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Concept design of the LiteBIRD satellite for CMB B-mode polarization

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Concept design of the LiteBIRD satellite for CMB B-mode polarization

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ABSTRACT

LiteBIRD is a candidate for JAXA's strategic large mission to observe the cosmic microwave background (CMB) polarization over the full sky at large angular scales. It is planned to be launched in the 2020s with an H3 launch vehicle for three years of observations at a Sun-Earth Lagrangian point (L2). The concept design has been studied by researchers from Japan, U.S., Canada and Europe during the ISAS Phase-A1. Large scale measurements of the CMB B-mode polarization are known as the best probe to detect primordial gravitational waves. The goal of LiteBIRD is to measure the tensor-to-scalar ratio (r) with precision of $\delta r < 0.001$. A 3-year full sky survey will be carried out with a low frequency (34 - 161 GHz) telescope (LFT) and a high frequency (89 - 448 GHz) telescope (HFT), which achieve a sensitivity of 2.5 μK-arcmin with an angular resolution of ~ 30 arcminutes around 100 GHz. The concept design of LiteBIRD system, payload module (PLM), cryo-structure, LFT and verification plan is described in this paper.

Keywords: Cosmic microwave background, space program, millimeter-wave polarization, cryogenic telescope

1. INTRODUCTION

LiteBIRD, Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection, observes the cosmic microwave background (CMB) polarization over the full sky at large angular scales.[1–5] Cosmological inflation predicts primordial gravitational waves, which imprinted large-scale curl (B-mode) patterns in the CMB polarization map.[6–9] Measurements of the CMB B-mode signals are known as the best probe to detect the primordial gravitational waves and to measure the inflation energy. The scientific objective of LiteBIRD is to test major inflationary models.[10] The power of the B-modes is proportional to the

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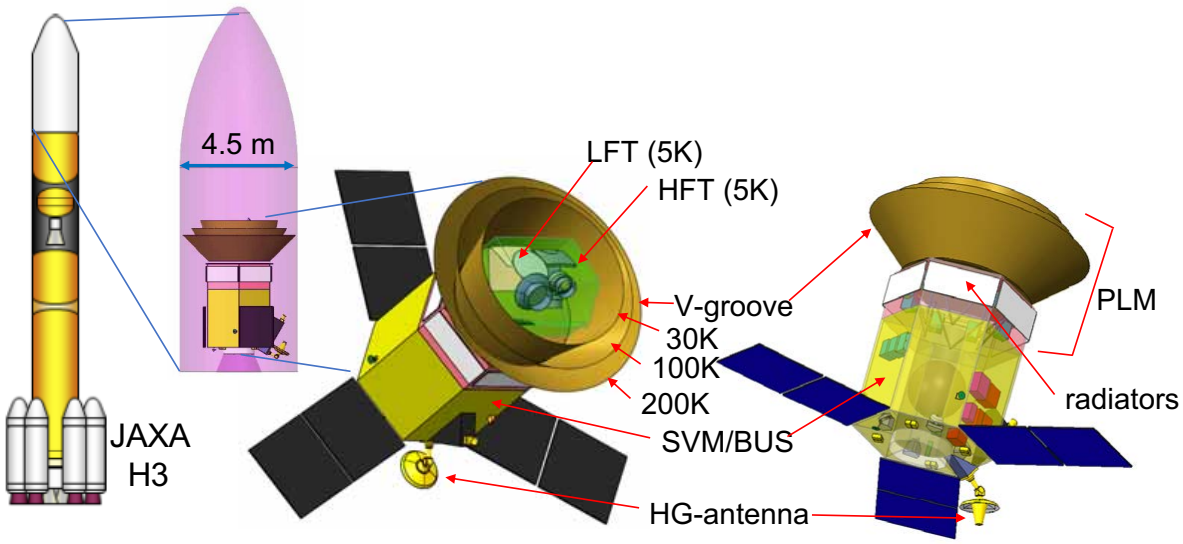

Figure 1. The LiteBIRD spacecraft

tensor-to-scalar ratio, r. The current upper limit on r is $r < 0.07$.[11] The mission goal of LiteBIRD is to measure r with a precision of $\delta r < 0.001$, which provides a crucial test of the cosmic inflation. The required angular coverage is $2 < l < 200$, where l (ell) is the multipole moment.

LiteBIRD is a candidate for JAXA's strategic large mission. LiteBIRD has been endorsed as one of the prioritized projects in the master plan 2017 by the Science Council of Japan. A down-selection by ISAS is planned around late 2018 $\sim$ early 2019. It is scheduled to be launched around 2027 with an H3 vehicle for three years of observations at a Lagrangian point (L2) of the Earth-Sun system. The concept design has been studied by researchers from Japan, U.S., Canada, and Europe since September 2016. This proceedings presents a part of the concept design. Details of the cryo-system,[12] electric system,[13] focal plane,[14] LFT optics,[15] and HWP[16] of LiteBIRD are separately reported.

