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Shunsuke Honda[a], Jihoon Choi[b], Ricardo Tanausu Génova-Santos[c], Makoto Hattori[d], Masashi Hazumi[e,f], Takuji Ikemitsu[a], Hidesato Ishida[d,g], Hikaru Ishitsuka[f], Yonggil Jo[h], Kenichi Karatsu[i,j], Kenji Kiuchi[k], Junta Komine[a], Ryo Koyano[l], Hiroki Kutsuma[d,g], Kyungmin Lee[h], Satoru Mima[g], Makoto Minowa[k], Joonhyeok Moon[h], Makoto Nagai[m], Taketo Nagasaki[e], Masato Naruse[l], Shugo Oguri[n], Chiko Otani[d,g], Michael William Peel[c], Rafael Rebolo[c], Jose Alberto Rubiño-Martín[c], Yutaro Sekimoto[n], Yoshinori Sueno[a], Junya Suzuki[a], Tohru Taino[l], Osamu Tajima[a], Nozomu Tomita[k], Yuta Tsuji[d,g], Tomohisa Uchida[e,f], Eunil Won[h], and Mitsuhiro Yoshida[e,f]

[a]Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan
[b]Korea Astronomy and Space Science Institute, 776 Daedeok-daero, Yuseong-gu, Daejeon 34055, Republic of Korea
[c]Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[d]Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan
[e]The High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[f]The Graduate University for Advanced Studies (SOKENDAI), Shonan Village, Hayama, Kanagawa 240-0193, Japan
[g]Institute of Physical and Chemical Research, 2-1 Hirasawa, Wako, Saitama 351-0198, Japan
[h]Korea University, 145 Anam-ro, Seongbuk-gu, Seoul, 02841, Republic of Korea
[i]Delft University of Technology, Mekelweg 5, 2628 CD Delft, The Netherlands
[j]SRON - Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[k]The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan
[l]Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan
[m]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[n]Japan Aerospace Exploration Agency (JAXA), 7-44-1 Jindaiji, Higashi-machi, Chofu-shi, Tokyo 182-8522, Japan

ABSTRACT

GroundBIRD is a millimeter-wave telescope to observe the polarization patterns of the cosmic microwave background (CMB). The target science topics are primordial gravitational waves from cosmic inflation and reionization optical depth. Therefore, this telescope is designed to achieve the highest sensitivity at large angular scales, $\ell = 6 - 300$. For wide sky observations ($\sim 40\%$ full-sky), scanning at a high rotation speed (120°/s) is important to remove atmospheric fluctuations. Microwave kinetic inductance detector (MKID) is utilized with the fast GroundBIRD rotation since its good time response. We have started the commissioning run at the Teide Observatory in the Canary Islands. We report the performance of the telescope, receiver, and data acquisition system, including cooling achievements, observations of astronomical objects, and observations taken during several days ahead of our main survey observations.

Keywords: CMB, polarization, GroundBIRD, Teide observatory, MKID, first light

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Further author information: (Send correspondence to Shunsuke Honda)
Shunsuke Honda: E-mail: honda.shunsuke.75r@st.kyoto-u.ac.jp, Telephone: +81-75-853-3870
Osamu Tajima: E-mail: tajima.osamu.8a@kyoto-u.ac.jp, Telephone: +81-75-853-3870

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1. INTRODUCTION

Since the discovery of CMB, various cosmological parameters have been measured precisely. Observations of the polarization power spectrum of the CMB have been the focus of ground-based CMB experiments in the last decade.

CMB polarisations is classified into two different modes: the E mode with even parity and the B mode with odd parity. These polarization patterns have already been observed as the power spectra (EE and BB) on small anglular scales, as shown in Fig. 1. While the spectrum of the B mode observed so far is lensing BB due to the gravitational lensing effect, the cosmic inflation theory predicts another B mode spectrum (primordial BB) generated by primordial gravitational waves. This is brightest at large angular scales. The EE spectrum on large angular scales is also important as it provides a measurement of the optical depth to reionization. The precise measurement of the optical depth constrains the sum of the neutrino masses. The neutrino is suggested to play a special role in some beyond the Standard Model theories because of its small mass compared to other fermions.[1]

Atmospheric $1/f$ fluctuations generally limit observations at large angular scales. GroundBIRD is designed to achieve the highest sensitivity at the large angular scales by employing fast scan modulation with continuous azimuth rotation at 120°/s. In this paper, we report the on-site performance of the GroundBIRD instrument, including cooling achievements and first light observations.

