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Prospects for Terahertz Radio Astronomy from Northern Chile

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Abstract

The terahertz (THz) frequency range (1-3 THz, or 100-300 μm wavelength) provides an important window on the far-infrared Universe. Recent studies of the transmission spectrum of Earth's atmosphere reveal that windows centered at 1.03 THz, 1.3 THz, and 1.5 THz become significantly transparent from high altitude (> 5000m) sites in northern Chile. We are currently building a small radio telescope antenna in order to assess the feasibility of ground-based THz astronomy. The antenna, an 800 mm diameter paraboloid, has a surface accuracy of 3 μm rms and a beam width of about 1 arcminute at 1.5 THz. It will be coupled to HEB receivers, also under development at SAO. Initial astronomical tests will be carried out in the 850 GHz and 1.03 THz atmospheric windows. Receivers for the two higher frequency bands are currently under development and are expected to be deployed towards the end of 2002.

Introduction

Between the far infrared and the shortest radio wavelengths lies a region of the electromagnetic spectrum rich in astrophysical information, yet virtually unexplored. The dearth of scientific data in this spectral region is not due to lack of interest, for it provides unique targets for both interstellar chemistry and star formation studies. However, even though windows at 225 and 200 μm had been observed from Pikes Peak as long ago as 1971 [1], and it had been predicted that the South Pole may offer some atmospheric transmission in the far infrared [2], it has been generally accepted that 1 THz represents the upper frequency bound for radio observation from the ground [3]. Hence, this frequency regime has been left to a few groups with access to balloons or aircraft, such as the Kuiper Airborne Observatory (KAO) [4], which was designed as a platform from which to make astronomical observations in the wavelength range 1 – 500 microns. Several groups have used the KAO to make spectroscopic measurements in the frequency range 1 – 3 THz, but it ceased operations towards the end of 1995. Since that time, radio astronomy observation above 1 THz has been relegated to the unenviable position of waiting for the 2008 launch of the Herschel Observatory [5], which will perform herterodyne spectrosopy in the frequency range from about 0.5 to 2 THz, or waiting for the KAO replacement, the Stratospheric Observatory For Infrared Astronomy (SOFIA) [6], which will carry a number of instruments and perform heterodyne spectroscopy to about 3 THz for approximately 20% of the time it operates.

Site selection and potential observations

In 1995, the National Radio Astronomy Observatory began a series of measurements to evaluate the feasibility of performing millimeter and submillimeter astronomical observations from Chajnantor, a plateau at 5,000 m altitude, in the Atacama region of northern Chile. It soon became apparent that this site offered excellent atmospheric transmission in both the millimeter and submillimeter, and is superior to any of the developed sites currently in use for radio astronomy. Largely as a result of the superior transmission offered at the Chajnantor site at 350 μm, we developed a purpose-built Fourier Transform Spectrometer (FTS) to evaluate the site for potential use for astronomical observation above 1 THz. The FTS continuously measures the sky brightness in order to determine the atmospheric opacity over the frequency range 350 GHz to 3 THz, and was installed at the Chajnantor site in the fall of 1997. Measurements made in the 1998 austral winter demonstrate that ground-based astronomical observations could be made from this site in the atmospheric windows centered at 1.03 THz, 1.3 THz, and 1.5 THz [7].

These windows provide unique targets to both interstellar chemistry and star formation studies. Put simply, cool interstellar clouds (10-15K) emit their strongest continuum emission in the 1.0-1.5 THz range. Also, in hot cores (50-200 K) where stars are currently forming, the high-*J* rotational transitions of common molecular species such as CO, CN, HCN, and HCO^+ emit their strongest rotational radiation in this frequency range. Near both young and evolved stars, molecules exist across a large range of excitation levels, with the more highly-excited states often lying closer to the exciting source or protostar. Surveys of objects in these lines will likely provide a good discriminator of the various stages of protostellar evolution, and for lines falling within the atmospheric windows, a ground-based telescope will offer substantial advantages over aircraft- and balloon-based platforms in terms of cost, logistics, and available observing time.