2. SYSTEM DESIGN

Requirements flow down from science goal of $\delta r = 0.001$. This requirement is equally divided into three; statistical uncertainty of less than $\delta r = 5.7 \times 10^{-4}$, systematic uncertainty of less than $\delta r = 5.7 \times 10^{-4}$, and a margin of $\delta r = 5.7 \times 10^{-4}$. The statistical uncertainty includes uncertainties of lensing B-mode and foregrounds subtraction.

One advantage of a space program for CMB B-mode polarization detection is foreground subtraction, which is studied with broadband and large angles. Several approaches have been investigated for LiteBIRD.[17–21] These studies found that it can be marginal to achieve $\delta r = 5.7 \times 10^{-4}$ with the 2016 baseline sensitivity presented at the last SPIE 2016 at Edinburgh.[4] So we have designed an enhanced HFT; both HFT and LFT have equal bandwidth of 1:5.

There are many sources of systematic errors. Each item of the errors contributes to be less than 1 % of $\delta r = 5.7 \times 10^{-4}$. The HWP can reduce differential systematic errors, including with beam patterns, gain, and bandpass.[22] On the other hand, the HWP itself can produce the systematic errors[23] and the study is in progress.

The LiteBIRD spacecraft is shown in Figure 1. The block diagram dipicting the preliminary task sharing of LiteBIRD is shown in Figure 2. The spacecarft is composed of payload module (PLM) and service module (SVM). The PLM consists of high frequency and low frequency telescopes, with their respective focal planes, and cryo-structure and room-temperature part of PLM. The cryo-structure is made of active cooling chain including sub-K cooler and passive cooling (V-groove), and mechanical structures. The basic parameters of LiteBIRD are tabulated in Table 1.

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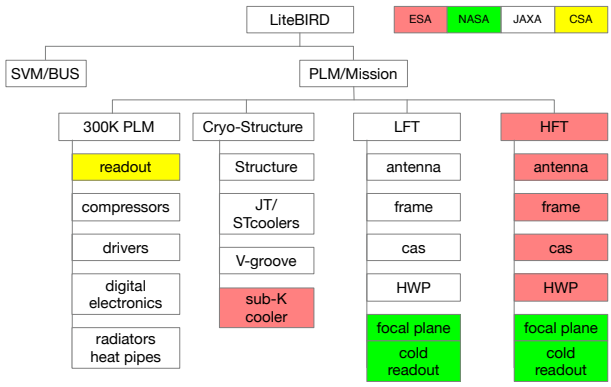

Figure 2. Preliminary work sharing of LiteBIRD. Red, green, and yellow indicate European, US and Canada contributions, respectively. cas: cold aperture stop.

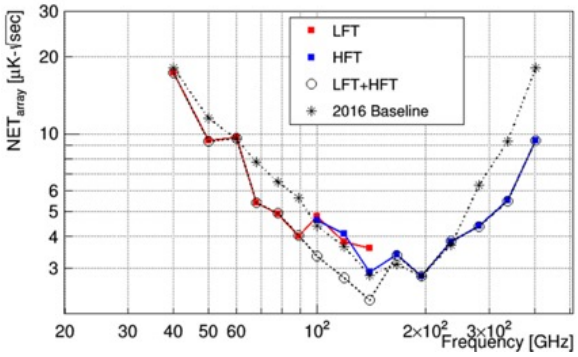

Figure 3. Sensitivity of LiteBIRD. The 2016 Baseline sensitivity was reported in Ishino et al.[4]

The design and operation of the LiteBIRD satellite are driven by requirements, which derive from the top requirement of $\delta r = 0.001$. A 3-year full sky survey will be carried out with LFT (34 - 161 GHz) and HFT (89 - 448 GHz) to achieve the unprecedented sensitivity (Figure 3 and Table 2) . The mission instruments are cooled down below 5 K with mechanical cryocoolers and a passive cooling system.

Due to the limited bandwidth of a half-wave plate for polarization modulation, LiteBIRD has two telescopes: a reflective low-frequency telescope with an aperture of 40 cm and a high-frequency telescope with an aperture of 30 cm. The angular resolution of each band is tabulated in Table 2. Both telescopes have polarization-sensitive multi-chroic TES array detector operated at 100 mK.[14]

The LiteBIRD mission plan envisions three years of observations at the Sun-Earth Lagrangian 2 point. It is a spinning satellite with a precession angle (α) of 45 degrees and spin angle (β) of 50 degrees with spin rate of 0.1 rpm and precession period of 93 minutes, which are optimized from crossing angles and revisits of previously scanned regions.

The BUS or service module (SVM) of LiteBIRD is shown in Figure 1. The SVM supports scan, pointing, power supply and communication as specified in Table 1. The mass and electrical power of LiteBIRD are 2.6 tons and 3.0 kW, respectively. The breakdown is tabulated in Table 3. The mass and electrical power of SVM include a 10 % margin. The mass and electrical power of PLM include a 20 % margin. The electronics system design of LiteBIRD has been reported by Tsujimoto et al.[13]

The power consumption of cooler compressors and drivers is about 1.5 kW, which is transferred to radiators with heat pipes. The area of the radiators is required to be around 10 m^2, so most outer panels of 300K PLM and some part of upper surface of SVM are used as radiators.

The data transfer and telecommunication are planned with a new JAXA 54 m ground station, GREAT (GRound station for deep space Exploration And Tele-communication), which is under construction near the USUDA 64 m station, Nagano prefecture, Japan.

