SUCCESSFUL OPERATION OF A 1 THz NbN HOT-ELECTRON BOLOMETER RECEIVER

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Abstract

A phonon-cooled NbN superconductive hot-electron bolometer receiver covering the frequency range 0.8 - 1.04 THz has successfully been used for astronomical observation at the Sub-Millimeter Telescope Observatory on Mount Graham, Arizona. This waveguide heterodyne receiver is a modified version of our fixed-tuned 800 GHz HEB receiver to allow for operation beyond 1 THz. The measured noise temperature of this receiver is about 1250 K at 0.81 THz, 560 K at 0.84 THz, and 1600 K at 1.035 THz. It has a 1 GHz wide IF bandwidth, centered at 1.8 GHz. This receiver has recently been used to detect the CO (9 → 8) molecular line emission at 1.037 THz in the Orion nebula. This is the first time a ground-based heterodyne receiver has been used to detect a celestial source above 1 THz.

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I. INTRODUCTION

As superconducting receiver technology has matured in recent years, low-noise heterodyne receivers have been developed for the THz frequency band. The first laboratory superconducting heterodyne mixer operating above 1 THz was reported in 1996 [1]. This receiver used an SIS mixer, which can offer nearly quantum-limited noise performance up to 1 THz, but which becomes very noisy above 1 THz. Since then, several groups have reported low noise performance at THz frequencies using receivers that employ superconductive hot-electron bolometer (HEB) mixers [2-4].

The Submillimeter Receiver Laboratory at the Harvard-Smithsonian Center for Astrophysics has been collaborating with the Moscow State Pedagogical University since 1994 to develop phonon-cooled HEB waveguide mixers. This effort has been very fruitful, and we have been able to routinely produce submillimeter and terahertz receivers having noise temperatures in the range of $10 - 20h\nu/k$, at operating frequencies up to 1.26 THz in our laboratory [5,6]. In the winters of 97/98 and 98/99, we installed our 800 GHz HEB receiver on the 10-m Heinrich Hertz Telescope on Mt. Graham, Arizona. This receiver was the first superconductive HEB receiver deployed outside a laboratory environment [7]. It was used successfully to detect molecular emission lines from a number of astronomical sources at 690 and 810 GHz [8].

In this paper, we report on improvements to this receiver that extend its frequency of operation to beyond 1 THz. Earlier this year, this receiver was successfully used to detect the molecular emission of CO($9 \rightarrow 8$) at 1.037 THz in the Orion Nebula (M42). This marks the first time a ground-based heterodyne instrument has ever detected a celestial source above 1 THz.

II. INSTRUMENT DESIGN

A. Hot Electron Bolometer Elements

The mixer elements are made from high-purity NbN film deposited on a heated 0.1-mm-thick z-cut crystalline quartz substrate. The film is about 4 nm thick. The critical temperature, T_c, of the film is about 9 K, and it has a transition width of about 0.5 K. The active area of the bolometer, lying between two normal-conducting TiAu electrodes, is about 2 μm wide by 0.2 μm long. The normal-state resistance (R_N) of the bolometers is fairly uniform over a single wafer.

The quartz wafer is first diced into small blocks of about 5 mm square before before lapped and polished to a thickness of 23 μm. After lapping, the individual mixer chips measure 90 μm wide and 1.4 mm long are diced from these square blocks. Even with these small dimensions the mixer chips are quite robust and are rather easy to handle. The particular device used in the astronomical receiver has a room temperature resistance of about 350 Ω and a critical current of 85 μA. The useful upper limit to the IF bandwidth of these devices is about 2.5 GHz.

B. Mixer Assembly Design

The mixer assembly is adapted from the design of the highly successful fixed-tuned SIS mixer we developed for the Submillimeter Array [9]. It is made in two sections. The front section carries the corrugated feed horn, which is electroformed and shrunk-fit into a copper mounting block. The horn terminates in a section of half-height rectangular waveguide, measuring $254 \times 64\,\mu$m. The back section of the mixer assembly houses a shorted section of waveguide, measuring $200 \times 50 \times 60\,\mu$m. The quartz chip is suspended across the waveguide and is clamped between the two halves of the mixer assembly. It is electrically contacted by two 75 μm diameter wires, one to the IF connector, the other is grounded in the mixer block.

