Toward Eurasian SubMillimeter Telescopes: the Concept of Multicolor SubTHz MKID-Array Demo Camera MUSICAM and its Instrumental Testing

Ran Duan  
National Astronomical Observatory  
Chinese Academy of Science  
Beijing, China  
duanran@nao.cas.cn

Vladimir Khaikin  
Special Astrophysical Observatory  
Russian Academy of Science  
St. Petersburg, Russia  
vkhstu@mail.ru

Mikhail Lebedev  
Special Astrophysical Observatory  
Russian Academy of Science  
St. Petersburg, Russia  
m.k.lebedev@gmail.com

Vladimir Shmagin  
Institute of Astronomy  
Russian Academy of Science  
Moscow, Russia  
csve00@gmail1.com

Grigory Yakopov  
Special Astrophysical Observatory, Institute for Physical Problems  
Russian Academy of Science  
Nizhny Arkhyz, Russia  
yakopov@gmail.com

Vyacheslav Vdovin  
Institute of Applied Physics  
Russian Academy of Science  
Nizhny Novgorod, Russia  
vvodvin@ipfran.ru

Grigoriy Bubnov  
Institute of Applied Physics  
Russian Academy of Science  
Nizhny Novgorod, Russia  
bubnov@ieee.org

Xinxin Zhang  
National Astronomical Observatory  
Chinese Academy of Science  
Beijing, China  
zxx214@126.com

Chenhui Niu  
National Astronomical Observatory  
Chinese Academy of Science  
Beijing, China  
peterniu@nao.cas.cn

Shaoliang Li  
National Astronomical Observatory  
Chinese Academy of Science  
Beijing, China  
lishaoliang@bao.ac.cn

Di Li  
National Astronomical Observatory  
Chinese Academy of Science  
NAOC-UKZN Computational Astrophysics Centre  
University of KwaZulu-Natal  
Durban, South Africa  
dili@nao.cas.cn

V. V., G. B. and I. Z. acknowledge the support by the IAP RAS state program 0035-2019-0005.

Abstract—New challenges in submillimeter wave astronomy require instruments with a combination of high sensitivity and angular resolution, wide field of view and multiband (multicolor) spectral range. New large single mm/submm telescopes are in high demand, as well as their inclusion in the global Event Horizon Telescope (EHT) VLBI network. At the same time, there are no large mm/submm telescopes in Asia at all while appropriate sites exist and their appearance in Asia or Eurasia is long overdue. Kinetic inductance detectors (KID) are ideal for large-format array implementation, which will be necessary for future telescope development. Concept of multicolor subTHz KID-array MUSICAM demo camera and its instrumental testing is given. It allows us to perform some necessary steps toward the creation of the Eurasian SubMillimeter Telescopes (ESMT), which concept and scientific tasks are presented as well.

Keywords—submillimeter astronomy, Eurasian SubMillimeter Telescopes (ESMT), multicolor KID-array

I. INTRODUCTION

One commonly used detector technology for submillimeter wavelengths proposed in 1994 is the transition edge sensor (TES), which is a cryogenic sensor based on the strongly temperature dependent resistance near the superconducting phase transition. To read the signal from a TES, a superconducting quantum interference device (SQUID) is coupled with the detector. TES have been used for the detection of submillimeter/millimeter radiation in many types of instruments; however, their complex fabrication process and readout method make them difficult to scale to larger arrays. Relatively new type of sensor is a kinetic inductance detector (KID; also MKID, where M stands for microwave) first developed at the Caltech and the Jet Propulsion Laboratory (JPL) in the early 2000s. Its action is based on change in the surface impedance of a superconductor due to increase of kinetic inductance caused by the incident photons.

In recent years, the KID technology was chosen and implemented in a number of wide-angle cameras for telescopes, including CCAT-prime. One of impressive MKID-array cameras is the dual-band (2.1 mm and 1.25 mm) NIKA camera for the 30 m IRAM telescope (Pico Veleta, Spain) with a sensitivity of 8 mJy·s$^{1/2}$ and 33 mJy·s$^{1/2}$, respectively, with a total of 2900 pixels (NIKA2) and a 6.5’×6.5’ field of view [1].
KIDs can be easily fabricated on a two- to three-layer wafer and frequency-domain multiplexed; all of the readout functions are performed by room-temperature electronics, with the exception of one cryogenic amplifier. KIDs are ideal for large-array implementation, which will be necessary for future telescope development. For many applications, MKIDs are the first choice, with much simpler fabrication, operation and lower cost than TES.