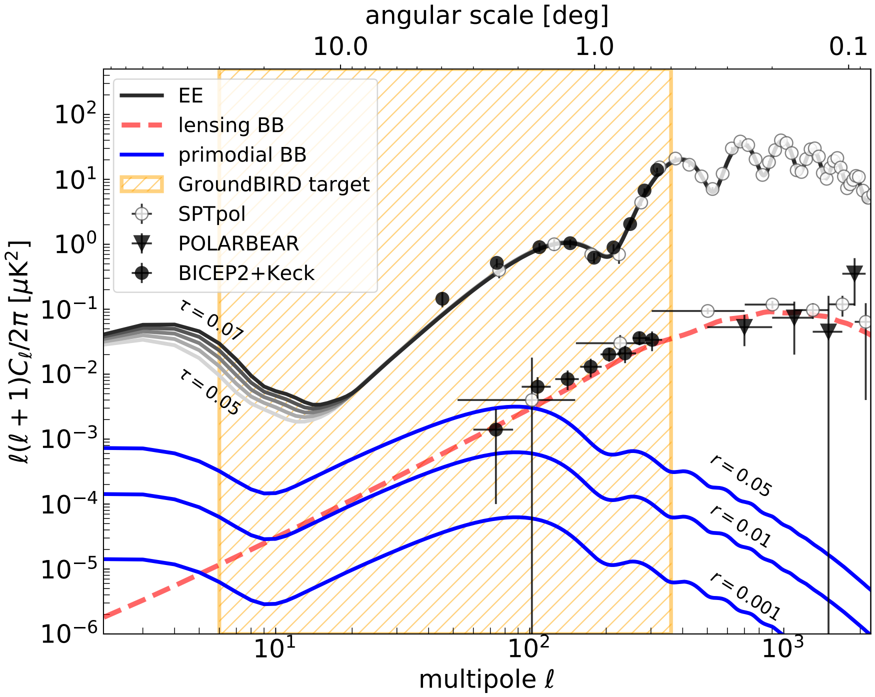


Figure 1: The polarization power spectra of the CMB (EE and BB) calculated with CAMB.[2] While the BB power spectrum is dominated by lensing BB in sub-degree scales, the primordial BB dominates at large angular scales. The cosmological parameters used here are from the Planck 2018 release,[3] although two parameters, r and τ, are plotted with various values. The r is tensor-to-scalar ratio in primordial BB and τ is reionization optical depth used in EE. Both parameters define the power spectrum level at large angular scales. GroundBIRD is designed to observe in $\ell = 6 - 300$. Data points obtained by SPT-pol, POLARBEAR, and BICEP2/KECK are also shown.[4–6]

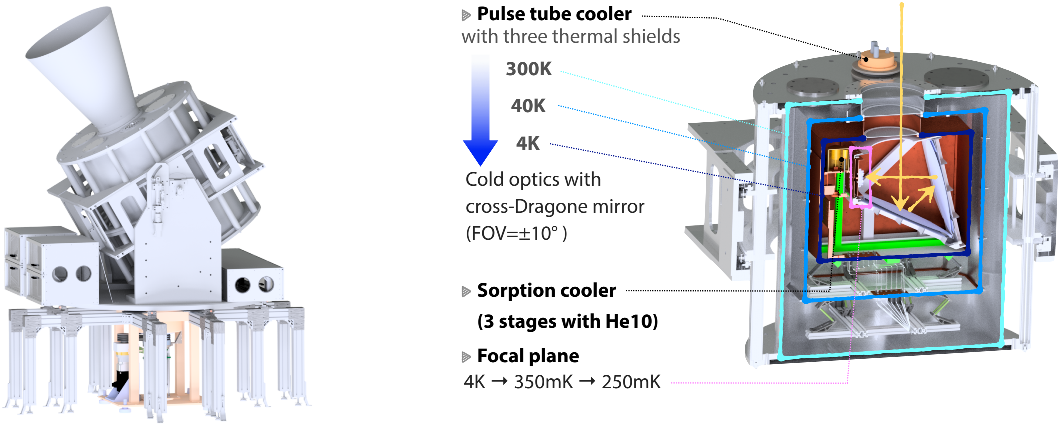
2. TELESCOPE SPECIFICATION

The GroundBIRD[*] telescope is composed of a compact cryostat chamber, data acquisition (DAQ) racks, and rotation structure (Fig. 2). Several methodologies are employed to observe at large angular scales with high sensitivity:

- azimuth rotation at 120°/s to mitigate the effects of atmospheric fluctuations[7]
- selectable elevation angle from 90° up to 60° to scan wide sky in one rotation
- cold optics with Cross-Dragone mirror at 4 K to reduce instrumental systematic effects
- MKID arrays on the focal plane at 250 mK
- two frequency bands at 145 GHz and 220 GHz for CMB and dust foreground estimation, respectively

The field of view of the telescope is approximately ±10° with a beam resolution of 0.5° full-width at half-maximum in 145 GHz band. GroundBIRD realizes $\sim 40\,\%$ sky coverage with 60° elevation.

MKID is a superconducting resonator that can be operated with an antenna to absorb incident radiation. MKID arrays are installed on the focal plane and are cooled down to 250 mK.



(a) (b)

Figure 2: Overview of the telescope instruments.

3. DATA ACQUISITION SYSTEM

The MKID response is obtained as the forward transmission (S_{21}) of the feedline on the array by transmitting a microwave at the resonant frequency of the MKID (typically $4-8$ GHz). The amplitude and phase of S_{21} are changed according to the amount of radiation absorbed by the MKID. The responses of MKIDs in the same array are read out using frequency division multiplexing. By designing MKIDs with different resonant frequencies, all MKID responses can be read out simultaneously with the sum of the microwaves of their resonant frequencies.

The readout wave generation and DAQ were implemented in a Kintex UltraScale field-programmable gate array (FPGA) board with a dedicated analog board (RHEA[†]) for the analog-to-digital converter (ADC) and digital-to-analog converter (DAC) interfaces.[8] The generated wave from the FPGA+RHEA at 200 MHz bandwidth, is up-converted to microwave range with a local oscillator (LO). The RF electronics, such as up/down conversions and amplifiers, were built in one readout box with LO and FPGA board per MKID array (Fig. 3).

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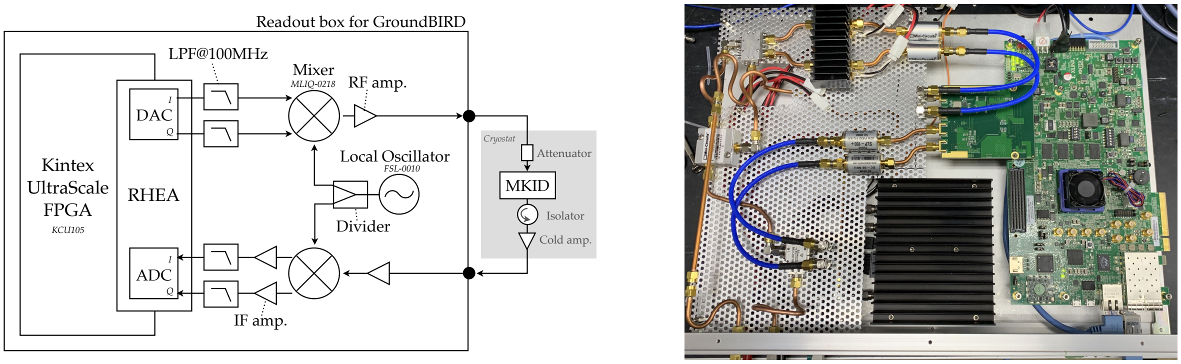
[*] Ground-based B-mode Imaging Radiation Detector

[†] RHEA is an acronym for "Rhea is a High spEed Analog board".



(a) (b)

Figure 3: (a) Schematics of the MKID readout system including DAC/ADC on the FPGA+RHEA board, RF electronics, and the cryostat with the MKID to be measured. (b) A photo of GroundBIRD readout box constructed in the IAC. The RF amplifiers were removed temporarily in this photo.