Figure 1 shows a selection of spectral lines falling within these windows, together with the measured atmospheric transmission from the Chajnantor site on the night of August 26th, 1998. In addition to lines from familiar molecules, there are many lines unique to the terahertz range including the N^+ ground-state fine structure transition at 1.461 THz, and the NH^+ fundamental rotational doublet at 1.013 THz and 1.019 THz. These two species are involved in the first steps of the theoretical synthesis chain for NH_3. The NH^+ ion has not been detected astronomically at any wavelength, despite its expected role in interstellar chemistry. Whereas the unresolved N^+ fine structure line is visible from the Galaxy in the COBE FIRAS spectrum, and an all-sky map with 7 degree angular resolution confirms that N^+ line emission will be widely detectable [8,9]. However, the kinematic information carried by this line, which can be studied in detail with heterodyne receivers, is not apparent from the COBE data. Also, and in contrast to optical lines of N^+, extinction effects by dust are insignificant at terahertz frequencies. Even a modest-sized terahertz telescope will offer better angular resolution than the COBE map by more than two orders of magnitude, and would be capable of detecting the N^+ line in nearby galaxies. The H_3^+ is an important species in ion-molecule chemistry in the interstellar medium, but it has no lines in the submillimeter. The H_2D^+ ion serves as a tracer for H_3^+, and its fundamental rotational transition at 1.370 THz is the best means of observing it in cool molecular clouds [10]. Of the metal hydride transitions shown in Fig. 1, HCl, LiH, and SH, the most important is likely to be the fundamental rotational transition of SH at 1.383 GHz. The only transitions of this molecule below 1 THz are at 867 GHz and 875 GHz, but have lower-state energy E/k = 527 K. Finally, a point not to be forgotten, the ability to perform line surveys in the terahertz windows will provide the potential to discover unexpected features of the interstellar medium.

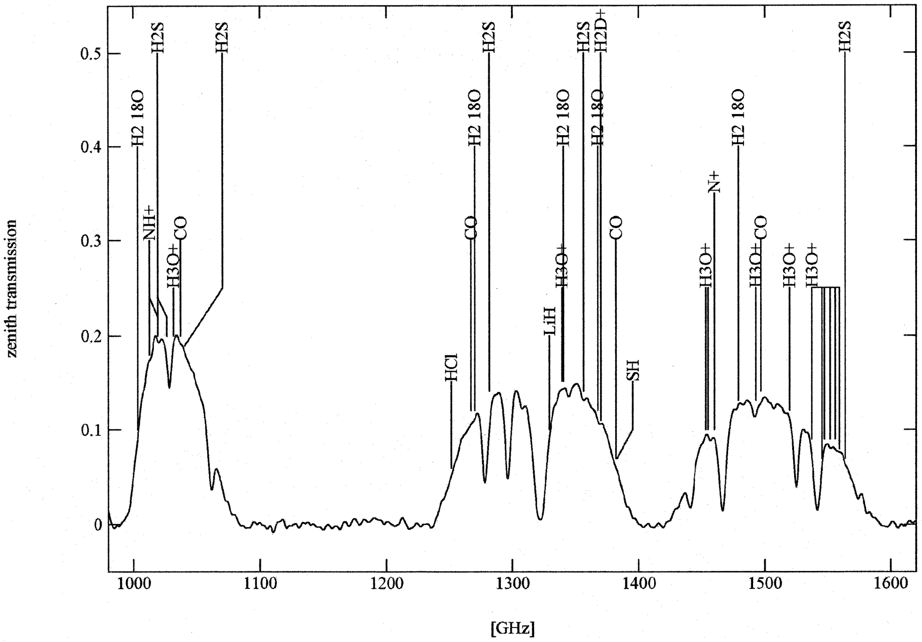


Figure 1 – Measured atmospheric transmission from the Chajnantor site on 1998 Aug 26, 06:00 UT, from a 10-minute FTS scan. The frequencies of selected molecular lines and the N^+ fine structure line are indicated for reference.

