text{ and } Q \text{ components are modulated at } 4f_{\text{HWP}}, \text{ whereas a part of the } I \text{ component is modulated at } 2f_{\text{HWP}} \text{ due to leakage from } T \text{ (I for CMB) to Polarization by the HWP imperfections (T-to-P leakage). The signal is also modulated by the scanning of the satellite, which combines a spin of 50 degrees in 20 min and a precession of 45 degrees in 3.2058 hr. The entire sky is scanned in half a year as the L2 point rotates around the Sun.}

### 3 Simulation

The compression ratio depends on how much information entropy is contained in the incoming data. This is primarily governed by how we allocate the dynamic range to the 24-bit length. Figure 2 depicts the dynamic range. We set the maximum to accommodate the saturation power ($\times2.5$ of the optical loading) of TES with an ample ($\times5$) margin, which corresponds to 1.9–4.8 pW. For 24 bits, the resolution is $0.22–0.58 \text{ aW bit}^{-1}$ or $\sim0.8–0.9 \mu K_{\text{CMB}} \text{ bit}^{-1}$.

We then simulated time-ordered data (TOD). The foreground components [1] (synchrotron, dust, free-free, and anomalous microwave emission) and the CMB (anisotropy) are given in the map domain using PySM [15] based on Planck observations. We mock-observed the sky using the bolometers in the actual focal plane layout modulated by the satellite scans and the rotating HWP. The CMB dipole was also simulated. We generated the TOD sampled at approximately 153 Hz using TOAST.\(^1\) They are discretized to 24-bit integers. In the time domain, we add the

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\(^1\) [https://github.com/hpc4cmb/toast](https://github.com/hpc4cmb/toast).
detector white noise with a $1/f$ component, cosmic-ray (CR) glitches [14, 16], and T-to-P leakage with the assumed leakage ratio of $10^{-3}$.

We started the mock observation from the vernal equinox for one year for all frequency bands. We focus on days 150 and 270 with the largest variation, in which the scan includes a pole of the CMB dipole and the Galactic center, respectively. In Fig. 3, the left panel shows a 6 s TOD in the 40 GHz band of LFT separately for each component. The total power is governed by the white noise centered at zero, the CR glitches positively biased but not time-resolved, and the T-to-P leakage modeled by $2f_{\text{HWP}}$. The right panel shows a 6000 s TOD in some representative bands. Passages of the Galactic plane are apparent particularly in high-frequency bands.

We calculated the information entropy for the simulated TOD in each day and each band to be 13–16 bits. Here, the information entropy is a quantity to describe how random the data are. If a variable $X$ takes a value $x_1, \ldots, x_n$ with a probability $P(x_1), \ldots, P(x_n)$, the information entropy of $X$ is defined as

$$I(X) = - \sum_{i=1}^{n} P(x_i) \log P(x_i).$$

We calculated the probability $P(x_i)$ based on the normalized histogram of simulated TOD. This is losslessly compressible as the TOD of CMB observations have temporal correlations, which we should exploit. Fortunately, some major components contributing to the information entropy are well-behaved and can be fitted with a simple model. We downlink both the best-fit parameters and the residual TOD so that we can fully reproduce the observed TOD on the ground.
We first tried the linear polynomial fitting employed in many compression algorithms for general use. We optimized the fitting parameters, but this did not work very well. This is because the major component of TOD, the T-to-P leakage, is a cosine curve in nature and is not appropriate to fit to a low-order polynomial. We next tried differential compression, in which the differential of the adjacent two samples is downlinked along with the first sample in a block, so that all samples in the block can be reproduced on the ground. This is effective in removing slowly changing components and yielded sufficient compression. We also exploit the primarily cosine nature of the TOD and fitted it with a function $A \cos (2\omega_{\text{HWP}} t + \phi) + c$, in which $A$, $\phi$, and $c$ are free parameters. The cosine term is intended for the T-to-P leakage component, and the constant term is for slowly varying foreground components and the bias of the CR glitches. We fit a certain length of TOD and subtract the model from the observed TOD. The optimum fitting length (1000 samples = 6.5 s) was chosen by the trade-off between long to constrain the T-to-P leakage parameters and short to catch up with the rapid changes of the foregrounds through Galactic plane passages and the change of $\phi$ as the satellite scans.

We actually applied all these algorithms (polynomial fitting, differentiation, and cosine fitting) to the simulated TOD. We then calculated the residual TOD after fitting or differentiation, which was filtered with the FIR and decimated to

![Fig. 3](left) Simulated TOD for 40 GHz in LFT separately for each component and their total. (right) Simulated TOD in day 150 for some representative frequency (L/M/H is for LFT/MFT/HFT), and the numbers are for the frequency in GHz

![Fig. 4](left) Average encoded length for day 150 (left) and 270 (right) for each frequency. Solid lines represent the results for fitting subtraction and dashed lines for differentiation.
19 Hz. We encoded the 19 Hz residual TOD using a lossless compression (Rice encoding [11]) and added the bit length of the fitting parameters to derive the average bit length. The result for the cosine fitting is shown in Fig. 4 for day 150 and 270. Without fitting, the 153 Hz TOD (“uncompressed”) can be encoded only to an average length of 19 bits. After subtracting the best-fit model (solid line) or calculating differentiation (dashed line), the average length decreases to 13.5 bits at the maximum (“compression”). After FIR filtering and decimation to 19 Hz (“FIR + decimation”) and Rice encoding (“Rice encoded”), the average length is 12 bits, achieving the compression ratio of 50%. Two high-frequency channels using fitting algorithm exceed the 12-bit limit in day 270. However, the length averaged over the entire frequency band weighted by the number of channels is below 12 bit, which is sufficient for our needs. The differentiation algorithm also yielded a similar compression rate (∼50%) with a block size of 24 samples. Each has its own advantages. The trade-off between them with further tuning under onboard resource constraints is a work to be done.

4 Conclusion

In this study, we calculated both the requirement and the achievable value of the data compression ratio in the orbit. In the case of lossless compression, the requirement was derived to be 0.50 from the data rate per channel, the number of channels, the bit length, and the exposure. The achievable value was estimated from the simulated TOD to be as realistic as possible using the currently available design values of the experiment. We investigated several representative algorithms and demonstrated that those based on the differentiation or the cosine fitting of the TOD meet the requirement.

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