The DAQ systems for telescope angles (azimuth and elevation) were also implemented using FPGA boards with independent clocks. While the DAQ system for azimuth is installed under the rotation structure, DAQs for elevation and MKID rotate with the telescope (Fig. 4). Due to the fast rotation of GroundBIRD, the detector response needs to be synchronized with encoded angles under more severe conditions than in other CMB experiments. The timing resolution required is $\sim 80\,\mathrm{ns}$. The FPGA board for the azimuth angle issues a pulse signal to other boards for synchronization via an electrical rotary joint. FPGA boards receive the pulse signal with an incremental ID every second. They store the ID number and delay time from the arrival of the sync-pulse to the previous DAQ timing. The information enables offline ajustment for all DAQs. The angles are interpolated to the timing of the detector DAQ after sync-pulse alignments. The synchronization procedure is shown in Fig. 4.

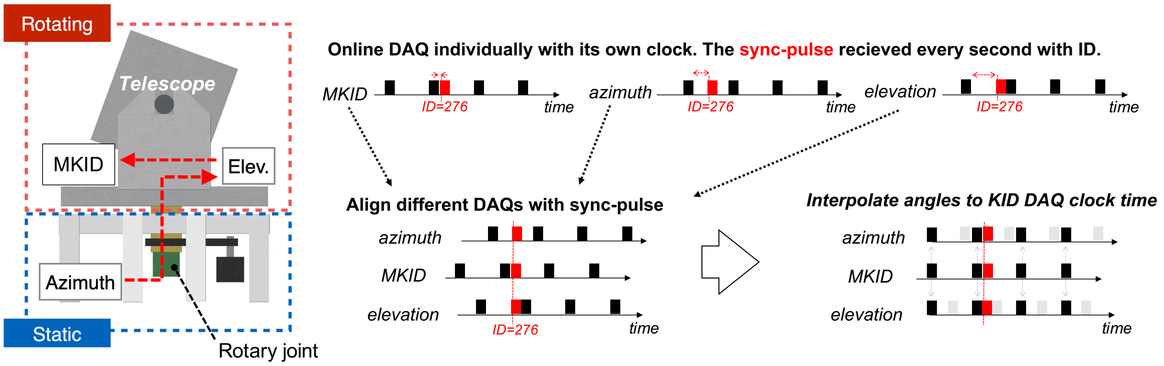


Figure 4: Synchronization scheme for MKID responses and telescope angles (azimuth and elevation). Left: the MKID and elevation DAQs are mounted on the rotation table, while the azimuth DAQ does not rotate with the telescope and is located under the rotation structure. In order to synchronize the timing in all DAQ systems, the azimuth DAQ issues a pulse signal named ‘sync-pulse’ indicated by the dotted red arrows. This pulse is sent to other DAQ boards through the electrical rotary joint. Right: the synchronization scheme for GroundBIRD. Each DAQ independently takes data at 1 k sampling per second (sps). When the sync-pulse arrives at each FPGA, its ID number (e.g., 276) and the time duration between the pulse arrival and the previous DAQ clock (red arrows) are stored. Using the stored synchronized pulse information, all the time stream data are aligned. The azimuth and elevation angles are then interpolated to obtain the angle values at each MKID clock timing.

4. TELESCOPE INSTALLATION

The observation site is Teide observatory in Tenerife, Spain, located at 2400 m altitude where precipitable water vapor is less than 3.8 (2.3) mm for 50 (25) % of the time.[9] The telescope was transported to Tenerife in 2019 after a demonstration experiment in Japan. The cryostat chamber was reconstructed and had a short cooling test in the laboratory space in the Instituto de Astrofísica de Canarias (IAC). It was then installed at Teide observatory in September 2019. The dome and rotation structure were installed in advance.[10] The telescope was confirmed to successfully rotate at 120°/s maintaining the coldest temperature of detectors after the GroundBIRD instrumentation was fully installed.

Figure 5: Installation of the GroundBIRD telescope. One of the enclosed spaces originally for the Very Small Array experiment is now used for GroundBIRD, as shown in the photo at the top left. The cryostat chamber was installed in the Teide observatory following the reconstruction and cooling test at the laboratory space of the IAC. The movie of the telescope rotating at 120°/s can be accessed via the QR code (`https://photos.app.goo.gl/ivjrHVkWJcSDzaHNA`).