The example of a multicolor MKID cameras is MUSIC [2]. The discussion in this paper is based on the MUSIC instrument build for CSO. The main goal of the proposed concept of MUSICAM demo camera and its instrumental testing is to perform some necessary steps toward the creation of the Eurasian SubMillimeter Telescopes (ESMT) [3, 4].

II. ESMT CONCEPT AND ATMOSPHERIC LIMITATIONS

In Table I, the largest mm/submm telescopes and antenna arrays, either currently operating or to come into operation until 2025 (the latter marked with *), are listed.

Table I shows that there are no large mm/submm radio telescopes in Asia at all, while appropriate sites exist. Astronomical observations are usually carried out in transparency windows, i.e. at local minima of the absorption spectrum (Fig. 1). Previously, the joint research group of the IAP RAS and NSTU created the equipment and developed methods for studying the astroclimate in the subTHz range. They investigate spectral characteristics of atmospheric transparency in laboratory conditions. Since 2012, regular field studies of the astroclimate have been performed for searching for new sites suitable for subTHz observations in Eurasia [5] (Fig. 1).

With the present technologies, it is unlikely that a 70 m radio telescope can be built that would be effective in mm/submm wavelength range, as currently there are no affordable means of surface control and correction with necessary precision for an antenna of this size. Thus we propose to regard the RT-70 radio telescope, which is under construction in Suffa, Uzbekistan, as an instrument for cm range astronomy applications only. The concept of the ESMT project implies building three new mm/submm telescope of 21 m class located in Suffa (Aktashtau), Uzbekistan (3383 m above sea level), Russia (above 3000 m a.s.l) and in Tibet, China (above 4000 m a.s.l.). The concept was developed by specialists in precise antennas, astroclimate research and subTHz matrix receivers from SAO RAS, IAP RAS and NAOC together with EIE Group (www.eie.it). It was suggested to take the design of European ALMA antennas (12 m) as a starting point, increase their diameter to the maximum possible without fundamental changes in the design of the truss frame and panels, and supplement them with an “active surface”, tertiary optics, including adaptive optics. The well-developed, closed, thermostatbale high modulus carbon fiber reinforced polymer truss structure preserves its shape, while all its dimensions increase proportionally. Mechanical and thermal modeling performed in EIE Group has shown the possibility and ways of such a scaling for the antenna diameter up to 20-21 m [4].

### Table I

| Facility   | Location        | Diameter, m | Altitude, m | Shortest wavelength, mm |
|------------|-----------------|-------------|-------------|-------------------------|
| LMT        | Mexico (Sierra Negra) | 50          | 4600        | 0.85                    |
| IRAM       | Spain (Sierra Nevada) | 30          | 2850        | 0.9                     |
| JCMT       | Hawaii (Mauna Kea) | 15          | 4092        | 0.4                     |
| APEX       | Chile (Atacama)  | 12          | 5058        | 0.23                    |
| GLT*       | Greenland (Summit, now in a test mode in Thule) | 12          | 3210        | 0.2                     |
| NOEMA*     | France (Alps, Plateau de Bure) | 15x12       | 2550        | 0.8                     |
| ALMA       | Chile (Atacama)  | 12×54 + 7×12 | 5100        | 0.32                    |
| SPT        | South Pole      | 10          | 2800        | 0.4                     |
| LLAMA*     | Argentina (Atacama) | 12          | 4820        | 0.35                    |
| SMT        | Mount Graham, Arizona, US | 10          | 3185        | 0.3                     |
| CCAT-prime* | Chile (Atacama)  | 6           | 5616        | 0.2                     |

Fig. 1. Sites tested for the astroclimate conditions (top), tipping radiometer in BTA tower window (middle), PWV cumulative distribution for BTA in 2014 (bottom).
The expected accuracy of the surface of the main mirror is not worse than 25 μm (RMS) for a diameter of 21 m and 15 μm (RMS) for a diameter of 15 m. The upper frequency band for such a telescope in the best Tibet atmospheric conditions is 1.5 THz (Ali2), 0.95 THz (Ali1), 0.85 THz (Yangbajing). Expected PWV and transmission for Yangbajing site in comparison with Atacama desert sites, (Yangbajing). Expected zenith Planck brightness temperatures $T_B$ at 220 GHz for Ali1 and Ali2 are 30-34 K and 19-23 K for 75% of time [7].