3. PAYLOAD MODULE

Requirements for payload module have been derived from the top-level requirement of achieving a tensor-to-scalar ratio error of $\delta r = 0.001$. LiteBIRD observes millimeter waves from 34 GHz to 448 GHz with two telescopes, LFT and HFT. A HWP for polarization modulation has a limited bandwidth, and so LiteBIRD has two telescopes to cover the frequency bands as defined in Table 4. This focal plane design is based on multi-chroic TES at 100 mK operation.[14]

The frequency coverages of LFT and HFT have been modified after the last SPIE conference[4,24] . Both telescopes have equal 1:5 band coverage: LFT observes Synchrotron and CMB bands, and HFT covers both CMB and dust bands. The CMB bands of 89 - 161 GHz are overlapped to reduce systematics associated with

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Table 1. LiteBIRD basic parameters

	Low Frequency Telescope (LFT)	High Frequency Telescope (HFT)
Frequency	$34 \sim 161$ GHz	$89 \sim 448$ GHz
field of view	> 20 deg $\times$ 10 deg	> 20 deg $\times$ 10 deg
aperture diameter	400 mm	300 mm
angular resolution	$20 \sim 70$ arcmin	$10 \sim 40$ arcmin
rotational HWP	88 rpm	170 rpm
number of detectors	$\sim$1000	$\sim$2100
data sampling rate	22 Hz	46 Hz
Uncertainty of r	$\delta r < 1 \times 10^{-3}$	
Observation period	3 years	
Scan	L2 Lissajous, precession angle 45 deg, spin angle 50 deg (0.1 rpm)	
Sensitivity	$< 3\mu$K·arcmin	
pointing knowledge	< 3 arcmin	
focal plane array	bath temperature 100 mK $\mathrm{NET}^{P}_{\mathrm{array}} = 1.7\mu\mathrm{K} \cdot \sqrt{s}$ detector $f_{\mathrm{knee}} < 20$ mHz	
data transfer	7 GByte/day	
mass	2.6 ton	
electrical power	3.0 kW	

Table 2. Sensitivity and beam size of LiteBIRD

Band	NET array	LFT		HFT		polarization
		beam size	$\mathrm{NET}_{\mathrm{array}}$	beam size	$\mathrm{NET}_{\mathrm{array}}$	sensitivity
GHz	μK-s$^{1/2}$	arcmin	μK-s$^{1/2}$	arcmin	μK-s$^{1/2}$	μK-arcmin
40	13.4	69.2	13.4			27.9
50	9.4	56.9	9.4			19.6
60	7.5	49.0	7.5			15.6
68	5.9	40.8	5.9			12.3
78	4.8	36.1	4.8			10.0
89	4.5	32.3	4.5			9.4
100	3.7	27.7	5.9	37.0	4.6	7.6
119	3.0	23.7	4.6	31.6	4.1	6.4
140	2.4	20.7	4.4	27.6	2.9	5.1
166	3.4			24.2	3.4	7.0
195	2.8			21.7	2.8	5.8
235	3.8			19.6	3.8	8.0
280	4.4			13.2	4.4	9.1
337	5.5			11.2	5.5	11.4
402	9.4			9.7	9.4	19.6

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Table 3. Mass and power estimates of LiteBIRD

		mass [kg]	electrical power [W]
5K PLM		260	
	LFT	148	
	HFT	91	
	sub-K cooler	7	
	margin	14	
Structure		188.4	
	truss	71.4	
	V-groove	107	
	harness	4	
	He pipes	6	
Coolers and compressors		297	
	ST coolers	86	450
	JT cooler compressors	86	165
	base, radiators	125	
Cooler drivers		149	
	ST drivers	110	651
	JT drivers		280
	sub-K driver	39	26
Electronics		44	
	HWP controller	5.2	52
	house keeping	5.2	26
	data compression electronics	28	26
	warm electronics unit		172
	squid controller		
	power distribution unit	6	20
	M-SWR (14port)		5
Radiator/heaters		108	
	MLI, heaters, sensors	15.4	
	radiator/heat pipes	93	
300K PLM sum		787	1873
300K PLM sum + 20 % margin + 5K PLM		1204	2247
SVM (including 10 % margin)		1357	715
Total		2561	2962

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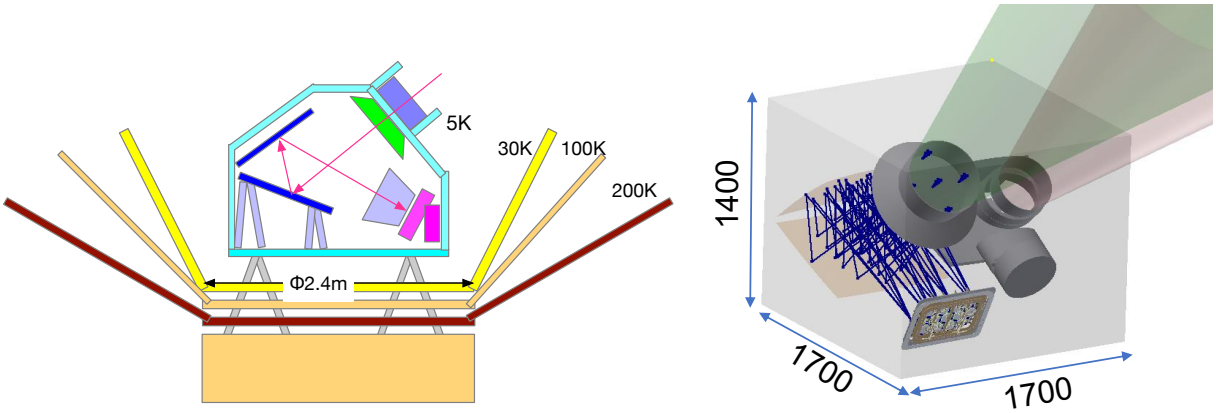