C. Receiver Layout

The layout of the receiver is shown in Fig. 1. The mixer assembly is mounted to the cold plate of a liquid helium-cooled cryostat that has a liquid nitrogen cooled radiation shield. The corrugated feed horn illuminates a 30° off-axis parabolic mirror ($f = 55$ mm) positioned near the center of the dewar cold plate. The beam reflected off the paraboloid passes through two layers of porous Teflon sheet thermally anchored to the cold plate. These are followed by a 5 mm thick crystalline quartz infrared blocking filter mounted on the 77 K radiation shield. 55 μm deep grooves are machined into both sides of the quartz for the purposes of eliminating surface reflections. A 0.5 mm-thick Teflon sheet is used as the vacuum window.

Radiation from the LO assembly is collimated by a 90° off-axis parabolic mirror before it is combined with the signal beam from the signal port in a Martin-Puplett interferometer (MPI), which is placed in front of the cryostat vacuum window. In the laboratory, the interferometer employs free-standing wire grid polarizers with 10 μm diameter wire. On the telescope, wire grid polarizers with 20 μm

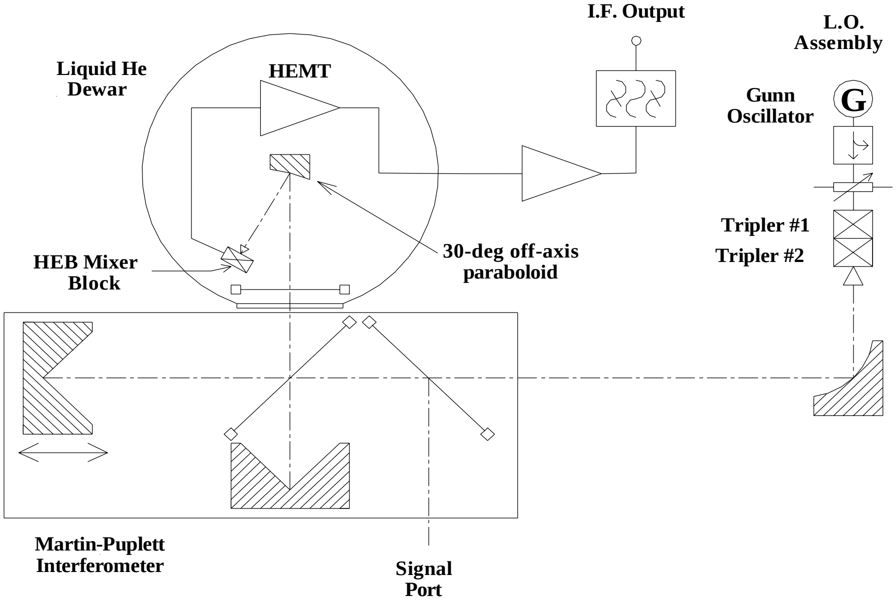

Fig. 1 Layout of the Receiver. The mixer assembly, parabolic mirror and the HEMT amplifer are mounted on the 4.2 K cold plate. The MPI is placed in front of the cryostat vacuum window. The optical path from the vacuum window to the signal port is approximately 0.5 m.

diameter wire are used. The insertion loss of the MPI is estimated to be $\sim 1\,\mathrm{dB}$.

The output of the mixer is connected to a $1.4-2.2$ GHz high-electron mobility transistor (HEMT) amplifier, mounted on the same 4.2 K cold plate, through a bias tee. No isolator is used between the mixer block and the amplifier. After second-stage room temperature amplification, the IF signal is fed through an equalizer to flatten the receiver output across the entire IF band. During actual telescope operations, the usable IF bandwidth is 1 GHz wide: $1.3-2.3$ GHz. In our laboratory, a 100 MHz wide IF filter, centered at 1.5 GHz, was employed for hot/cold load receiver noise measurement.

D. Local Oscillator Sources

We estimate that the incident LO power at the LO port of the MPI is less than 1 μW, when the mixer is biased at its optimal operating point. With some care in the optics design, we were able to provide sufficient LO power using all solid-state LO units, each comprised of a Gunn oscillator followed by 2 stages of varactor multiplication [10].