5. FIRST LIGHT CAMPAIGN

After setting up the telescope, we demonstrated that the entire system is working correctly via several first light observations. The test MKID array provided by SRON was used for performance evaluations during the first light campaign with the 220 GHz optical band filter. It consists of NbTiN-Al MKIDs coupled to single-polarization twin-slot antennas, which utilizes elliptical lenses to focus incoming radiation.[11,12] The results from observations with four pixels simultaneously are shown in this report.

Prior to the observations, the noise spectra of the test MKID array with sky loading were measured. The result for one MKID pixel is shown in Fig. 6. The spectral shape derived by the MKID is well measured in the phase response with sufficiently low readout noise level of $\sim -88\,\mathrm{dBc/Hz}$ determined by the noise level of the 4 K cold amplifier. The device achieves photon noise limited performance in the phase readout at 1 ksps.

5.1 Moon Observation

The first light was achieved by the moon observation on 21st September 2019 with a slow telescope rotation at 30°/s. The observation was subsequently repeated at 120°/s. Since the synchronization between the MKID and telescope angle works correctly, the obtained moon image is consistent with the optical design. The moon image obtained with four pixels is shown in Fig. 7a.

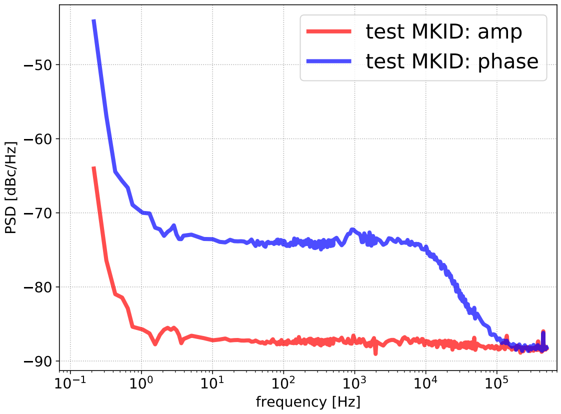
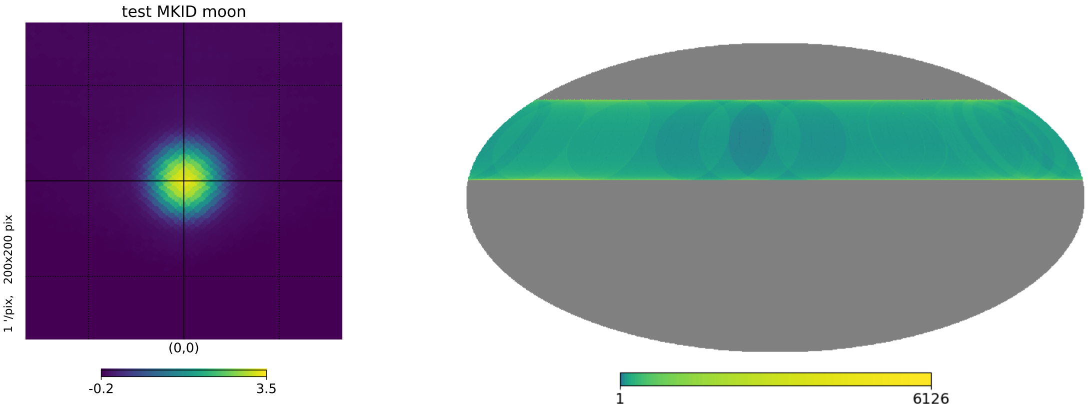


Figure 6: Power spectral density of one MKID pixel used in the first light campaign. The readout noise is determined by the 4 K cold amplifier of ~ -88 dBc/Hz and is low enough to obtain the spectrum of the MKID in the phase response, where the device achieves photon noise limited performance. The amplitude spectrum of the MKID under the GroundBIRD readout noise level, which has low sensitivities to the induced radiation power. The $1/f$ knee is ~ 1 Hz due to loading from the sky, which will be reduced by retreiving polarization loading only.

5.2 Initial Observations Over Several Days

Stability of the telescope performance was demonstrated by continuous observations over several days. MKID parameters, including the resonant frequency, were calibrated every hour. The entire sky region that the test MKID pixels in GroundBIRD can observe with 70° elevation was successfully scanned with four pixels, as shown in Fig. 7b.