Figure 4. Left: a cartoon of the payload module (PLM) including 300 K part. Right : LFT and HFT. This LFT drawing shows cold aperture stop (CAS), two mirrors and the focal plane array. HFT is the smaller one. The envelope of LFT and HFT is less than 1.7 m × 1.7 m × 1.4 m height.

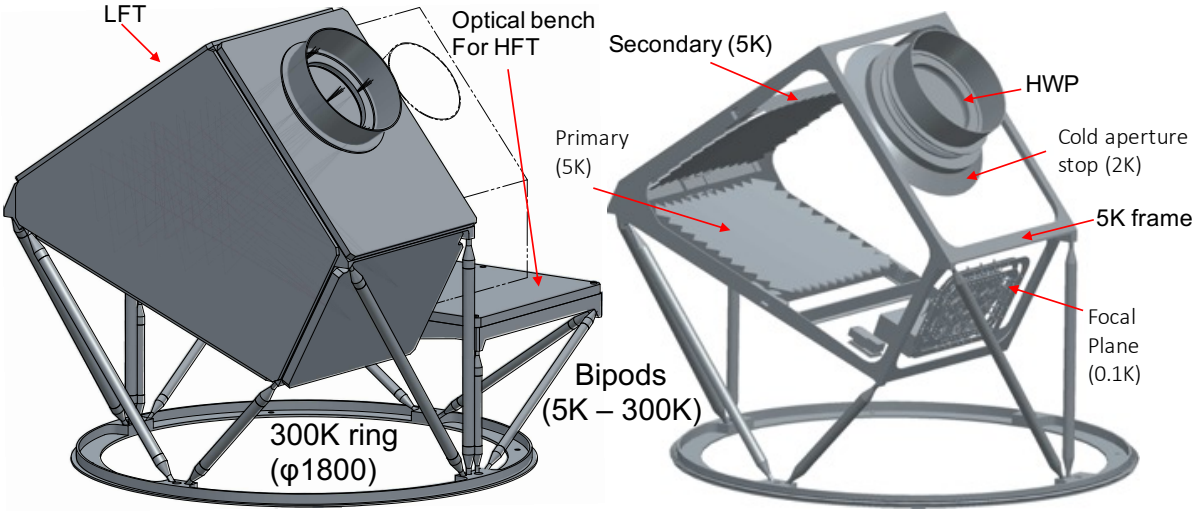

Figure 5. LFT and its support structure. There is a 5K optical bench for HFT in the back side. The outmost of both telescopes is less than1.7 m × 1.7 m × 1.4 m height. LFT and HFT have apertures of 400 and 300 millimeter, respectively. The right-side panel shows the low frequency antenna design, which is supported from the 300K ring ($\phi = 1800$ mm) by bipods.

the telescope and as a redundancy. A design of LFT and PLM is shown in Figure 5. Both telescopes are cooled down to 5K. The major requirements on the PLM of LiteBIRD are tabulated in Table 5.

LFT has an aperture of 40 cm, and HFT has an aperture of 30 cm. The envelope of LFT and HFT is less than 1.7 m × 1.7 m × 1.4 m height. This size should be kept as small as possible, because the radiative cooling power of a non-expandable V-groove is dependent on the opening angle. The weights of LFT and HFT are expected to be 148 kg and 91 kg, respectively. This is also kept as light as possible, because the thermal conductivity of the support truss depends on the mass.

HFT has been designed by the European consortium and the European Space Agency (ESA). Current baseline design of HFT is a reflective antenna with a reflective HWP. The broadband capability of the reflective HWP has been demonstrated.[25] An optical design of the HFT has been presented by Hasebe et al.[26]

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4. LOW FREQUENCY TELESCOPE (LFT)

Challenges of LiteBIRD are wide field-of-view (FoV) and broadband capabilities of millimeter-wave polarization measurements, which are derived from the sensitivity requirements. The wide FoV corresponds to a large focal plane area; a detector pixel has different spill-over or edge-taper depending on the pixel position on the focal plane. Possible paths of stray light increase with a wider FoV. The broad-band (1:5) capability requires different frequency modules. Current planar band-pass filter technology has limited bandwidth, so for example, one frequency module receives 40 GHz, but the higher frequency modules reflect 40 GHz (see Table 4). There are many band edges, where the feed pattern may distort. The telescope has many reflection paths among FP, CAS, HWP, among quasi-optical LP Filters. The absorbers covering the optics and the focal plane are not ideal and they have frequency dependence as well as angle dependence of reflectance. These challenges shall be overcome by design and demonstrations.