Two LO units were available for operation at the telescope. The first one covers 780–840 GHz. This unit uses a 130 - 140 GHz Gunn oscillator and a cascaded frequency doubler and tripler. The second LO unit covers 1.017–1.035 THz, with a 112 - 115 GHz Gunn oscillator and a cascade of two triplers. In addition, a third unit covering 800 - 936 GHz was available in the laboratory. This unit incorporates a Gunn oscillator operating between 100 and 117 GHz, linked to a first-stage doubler and a second-stage quadrupler.

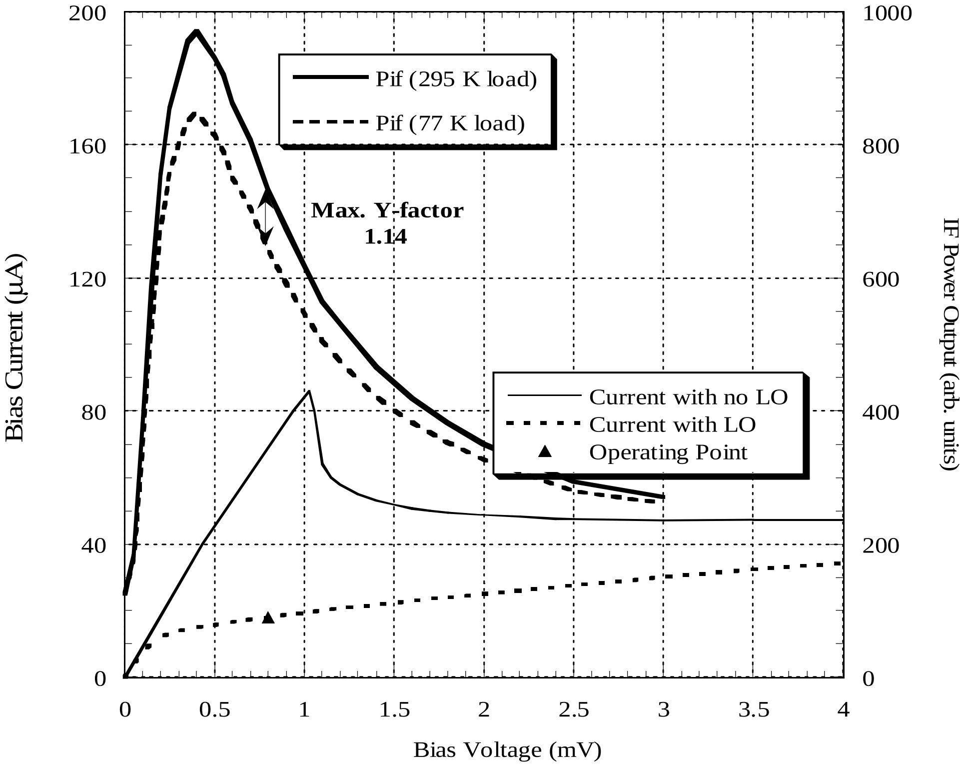

Fig. 2 Current-voltage characteristics of the HEB mixer, with and without LO drive at 1.035 THz. Also shown is the receiver IF power as a function of bias voltage in response to the hot (295 K) and cold (77 K) loads. A maximum Y-factor is recorded at a bias voltage of 0.8 mV and a bias current of 18 μA.

III. MEASURED PERFORMANCE

The current-voltage $(I-V)$ characteristics of the mixer are plotted in Fig. 2. Shown in the same figure are the curves of receiver IF output power in response to hot and cold loads placed at the signal port, the LO frequency was 1.035 THz. The graph shows that a Y-factor of 1.14 was obtained at a bias voltage of 0.8 mV and a bias current of 18 μA. The double-side-band (DSB) conversion loss at this operating point is estimated to be about 17 dB. The choice of this operating point is also dictated in part by stability consideration. At slightly lower bias voltage, the conversion efficiency of the mixer is higher and the Y-factor is comparable but the stability is not as good. At our optimal operating point, the receiver IF output power fluctuates by less than 0.5% over about 1 minute.