| Site                                           | Altitude, m | PWV, mm | Minimum transmission, % $\lambda = 350$ μm | Minimum transmission, % $\lambda = 200$ μm |
|------------------------------------------------|-------------|---------|------------------------------------------|------------------------------------------|
| Yangbajing, Tibet, China (CCOSMA)              | 4300        | 1.21    | 2.45                                     | 19                                       |
| Ali1, Tibet, China (AliCPT)                    | 5250        | (0.55)  | (0.871)                                  | <49                                      |
| Ali2, Tibet, China                            | 6100        | (0.25)  | (0.459)                                  | >65                                      |
| Chajnantor plateau, Chile (ALMA, APEX)        | 5058        | 0.39    | 0.53 (0.618)                             | 56                                       |
| Cerro Chajnantor, Chile (CCAT)                | 5612        | 0.27    | 0.37 (0.48)                              | 65                                       |
| Cerro Macon, Argentina                         | 5032        | 0.47    | 0.66                                     | 49                                       |
| Summit, Camp, Greenland (GLT)                 | 3210        | 0.36    | 0.51                                     | 42                                       |
| Mauna Kea, Hawaii (JCMT)                      | 4100        | 0.62    | 0.91                                     | 40                                       |

III. SCIENTIFIC TASKS FOR ESMT

Observations with large millimeter/submillimeter telescopes are important for solving a number of topical astrophysical problems. These include, for ESMT, in particular, the following.

Studies of the star formation process. Despite the large number of works in this direction, many important aspects of this process remain unclear. This is especially true for the formation of massive stars. The peak of radiation from star-forming regions in spectral lines and in the continuum falls in the submillimeter range, which makes the observations of such objects in this range especially important. Studies of star-forming regions will be carried out both in our galaxy and in other galaxies.

The expected accuracy of the surface of the main mirror is not worse than 25 μm (RMS) for a diameter of 21 m and 15 μm (RMS) for a diameter of 15 m. The upper frequency band for such a telescope in the best Tibet atmospheric conditions is 1.5 THz (Ali2), 0.95 THz (Ali1), 0.85 THz (Yangbajing). Expected PWV and transmission for Yangbajing site in comparison with Atacama desert sites, (Yangbajing). Expected zenith Planck brightness temperatures $T_B$ at 220 GHz for Ali1 and Ali2 are 30-34 K and 19-23 K for 75% of time [7].

IV. CONCEPT OF THE MUSICAM DEMO

Just like the MUSIC Multiwavelength Sub/millimeter Inductance CAMera [2], the proposed demo device (the MUSICAM-demo camera) will combine sensors for four wavelength ranges corresponding to water vapor transparency windows of 2.0 mm, 1.33 mm, 1.04 mm, and 0.86 mm, with $5 \times 5 \times 4 = 100$ pixels. Broadband superconducting phased-array slot-dipole antennas will be used to form beams, and lumped element on-chip bandpass filters will define spectral bands. Expected NEP of KIDs in these ranges is $5.6, 7.8, 8.2, \text{ and } 8.9 \times 10^{-17}$ W·Hz$^{-1/2}$ [12]. To

Study of galaxy clusters based on observations of the Sunyaev — Zeldovich effect. This task is now especially urgent in connection with the successful start of the operation of the Spektr-RG space observatory, which records the X-ray radiation of these objects. The combination of observational data in the X-ray and radio ranges allows one to estimate both the physical characteristics of the clusters and some cosmological parameters.

Research of sources of gravitational waves and gamma-ray bursts. A burst of gravitational waves from merging black holes was first recorded several years ago. Since then, several similar events have been recorded, including such a burst from the merger of neutron stars. Till now, there is almost no identification of these events with known astronomical objects. To identify and study the properties of these sources, observations in various ranges, including those at submillimeter waves, are important. Gamma-ray bursts have been observed for a long time, but the mechanism of their generation is still unclear. Observations of the emission spectra of gamma-ray burst sources in different wavelength ranges are important for solving this problem.

Search for new chemical compounds in space, in particular, complex organic molecules. This task is important, in particular, for the search for life in the Universe, which is one of the main challenges for the mankind.

Search for distortions of the microwave background spectrum due to primary molecules and energy release in the early Universe [8, 9]. Apparently, this is the only way to get information about the so-called “Dark Ages” of the Universe, the era between the recombination of the primary plasma and the formation of the first stars and galaxies. Such information will make possible the understanding of the processes of formation of structures in the early Universe, from which the observed objects arose.