After various trade-off studies of various optical configurations including a front-fed Dragone,[27] we concluded that the crossed Dragone antenna is the best option for LiteBIRD. Wide FoV design of a crossed Dragone antenna has been studied by Kashima et al. 2018.[28] A ray diagram of LFT is shown in Figure 6, which has an FoV of 20 degrees $\times$ 10 degrees. The F#3.0 and the crossing angle of optical axes of 90 degrees are chosen after an extensive study of stray light. We found that "clipped" side lobe[29] or triple reflection[15] of the crossed Dragone optics can be avoided with this configuration. Primary and secondary mirrors have rectangular shape ($\sim$ 900 mm $\times$800 mm) with serrations to reduce diffraction pattern from the edges of mirrors. An optimization for the serration pattern has been reported.[30] The far sidelobe knowledge of -60 dB (see Table 5) is one of challenging requirements. In flight, the calibration accuracy of LiteBIRD is not as good as that of the Planck satellite. The far sidelobe is designed as low as possible in order to predict it from room temperature measurements of the far sidelobes, cryogenic measurements of near sidelobes, and in-flight calibration of near sidelobes.

Physical optics simulation of LFT with GRASP10[31] is reported by Imada et al.,[15] the simulated telescope elements including LFT reflectors and cold aperture stop. At this stage, the HWP, which may generate additional side-lobes, is not taken into account for the physical optics simulation. LiteBIRD is more challenging for modeling the optics than Planck.[32] It is necessary to take into account following items: (1) absorbers on enclosures, aperture stops, hoods, baffles; (2) broadband feeds with lower return loss and larger side lobes; (3) HWP effects including the rotation mechanism on the beam.

There is a trade-off of mechanical structure in LFT between a frame type and an optical bench type. A frame-type design of LFT is shown in Figure 5. The frame and LF mirrors are made of aluminum in order to shrink similarly to 5 K. The mass of LFT including the focal plane is estimated to $\sim$ 150 kg. The frame is supported by trusses made of CFRP via a kinematic mount to release thermal stress.

In the optical bench configuration as shown in Figure 4, the LF-antenna, 5K enclosure and the focal plane are independently supported on the optical bench. The 5K enclosure supports the HWP and cold aperture stop. The 5K frame plays the roles of an optical bench, 5K enclosure, and support for LF mirrors, and thus the mass of LFT can be reduced. There is a concern on possible distortion of the 5K frame by thermoelastic effect of absorbers or the rotating HWP. The absorber, made of plastic/carbon is adhered to a panel with epoxy, then the panel is fixed to the 5K frame. The cryogenic contraction of the absorber and the epoxy is a potential source of thermal deformation of the antenna. If there is non-uniformity of mass distribution of the HWP at 88 r.p.m., the HWP may be a possible source of distortion. The optical bench can mitigate such distortions. From the view point of verification and tests, the frame architecture can be used as an LF antenna structure. The 5K frame has a position reference for the focal plane and the HWP. The current baseline of HWP is a transmissive one, then extremely precise alignment is not required. In the case of reflective HWP, very precise alignment between the mirrors and HWP is required.

The 5 K frame is directly connected by the trusses, which have a temperature gradient from 300K to 5K and a finite thermal expansion coefficient. Because the trusses for the 5K frame architecture have different lengths, this can be a possible source for cryogenic deformation of the crossed Dragone antenna, but it can be mitigated by measuring the the thermal expansion coefficient.

A transmissive sapphire HWP has been developed for LiteBIRD.[16,33] The HWP is placed as the first optical element of the telescope, which is in front of the cold aperture stop or entrance pupil. The HWP is inclined at 5

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Table 4. Frequency bands and detector configuration. The CO lines are avoided with planar notch filters. This table shows only optical TESs. There are additional dark TESs for the monitor purpose.

	Type	Center [GHz]	BW	Low [GHz]	High [GHz]	Num. of wafers	TES channels Opt/wf	Total
LFT 34 - 161 GHz	1	40	0.30	34	46	3	14	42
		60	0.23	53	67	3	14	42
		78	0.23	69	87	3	14	42
	2	50	0.30	43	58	4	14	56
		68	0.23	60	76	4	14	56
		89	0.23	79	99	4	14	56
	3	68	0.23	60	76	3	38	114
		89	0.23	79	99	3	38	114
		119	0.30	101	137	3	38	114
	4	78	0.23	69	87	3	38	114
		100	0.23	89	112	3	38	114
		140	0.30	119	161	3	38	114
HFT 89 - 448 GHz	5	100	0.23	89	112	3	74	222
		140	0.30	119	161	3	74	222
		195	0.30	166	224	3	74	222
	6	119	0.30	101	137	2	74	148
		166	0.30	141	191	2	74	148
		235	0.30	200	270	2	74	148
	7	235	0.30	200	270	1		
		337	0.30	286	388	1	338	338
	8	280	0.30	238	322	1	338	338
		402	0.23	356	448	1	338	338
Total								3102
LFT								978
HFT								2124