In order to enhance our understanding of the weather above Chajnantor, SAO joined NRAO, ESO, and Cornell University in a collaboration to collect radiosonde data above the site [11]. Over the past three years, a number of radiosonde launches were under a variety of atmospheric conditions, including periods of excellent transmission, as determined by the FTS measurements. From the data, an example of which is given in Fig. 2, it appears that a layer of water vapor is often trapped above the site by a temperature inversion that is sometimes only several hundred metres higher. This implies that even a modest gain in altitude might result in a significant improvement in atmospheric transmission.

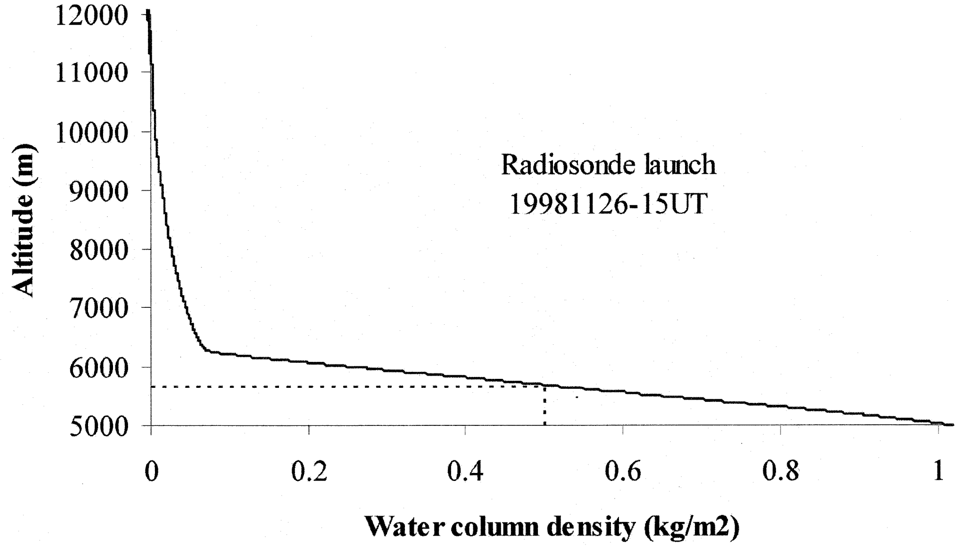
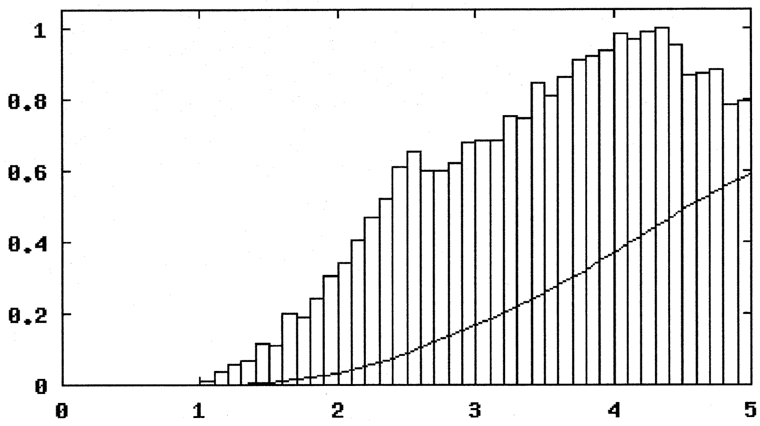
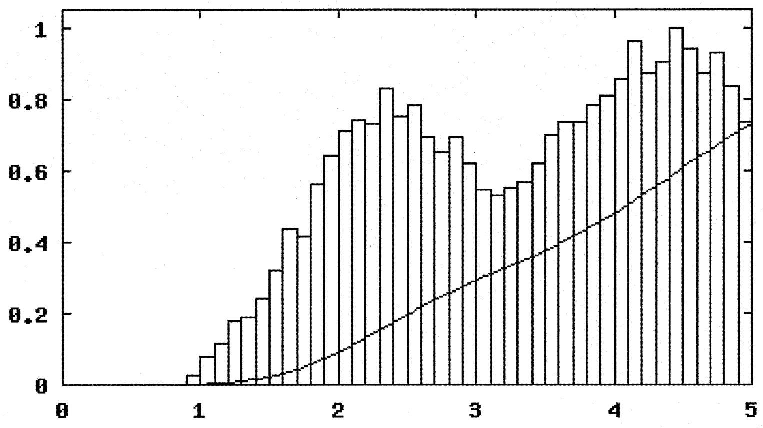