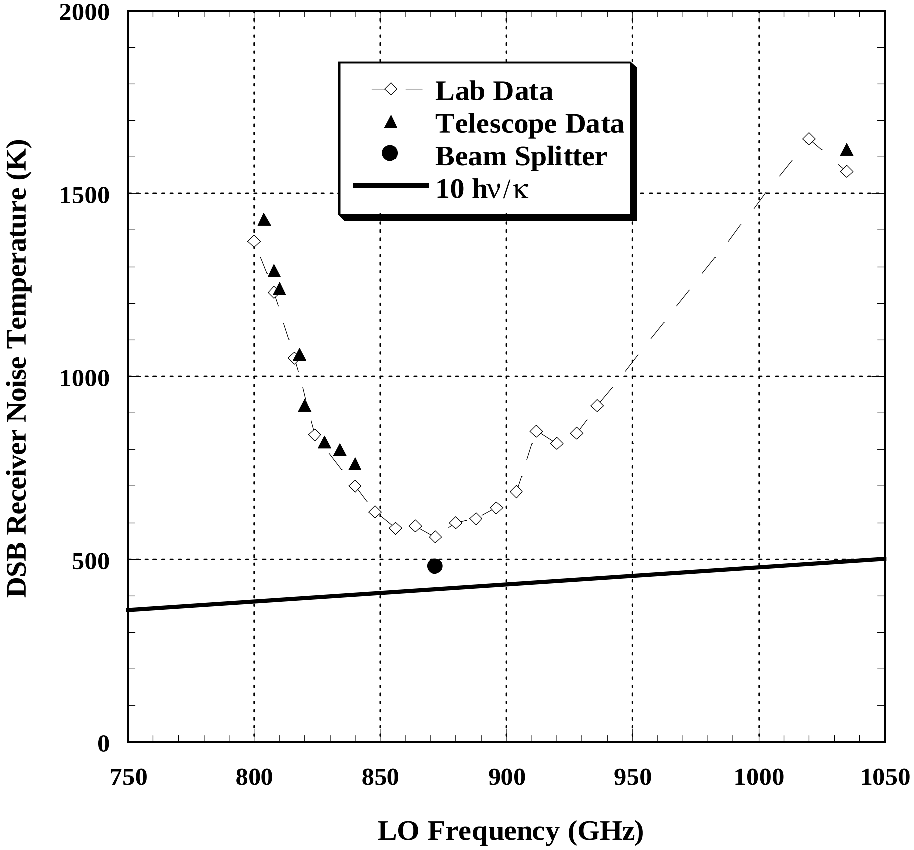

Fig. 3 Double-side-band receiver noise temperature calculated from the Y-factor for both hot/cold load measurements in the laboratory and on the telescope. Also shown is the data for the case when the MPI was replaced by a beam splitter in the laboratory.

In Fig. 3, we have plotted the receiver noise temperature calculated from the measured Y-factor as a function of LO frequency. The receiver is most sensitive at around 872 GHz where a DSB noise temperature of 560 K was measured in our laboratory. When the MPI was replaced by a wire grid diplexer with 10% coupling, the Y-factor improved to 1.39, corresponding to a receiver noise temperature of 480 K, or $11.5\,h\nu/k$. The receiver noise temperatures measured on the telescope were found to be comparable to those measured in the laboratory, demonstrating that low noise performance is repeatable in drastically different environments, and with different operators.

The radio beam emerging from the cryostat was measured and aligned in our laboratory using a near-field vector measurement set-up [11,12]. In this procedure, the MPI was first replaced by a mylar beam splitter. A Gunn oscillator pumping a harmonic generator was mounted on a near-field measurement X-Y stage. Measurements were carried out at 807.5 GHz. A WR-1.5 probe was employed to give a spatial resolution of 0.4 mm. On the measurement plane, the diameter of the beam at the $-10\,\mathrm{dB}$ points is about 12 mm. Therefore, the ratio between the beam size to the cross-sectional area of the waveguide probe is about 3000. Even so, a signal-to-noise ratio in excess of 30 dB was obtained at the center of the beam. We believe that this is the highest frequency near-field vector scan that has ever been performed.

Successive scans were performed. The resultant vectorial beam maps were used to determine the optical axis of the receiver. Using these data, the various optical elements of the receiver setup were adjusted. As a result of defects of the dewar, the 30° off-axis paraboloid inside the cryostat had to be shimmed substantially to obtain a straight beam. Finally, the MPI was inserted, and the output beam of the receiver was mapped again. Both the amplitude and phase maps of the beam are plotted in Fig. 4. Note there are no side lobes above $-25\,\mathrm{dB}$. The final beam size is larger than the design value. This is probably caused by the shimming of the parabolic mirror, which results in a change of the effective focal length of the mirror. Our calculation suggests that this slower beam would produce an edge taper of about 17.5 dB on the telescope's secondary instead of the 12 dB designed taper.