Search for HeH$^+$ and other primordial molecules such as LiH, HD$, H_2D^+$ in the Universe [9, 10].

Studies of supermassive black holes in the centers of galaxies as part of the global interferometric network “Event Horizon Telescope” (EHT). Quite recently, the EHT collaboration presented the first results of observations of the “shadow” of a supermassive black hole in the M87 galaxy [11]. The extension of this network with submillimeter telescopes in Asia (where they are currently absent) will significantly increase its capabilities and allow obtaining better images of such objects. The angular resolution of the terrestrial network so far allows us to study practically only two such objects, in M87 and in the center of our Galaxy. In the future, with the advent of a space telescope of the millimeter range (the Millimeter project), the list of objects will be significantly expanded.
achieve physical temperature of 250 mK a compact dilution cryostat will be used [13].

A. Design of camera wafer

As shown in Fig. 2, signal is first received by the phased-array antenna and then split into different frequency bands determined by the BPF network. The output of each filter is fed into one LC resonator, which is coupled to the feedline.

As shown in Fig. 3, when the aluminum superconductor receives photons, the photons break Cooper pairs and create quasiparticles, which change the surface impedance of the aluminum superconductor. Because the aluminum section is part of the meander inductor of the LC resonator, the photons cause the inductance of the LC resonator to change, thereby affecting its resonance properties including the phase and power (i.e., a measure of how the resonator couples to the microstrip line). By monitoring the resonance properties, we can detect signals at submillimeter wavelengths. We call such an LC resonator a microwave KID. Overall, the KID-based instrument that we developed is an ideal choice for use in submillimeter instruments because of the following features: 1. The detectors are frequency-domain multiplexed with hundreds of detectors coupled through one feedline. 2. The process for fabricating a large detector array is relatively simple, consisting of two to four layers of a lithographic process on a silicon wafer. 3. The readout system for this large detector array has been developed and demonstrated to satisfy large-array requirements. These advantages not only make the KID-based instrument scalable to larger arrays but also allow for cost control on a per-pixel basis.

B. Readout for Kinetic Inductance Detectors

The readout system will perform frequency domain multiplexed real-time measurements of complex microwave transmission coefficient in order to monitor the instantaneous resonant frequency of superconducting microresonators and changes in their energy dissipation. Each readout unit similar to those used in the MUSIC device will be able to cover up...
to 550 MHz bandwidth and read 256 complex frequency channels simultaneously [14]. The digital electronics include the customized DAC, ADC, IF system and the FPGA based signal processing hardware developed by CASPER group.

In general, the procedure for the KID readout is as follows:

1. A drive tone or carrier tone (which generally ranges from approximately 100 MHz to a few gigahertz) is sent through the transmission line on the device with which the detector is coupled. The drive tone is then modulated by the detector as it responds to the power of the astronomical signal.

2. If the modulated carrier tone is at a frequency that is too high to be directly digitized, it is down-converted using a mixer.

3. The received tone is digitized and processed. This step includes digitizing the analog signal and processing the digital signal using a field-programmable gate array (FPGA), a graphics processing unit (GPU), a central processing unit (CPU), or some combination thereof. The signal from the detector generally requires real-time processing to capture the signal source, reduce the data rate, and extract useful information.

4. Auxiliary information such as a timestamp or information regarding the telescope is stored on the data acquisition (DAQ) computer.

5. Frequently, the raw data must be subjected to additional computer-based processing steps prior to use. These steps may include serialization of the data stream, noise reduction, trans-formation of the data format or units, calibration, or map making.