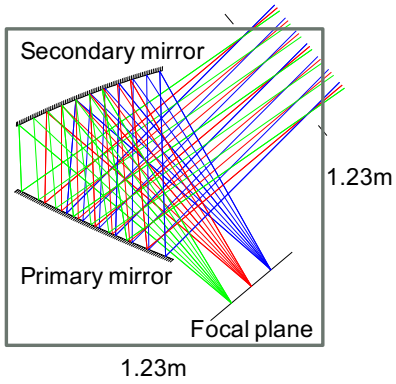

Figure 6. Ray trace of LFT crossed Dragone optics with an aperture diameter of 400 mm and FoV of 20 degrees × 10 degrees. The optical configuration is F#3.0 and the crossing angle of the optical axes of 90 degree.

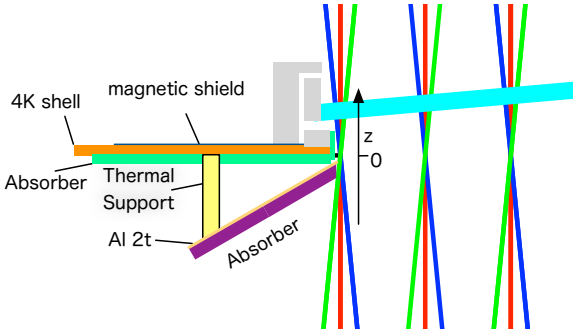

Figure 7. A design of cold aperture stop at 2 K. The HWP is inclined at 5 degrees.

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Table 5. Major requirements of PLM and verification methods. CT represents cryogenic test, A analysis, T room temperature test. DM: demonstration model, STM: structure thermal model, EM: engineering model, FM: flight model.

Requirements		Method	Model	method
Instrument Sensitivity	Table 2	CT	DM, EM, FM	hot-cold
Spectral optical response	0.10%	CT	DM, FM	CW/FTS
Band definitions	Table 4	CT	DM, FM	CW/FTS
Data loss due to Cosmic rays	5%	A	DM, EM, FM	hot-cold
Operating life of instruments	3 years	A, CT	DM, EM	
Post demodulation 1/f noise	$f_{knee} < 0.2$ mHz	CT	DM, EM, FM	rotating wire grid
Modulation synchronous instr. pol.	< 0.03 %	CT	DM, FM	rotating wire grid
Far sidelobe knowledge	-60dB(diffuse)	T, A	DM, FM	compact range
Near sidelobe knowledge	TBD	CT	DM, FM	phase retrieval near field
Beam flattening	< 15 %	CT	DM, FM	phase retrieval near field
Response non-linearity	TBD	CT	DM, EM, FM	hot-cold
Gain variation in time (single det.)	< 10 % (600sec)	CT	DM, EM, FM	hot-cold
Linear pol. responsivity	TBD	CT	DM, FM	rotating wire grid
Pointing offset knowledge	< 3 arcmin	CT, A	DM, FM	phase retrieval near field
Abs. pol. angle knowledge	< 3 arcmin	CT	DM, FM	rotating wire grid
Cooling capability		CT	STM, EM, FM	
Mechanical properties		T, A	STM, EM, FM	standard tests

degrees to mitigate multiple reflections including optical ghost between the HWP and the focal plane. The HWP uses superconducting magnet for levitation. The eddy current and magnetic hysteresis dissipate and increase the temperature of rotating HWP from 5 K to 10 K. The re-cooling of HWP synchronizes to the re-cycling of the sub kelvin cooler.

A design of the cold aperture stop at 2.0 K with inner and outer diameters of 400 mm and 800 mm, respectively, is shown in Figure 7. This works to make good beam shape and to reduce the photon noise for relatively low edge taper of ~ 3 dB configuration. It is thermally isolated from the 5K structure with CFRP pipes. A millimeter absorber, TK-RAM,[34,35] is attached on Aluminum cone, which is connected to 1.8 K stage with thermal strap. The weight of the cold aperture stop including the absorber is estimated to be 7 kg. The first eigen frequency of the cold aperture stop was analyzed to be 120 Hz. The heat load to the 1.8K stage is around 2.0 mW including heaters to stabilize the temperature to less than 0.2 mK peak-to-peak.

Millimeter absorbers to reduce reflections are attached on the inside surface of the 5K frame, which plays an role of a cavity. Eccosorb AN72 and HR10 are candidates of such absorber, however, they have large TML (total mass loss) and CVCM (collected volatile condensable materials). According to NASA outgass database,[36] AN72 washed with ethanol shows reasonable TML and CVCM.

LF focal plane has been described by A. Suzuki et al.[14] The lens and sinuous antenna have broadband capability.[37] The focal plane with AlMn TES is cooled to 100 mK. Cosmic ray mitigation has been investigated.[38] A quasi-optical metal-mesh low-pass filter[39] is put in front of hexagonal modules to reduce thermal loads from the 5 K cavity. The focal plane is covered with a hood to reduce stray light. Magnetic shield to reduce magnetic variation from HWP covers the focal plane except for the optical input.