The receiver is not affected by saturation and direct detection effects. From the total power - voltage curve in Fig. 2 and our estimate for the conversion loss, we estimate that the mixer would require about 10 nW at its input to be driven into output saturation. This value is significantly higher than the power due to incident thermal radiation from an ambient load with an IF bandwidth of about 2 GHz. From the noise temperature plot of Fig. 3, we estimate that the RF bandwidth of the receiver is about 200 GHz. The incident radiation from an ambient load with 200 GHz bandwidth is more than an order of magnitude smaller than the LO power used to operate the receiver. Thus, direct detection effects are also expected to be minimal. At the optimal operating point given in Fig. 2, the bias current changes by 60 nA, or about 0.3%, when switching between hot and cold loads,

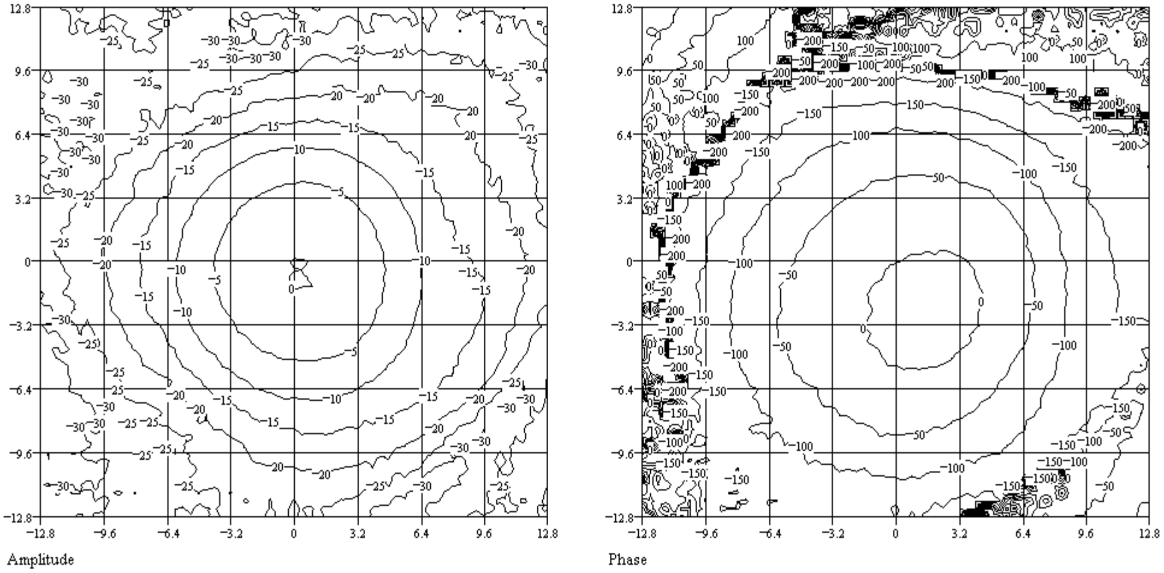

Fig. 4 Amplitude (dB) and phase (deg) maps of the receiver beam at the signal port of the MPI at 807.5 GHz. 65 x 65 data points are taken at a step size of 0.4 mm. At the center of the beam, a signal-to-noise ratio of more than 30 dB was obtained. The phase map shows that there is a residual beam tilt of 0.3 degrees off boresight. This residual misalignment was taken out during installation on the telescope.

under constant voltage bias. When the MPI is replaced by a beam-splitter, the change in bias current is approximately doubled because the MPI admits only half of the bandwidth of the incident thermal radiation from the hot and cold loads. In all our measurements, bias current changes due to direct detection are less than 1%. Therefore, the effects of direct detection on the actual heterodyne sensitivity are very small. This is confirmed by the fact that the calibration of astronomical spectral lines recorded by this receiver matches that of the same spectral lines recorded by other telescopes.