Figure 2 – Specific water vapor column density calculated from measured radiosonde data above Chajnantor. By ascending to just 650m above ground level, the water column density is reduced by half.

Following our measurements on Chajnantor, we deployed the FTS on a plateau, below the peak of Cerro Sairecabur, at 5,500 m altitude. In Fig. 3 we plot the cumulative distribution of opacities, from both sites in the 1.3 THz atmospheric window. The Chajnantor data was collected during the period from October 1997 to December 1999 and includes 37,000 spectra [12], and the data from Sairecabur was collected during the period October 2000 to January 2002 and includes 19,000 spectra. Both sets of data include periods of good and bad weather, and are considered to be representative samples of the four seasons. From the data we conclude that, on average, the opacity from Sairecabur is about 0.6 below that from Chajnantor. For example, we observe an atmospheric transmission of 8 % or better from the Chajnantor site 10% of the time; whereas from the Sairecabur site we observe a transmission of 15 %, again for 10% of the time, 24 hours/day, 365 days/year.



Opacity at Chajnantor



Opacity at Sairecabur

Figure 3 – Normalised histograms and cumulative distribution functions calculated for Chajnantor and Sairecabur. The Chajnantor data set represents 37,000 spectra taken between December 1997 and October 1999, and the Sairecabur data set represents 19,000 spectra taken between October 2000 and January 2002.

Instrument development

During the past several years there has been an effort to further develop heterodyne receiver technology, for the 1 – 3 THz frequency range, to be flown on future airborne and spaceborne astronomy missions. Superconductor-insulator-superconductor mixers are currently being developed to 1.4 THz, and a number of groups are working to develop the superconducting hot electron bolometer (HEB) mixer for use in the 1 – 3 THz spectral range.

Since 1995 we have been collaborating with the group at th Mscow State Pedagogical University to develop the phonon-cooled HEB mixer, and, since 1999, have successfully used this class of mixer for radio astronomical observations below 1 THz. In January 2000 we made the first fully resolved astronomical observation of CO at 1.037 THz from a ground-based site [13], and for the past two years have been working towards developing HEB mixers for use in the atmospheric windows above 1 THz. Figure 4 summarizes the current status of SAO HEB mixer receiver performance.