5. CRYO-STRUCTURE

Thermal design of LiteBIRD is based on studies for SPICA.[40,41] Cooler configuration composed of active mechanical coolers and passive radiative cooler is shown in Figure 8.

Radiative cooling with V-groove[42] is efficient especially for Sun-Earth Lagrangian 2 point, as Planck satellite demonstrated efficient passive cooling capability with V-groove.[43] The V-groove consists of several cones, whose facing surfaces are not parallel but open for sky. Infrared photons between them are radiated to cold space in a

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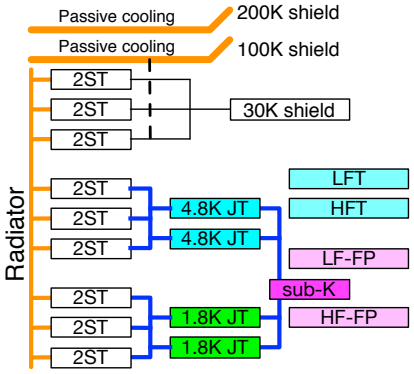

Figure 8. Cooler configuration of LiteBIRD. The V-groove consists of 200K, 100K, and 30K shields. Two coolers of 4.8K JT and 1.8K JT are redundant. 2ST represents 2 stage stirling cooler.

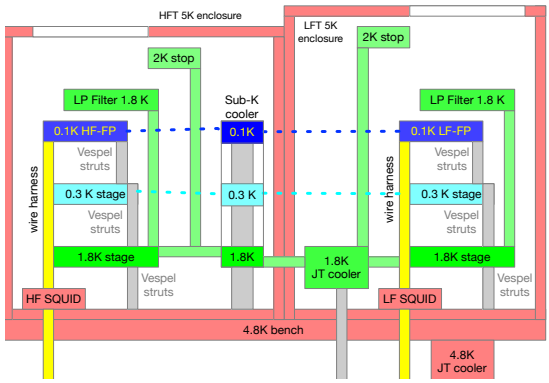

Figure 9. A schematic drawing of 5K part with coolers. HFT and LFT share a sub-Kelivin cooler, 1.8K JT and 4.8K JT coolers.

few reflections. The V-groove has been designed wit for the current scan strategy with a spin angle of 50 degrees. Details of the thermal design are described by Hasebe et al.[12]

Radiative cooling power of the V-groove is roughly proportional to the opening angle/area. The outer circumference of the V-groove is limited by the fairing of the H3 vehicle, 4.5 m, if an expanding/deployment mechanism after the launch is not employed. To keep the current radiative cooling power, the outer circumference of the 5 K enclosure shall be less than a diameter 2.4 m (1.7 m $\times$ 1.7 m). We are investigating the possibility to reduce the volume/size of LFT to increase available 4.8K cooling power.

A schematic drawing of the cryogenic design of LFT and HFT is shown in Figure 9. In this figure, one 1.8K JT cooler and one 4.8K JT cooler are drawn as a single functional element, although there are two 1.8K JT coolers and two 4.8K JT coolers as redundancy in Figure 8. The 4.8K-JT and 1.8K-JT coolers have cooling capacities of 40 mW at the 4.8 K stage and 10 mW at the 1.8 K stage, respectively, at the end of life (EOL).[41] The 2ST cooler has cooling capacity of 200 mW at the 20 K stage at the end of life (EOL).[41] Taking into account the 30% margin for these mechanical coolers, available cooling powers at the 4.8 K stage and 1.8 K stage are 30 mW and 7 mW, respectively. The redundancy of the mechanical coolers for SPICA has been studied by Shinozaki et al.[41] The 4.8K JT and 2ST coolers achieved TRL (technical readiness level) 8 and the 1.8K JT cooler did TRL 5.

A candidate for a sub-Kelvin cooler is an ADR/sorption hybrid cooler developed by CEA.[44] This cooler has been demonstrated with JT/ST coolers by the cooling chain core technology program.[45] This cooler achieved TRL 6. The hybrid cooler needs recycling phase once per day. The recycling heat load of $\sim$ 10 mW for the 4.8K JT cooler is a bottle neck of the thermal design. To reduce the heat load, there is an option that two hybrid coolers for two telescopes have different recycling phase.

Another candidate for a sub-Kelvin cooler is a closed-cycle dilution refrigerator (CCDR)[46] developed by Neel institute and IAS. The CCDR is continuously operated, but it requires large cooling power for the 1.8K stage. A program to raise the TRL to 5 is running.

A structure analysis of the whole PLM including V-groove structures predicts the first eigen frequency of 74 Hz and 34 Hz for vertical and horizontal axes, respectively. An estimate of conductive and radiative load to the 5 K cooler is 12 mW. Then, the available cooling power for HWPs of LFT and HFT and sub-Kelvin cooler(s) at 4.8 K is 18 mW. The available cooling power of 7 mW at 1.8K is used for cold aperture stops and focal planes of LFT and HFT.

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6. ASSEMBLY, INTEGRATION, AND VERIFICATION (AIV) PLAN

The verification and calibration of a warmly-launched cryogenic telescope on the ground are challenging. After the accident of the Hitomi satellite[47] in March 2016, JAXA has been carrying out operational reform, which suggests a front heavy assembly, integration, and verification (AIV) plan. It requires that technical challenges of a mission shall be verified before PDR (preliminary design review). Technical challenges of LiteBIRD are (1) sensitive polarization measurement capability and (2) cooling chain down to 0.1K and mechanical support structure.