IV. TERAHERTZ DETECTION

In January this year, we took advantage of a period of excellent weather conditions on Mount Graham to operate the receiver above 1 THz. The zenith opacity of the sky at 225 GHz dropped to below 0.03, as indicated by a tipping radiometer near the telescope. Near 1.037 THz, the receiver noise temperature was 1600 K, and the total system single-sideband noise temperature was about 4×10^5 K. The zenith atmospheric transmission was approximately 3%, and towards the source

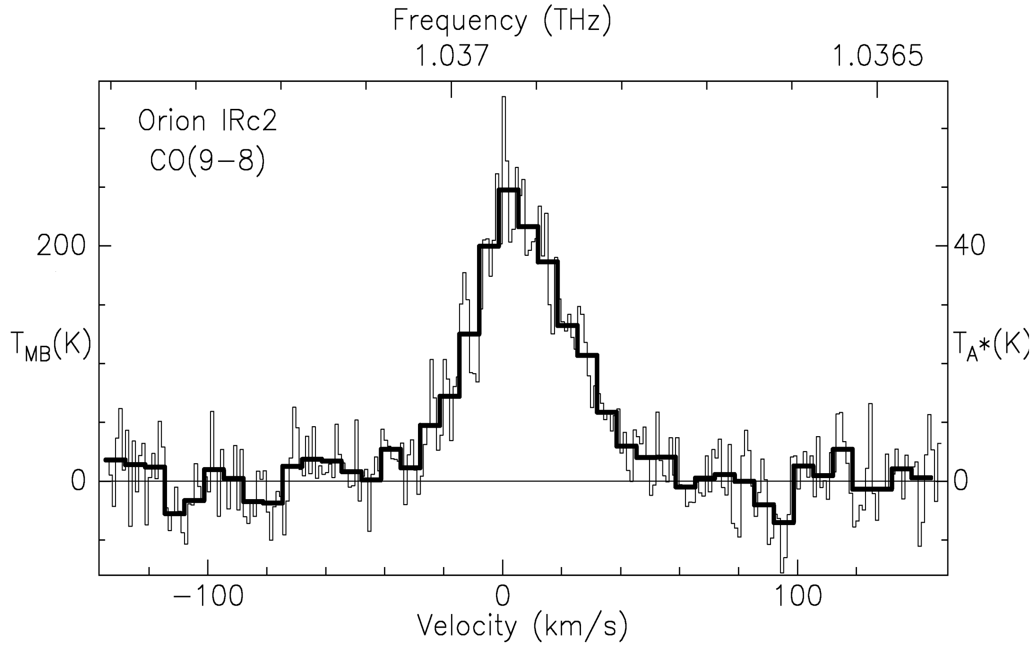

Fig. 5 Spectrum recorded by the HEB receiver at an LO frequency of 1.0352 THz from the Orion nebula. The resolution of the IF spectrometer was 4 MHz. The solid line shows a smoothed spectrum at a resolution of 25 MHz. The temperature scale of the spectrum is calibrated by taking into account the receiver noise temperature, estimated atmospheric opacity and estimated efficiency of telescope.

we observed, which is at an elevation angle of 50°, the transmission was about 1%. However, with just 8 minutes of integration time and a spectral resolution of 4 MHz, we recorded a fully resolved, clear spectrum of the CO($9 \rightarrow 8$) molecular line emission at 1.037 THz in the Orion Nebula. Fig. 5 shows the spectrum recorded by the acousto-optical spectrometer of the telescope. The peak antenna temperature, T_A^*, which is corrected for atmospheric absorption, is about 50 K and the baseline rms noise level is about 5 K, at a resolution of 4 MHz.

Since no observations of planets were possible, we have no reliable measurement for neither the telescope aperture efficiency nor the main-beam efficiency. However, by extrapolating the data that we obtained near 800 GHz with the same receiver, we estimate the efficiency of the telescope to be about 20%. We therefore infer that the brightness temperature, $T_{\rm MB}$, of the emission line is $\sim 250\,$K within the $8''$ diameter beam of the telescope. Note that the signal-to-noise ratio is in excess of 10 for a spectral resolution of 25 MHz.

V. CONCLUSION

A waveguide-mounted phonon-cooled NbN hot-electron bolometer receiver has successfully been installed for operation at the Submillimeter Telescope Observatory on Mount Graham, Arizona. The receiver covers the frequency range 0.8 - 1.04 THz, and it has been used in the first ground-based heterodyne detection of a spectral emission from a celestial source above 1 THz. We have demonstrated the feasibility of making THz observations even from ground-based instruments. Recent FTS measurements at other, higher altitude sites confirm that there are atmospheric windows with sufficiently high transmission above 1 THz [13] to justify a ground-based facility for THz radio-astronomy.

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