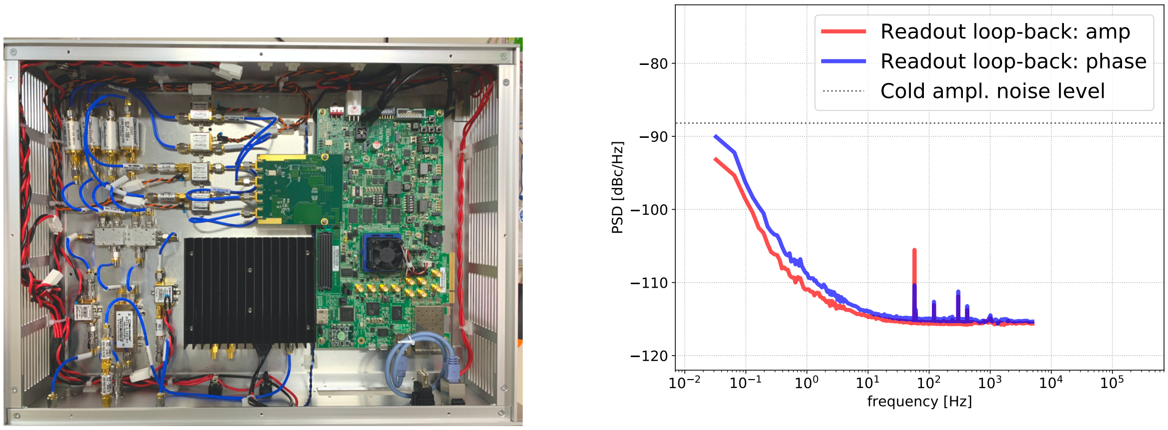
(a)

(b)

Figure 7: Observation results in the first light campaign. The test MKID array provided by SRON was used. Four pixels with different resonant frequencies within the RHEA bandwidth took the observation data simultaneously. The telescope scanned the sky at a continuous azimuth rotation speed of 120°/s at 70° elevation. (a) Moon image obtained in the phase responses of the test MKID array. The pixel width is $1'$ and 200×200 pixels are shown in the moon centered map. The map is averaged over four pixels. (b) Integration time per $0.11° \times 0.11°$ pixel in milliseconds after the observation time of ~ 80 hours. Entire sky region that can be measured by the test MKID pixels were scanned.

6. TOWARDS SCIENCE OBSERVATION

Currently, we are preparing MKID arrays that will be used in the science observation. The new MKID array will include 23 pixels with single-polarization antennas. The performance of the 32-channel simultaneous readout was investigated, of which 23 channels will be used to read out the MKID pixels, and nine channels will be used for common noise subtraction at non-resonant frequencies (e.g., noise from the AC power supply at 50 Hz) or for antenna-less MKID to monitor the focal plane temperature. The new readout box was built in Japan with small updates to adjust the readout power for the 32-channel DAQ (Fig. 8a). Obtained noise spectra of readout box are shown in Fig. 8b, which is lower than the noise level of 4 K cold amplifier at ~ -88 dBc/Hz.



(a) (b)

Figure 8: (a) Photo of the new readout box. Amplifiers were newly added in the coaxial lines just after DAC of RHEA. Cables were also replaced with more flexible ones to avoid large physical tensions to the board and RF components. (b) Power spectral density of the readout electronics. Intrinsic noise of the readout electronics with RF loopback was evaluated. Simultaneously obtained spectra of 32 channels were averaged. The averaged spectrum over 32 channels is lower than the noise level of 4 K cold amplifier at ~ -88 dBc/Hz (see Fig. 6).

7. CONCLUSION AND PROSPECTS

GroundBIRD is a millimeter-wave telescope to observe polarization patterns of CMB. Continuous rapid scanning at 120°/s will enable large angular scale observations. The telescope was installed in Teide Observatory in September 2019 and achieved the first light by observing the moon. Entire sky region of GroundBIRD were also successfully observed with four MKID pixels simultaneously. We are now fabricating the full MKID arrays for the science observation. After upgrading the detector arrays with new readout boxes, we will start the science observation in 2021.

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