The Demonstration model (DM) of LFT is fully characterized to verify its millimeter-wave beam and noise performances under the cryogenic environments. The requirements are tested and calibrated as shown in Table 5. A dedicated cryogenic chamber will be built for LFT to measure millimeter polarization performance with phase-retrieval near field beam measurements (eg. Manabe et al.[48]), spectral responses with FTS (Fourier transform spectrometer) or CW (continuous wave) sources, and polarization angles with rotating wire-grid mechanism. An FTS has crude spectral resolution of 1 GHz, in general. LiteBIRD needs fine spectral resolution at synchrotron frequencies or for CO lines. A broadband CW source with an appropriate optical design has fine spectral resolution of 0.01 GHz to measure the spectral response. A candidate of the CW source is a photomixer.[49,50]

One of the issues of the ground calibration is far sidelobe measurement. It is ideal to measure the far sidelobe pattern in the cryogenic environment with the focal plane, but, it is difficult to prepare the cryogenic test-set within the reasonable cost. In this current plan, the far sidelobe is measured with a representative feed at room temperature. The main lobe and near sidelobes measured at cryogenic temperature are compared with those at room temperature, then the far side lobe at the cryogenic temperature is estimated with auxiliary simulations.

Procedure of LFT assembly, integration and verification (AIV) is as follows: 1) dimensions of the 5K frame are measured with a 3D coordinated measurement machine; 2) primary and secondary mirrors are fixed to the frame. After the reference positions of the mirrors are checked with the 3D coordinated measurement machine, the mirror shape is measured with photogrammetry at both room and cryogenic temperatures. Millimeter beam pattern is measured at room temperature; 3) absorbers and cold aperture stop are fixed to the frame. The millimeter beam is measured at both room and cryogenic temperatures. 4) focal plane is fixed to the frame. The millimeter beam, polarization angle, and spectral response are measured at cryogenic temperature. 5) the HWP is installed into the frame. The millimeter beam, polarization angle, and spectral response are measured at cryogenic temperature. Multiple reflections among HWP, FP, reflector and baffles are extensively studied with LFT DM.

A structure thermal model (STM) of the mission payload is constructed and tested with mechanical coolers down to 0.1K and V-grooves to verify mechanical and thermal interfaces. The STM consists of cryo-structure, dummy LFT and dummy HFT. Standard vibration tests to verify the mechanical interfaces of PLM are planned. Both DM and STM are verified in parallel before PDR in the current schedule.

The STM and DM of LFT will be refurbished and used as an Engineering model (EM). The first integration of PLM including HFT is planned with EM to verify all interfaces. This means that one model of LFT and cryo-system is manufactured and is used for both DM and EM. End-to-end tests of noise and optical efficiency measurements are planned with hot-cold loads in front of the apertures of both telescopes. A topic of EM is EMC/EMI tests with electrical power supplies and HGA (high gain antenna) power amplifiers. SVM (service module/BUS) is manufactured as proto-FM (PFM), so EM doesn't test SVM.

A preliminary integration plan of flight model (FM) is shown in Figure 10. It takes long time to make AIV and calibrations of LFT and HFT, so which are done in parallel.

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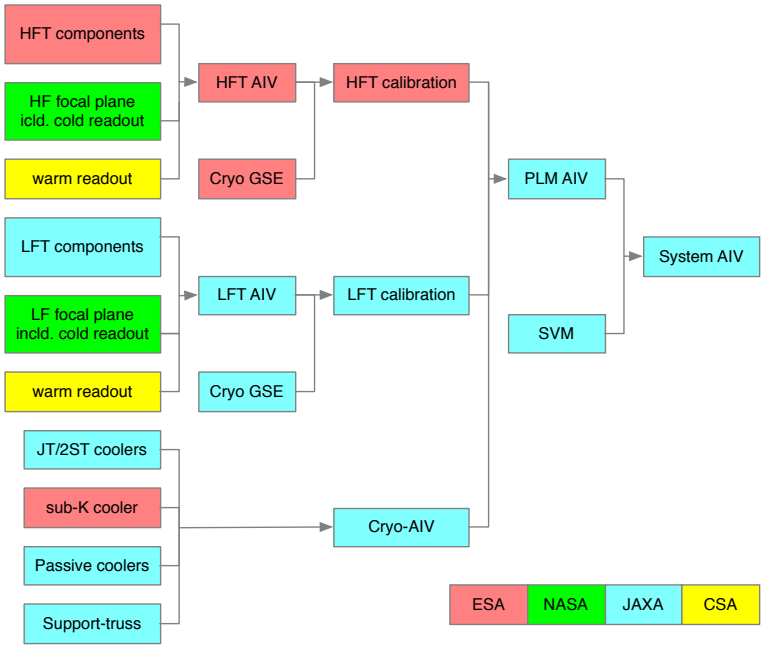

Figure 10. Preliminary integration plan of flight model (FM) of LiteBIRD

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