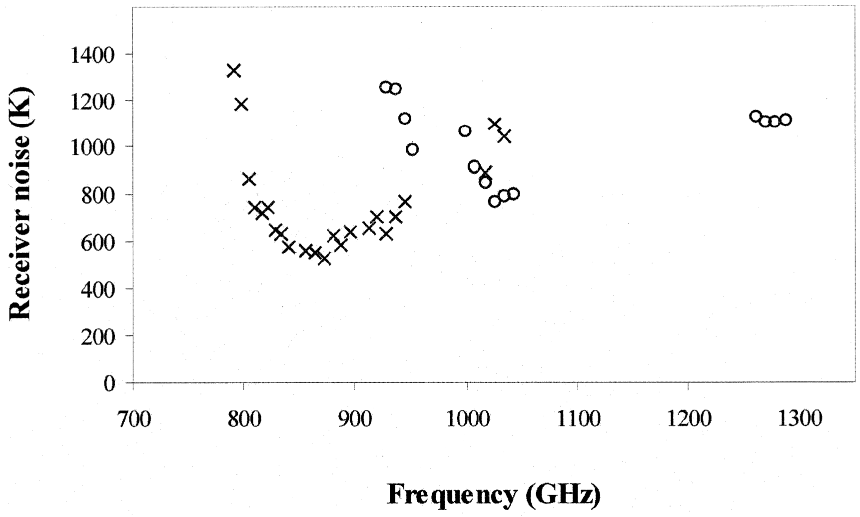


Figure 4 – Measured DSB receiver noise performance as a function of local oscillator frequency for two HEB mixer receivers developed at SAO. The lower frequency receiver covers the atmospheric windows centered at 850 GHz and 1.03 THz, the other is for use in 1.3 THz atmospheric window and provides redundancy at 1.03 THz. A third mixer, currently under development for use in the 1.5 THz atmospheric window, will provide redundancy at 1.3 THz.

If we assume that the mixers are double sideband, a reasonable assumption given the low intermediate frequency of the HEB mixer, we estimate single sideband receiver noise temperatures in the range 1,000 – 2,500 K for frequencies from 800 GHz to about 1,300 GHz. Suppose now that the average atmospheric transmission towards the source during an astronomical observation is about 10 %, we then calculate system temperatures of between 10,000 and 25,000 K which are similar to the receiver noise temperatures of heterodyne instruments previously flown on the KAO [14,15]. In other words, observations made from the Sairecabur site could be made with almost identical sensitivities as those made from the KAO. Such observations would be limited to the atmospheric windows shown in Fig. 1. However, a ground-based instrument will offer substantial advantages over aircraft, balloon, and space -based platforms in terms of cost, logistics, and available observing time.

With one exception, all spectral line radio astronomy at frequencies in excess of 1 THz has been made using relatively small antennas. For example, the KAO antenna was 0.91 m in diameter, and the ISO reflector was only 0.6 m across. The Herschel satellite will incorporate a 3.5 m diameter antenna, and SOFIA will have an antenna 2.5 m across. For our test instrument we selected a reflector diameter of 0.8 m. This should permit scientifically interesting astronomical observation at reasonable cost. Since the aim of this work is only to evaluate the prospects for ground-based terahertz radio astronomy, it is important that any test facility should require only a minimum of infrastructure. We therefore decided to house the antenna on the top of a 20-foot shipping container that will also serve as a control room.

The reflector is made of a single piece of aluminum has an rms surface error of less that 3μm and supported on an alt-az mount with a standard coudee optical configuration. The azimuth and elevation axes are both driven by off-the-shelf brushless DC servomotors, followed by zero-backlash, high ratio reducers: a harmonic drive in the case of the elevation axis, and a worm drive for azimuth. The motors are driven by off-the-shelf intelligent PWM servo amplifiers, which provide electronic commutation. In addition, the commutation encoder is used to operate a velocity-feedback (speed control) loop in the amplifier itself. A DC velocity command is sent to each of the servo amplifers from a computer D-A card. High-resolution optical encoders with quadrature sine-wave outputs are mounted directly on each axis, and an interface PC card provides 1024 interpolation for each cycle, giving a total resolution similar to a 24-bit encoder. A simple position servo loop runs in the PC for both axes. With the velocity loop of the servo amplifer properly tuned, this provides an extremely smooth, well-behaved servo system, with a slew speed of up to 4 degrees per second and sidereal tracking errors less than 2 arcseconds.

Summary

We have demontrated that there exist new opportunities in terahertz astronomy from northern Chile. This spectral region is rich with scientific possibilities, and advanced receiver technologies, largely developed at SAO, will make sensitive heterodyne observations in this little explored region of frequency space possible.

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