V. INSTRUMENTAL TESTS OF MUSICAM-DEMO CAMERA

For instrumental tests of the MUSICAM-demo camera in all four bands Russian telescopes BTA (Nizhny Arkhyz, 2100 m) and Zeiss-2000 (Terskol, 3100 m) will be used. To use the MUSICAM-demo efficiently, tertiary and relay sub-THz quasi-optics must be developed in order to match the camera to a particular telescope. The optimal matching has to meet two requirements: (I) two celestial objects just resolved by the telescope optics must map on two adjacent pixels in the image plane; (II) elements of the receiver array must be fed appropriately, which in the case of the MUSICAM-demo receivers means that the output beam of the entire system lit by a parallel ray bundle must have an effective f-number of 3.0. Given the telescope f-number and its focal distance, as well as pixel spacing and overall dimensions of the sensor array, one can design the necessary matching system. The possible optical layouts for matching MUSICAM-demo with BTA and Zeiss-2000 are presented in Fig. 6. The Strehl ratio for all the beams is greater than 0.98 in both cases. Modeling shows that because of vignetting the matching optics for the BTA and Zeiss-2000 telescopes must be designed to provide certain oversampling, i.e. overlapping of the adjacent beams at level higher than -3 dB, which will allow for simultaneous testing of all the pixels at the expense of reducing the FOV of the system. Tests of the MUSICAM-demo camera in the wavelength ranges of 2 mm/1.3 mm and 1.08/0.86 mm are planned to be conducted at BTA and Zeiss-2000 respectively. The percentage of days suitable for qualitative observations at 2 mm and 1.3 mm with BTA is, according to AIRS data, more than 25 and 7, respectively. To assess the possibility of performing effective observations on Zeiss-2000 at wavelengths of 1.08 mm and 0.86 mm, a long-term study of the astroclimate in subTHz range at Terskol began. The first results of measurements of the optical depth at a wavelength of 2 mm in Terskol are encouraging. The latest astroclimate measurements of sites under study are given in [15]. Some results of astroclimate study and more details about the ESMT concept are presented in [16].

REFERENCES

[1] R.Adam et al., “The NIKA2 large-field-of-view millimetre continuum camera for the 30 m IRAM telescope,” A&A 609, A115, 2018.

[2] J. Sayers et al., “The status of MUSIC: the multiwavelength sub-millimeter inductance camera,” Proc. SPIE 9153, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, 915304, 2014.

[3] R. Duan et al., “Toward Eurasian SubMillimeter Telescopes: the concept of multicolor subTHz MKID-array demo camera MUSICAM and its instrumental testing,” All-Russian Microwave Week 2020. (Arxiv: 2008.10154)

[4] G. Marchiori, F. Rampini, M. Spinola, S. De Lorenzi, R. Bressan, and M. Tordi, “Towards the Eurasian Sub-Millimeter Telescope (ESMT): concept outline and first results,” All-Russian conference “Terrestrial astronomy in Russia. XXI century”, N.Arkyz, September 21-25, 2020.

[5] G. M. Bubnov et al., “Searching for new sites for THz observations in Eurasia,” IEEE Trans. THz Sci. Technol., vol. 5, no. 1, pp. 64–72, 2015.

[6] P. Tremblin, N. Schneider, V. Minier, G. Al. Durand, and J. Urban, “Worldwide site comparison for submillimetre astronomy,” A&A 548, A65, 2012.

[7] Chao-Lin Kuo, “Assessments of Ali, Dome A, and Summit Camp for mm-wave Observations Using MERRA-2 Reanalysis,” Astrophys. J., vol. 848:64 (11pp), 2017.

[8] Y. B. Zeldovich, and R. A. Sunyaev, “The interaction of matter and radiation in a hot-model universe,” Astrophys. Space Sci., vol. 4, pp. 301–316, 1969.
[9] V. Dubrovich, A. Bajkova, V. Khaikin, “Spectral spatial fluctuations of CMBR: Strategy and concept of the experiment,” New Astronomy, vol. 13, no. 1, 2008.

[10] I. Zinchenko, V. Dubrovich, and C. Henkel, “A search for HeH and CH in a high-redshift quasi-stellar object,” Mon. Not. R. Astron. Soc., 415, L78, 2011.

[11] The Event Horizon Telescope Collaboration, “First M87 Event Horizon Telescope results. I. The shadow of the supermassive black hole,” Astrophys. J. Lett., vol. 875, no. 1, 2019.

[12] R. Duan, “Instrumentation for KID-based Submillimeter Radio Astronomy,” PhD thesis, Caltech, 2013.

[13] V. S. Edelman, and G. V. Yakopov, “A dilution microcryostat cooled by a refrigerator with an impulse tube,” Instrum. Exp. Tech., vol. 56, pp. 613–615, 2013.

[14] Ran Duan et al., “An open-source readout for MKIDs,” Proc. SPIE 7741, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V, 77411V, 2010.

[15] Yu. Yu. Balega et al., “Development of receivers for space, balloon and ground radio telescopes and the development of subterahertz astronomy,” Izv. vuzov. Radiophysics, in press.

[16] V. Khaikin et al. On the Eurasian submillimeter telescopes project (ESMT). all-Russian Microwave Week 2020, Moscow, Nov. 2020.