Terahertz Initiatives at the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)

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ABSTRACT

The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) is a 1.7-meter diameter offset Gregorian instrument located at the NSF Amundsen-Scott South Pole Station. This site is exceptionally dry and cold, providing opportunities for Terahertz observations from the ground. Preliminary analysis of recent site testing results shows that the zenith transparency of the 1.5 THz atmospheric window at South Pole frequently exceeds 10% during the Austral winter. Routine observations at 810 GHz have been conducted over the past two years, resulting in large-scale maps of the Galactic Center region and measurements of the ^{13}C line in molecular clouds. During the next two years, the observatory plans to support two Terahertz instruments:

1) TREND (*Terahertz Receiver with Niobium Nitride Device*—K. S. Yngvesson, University of Massachusetts, P. I.), and

2) SPIFI (*South Pole Imaging Fabry-Perot Interferometer*—G. J. Stacey, Cornell University, P. I.).

AST/RO could be used in future as an observational test bed for additional prototype Terahertz instruments. Observing time on AST/RO is available on a proposal basis (see `http://cfa-www.harvard.edu/~adair/AST_RO`).

I. The AST/RO Instrument

The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) is an instrument routinely used for the measurement of submillimeter-wave spectral lines over regions several square degrees in size toward the Milky Way and Magellanic Clouds. AST/RO is a 1.7m diameter offset Gregorian telescope, with optics designed for wavelengths between 200 μm and 3 mm. All of the optics in AST/RO are offset for high beam efficiency and avoidance of inadvertent reflections and resonances. The design of

AST/RO is described in Stark et al. (1997) . AST/RO site testing, logistics, capabilities, and observing techniques are described in Stark et al. (2001).

Currently, there are five heterodyne receivers mounted on an optical table suspended from the telescope structure in a spacious (5m × 5m × 3m), warm Coudé room:

1. a 230 GHz SIS receiver, 85 K double-sideband (DSB) noise temperature (Kooi et al. 1992);
2. a 450–495 GHz SIS quasi-optical receiver, 165–250 K DSB (Engargiola et al. 1994, Zmuidzinas & LeDuc 1992);
3. a 450–495 GHz SIS waveguide receiver, 200–400 K DSB (Walker et al. 1992, Kooi et al. 1995), which can be used simultaneously with
4. a 800-820 GHz fixed-tuned SIS waveguide mixer receiver, 950–1500 K DSB (Honingh et al. 1997);
5. an array of four 800-820 GHz fixed-tuned SIS waveguide mixer receivers, 850–1500 K DSB (the PoleSTAR array, see `http://soral.as.arizona.edu/pole-star` and Groppi et al. 2000).

Spectral lines observed with AST/RO include: CO $J = 2 \rightarrow 1$, CO $J = 4 \rightarrow 3$, CO $J = 7 \rightarrow 6$, HDO $J = 1_{0,1} \rightarrow 0_{0,0}$, [C I] $^3P_1 \rightarrow {}^3P_0$, [C I] $^3P_2 \rightarrow {}^3P_1$, and [^{13}C I] $^3P_2 \rightarrow {}^3P_1$. A proposal is currently pending to the Smithsonian Institution to purchase a local oscillator to cover 650–700 GHz, a frequency range which includes the ^{13}CO $J = 6 \rightarrow 5$ line. There are four currently available acousto-optical spectrometers (AOS), all designed and built at the University of Cologne (Schieder et al. 1989): two low-resolution spectrometers with a bandwidth of 1 GHz (bandpass 1.6–2.6 GHz); an array AOS having four low resolution spectrometer channels with a bandwidth of 1 GHz (bandpass 1.6–2.6 GHz) for the PoleSTAR array; and one high-resolution AOS with 60 MHz bandwidth (bandpass 60–120 MHz).

AST/RO has been open to proposals from the general astronomical community since 1997. AST/RO research is a three part effort, where approximately equal time is given to each of these initiatives:

1. large-scale surveys of regions of general interest: the Galactic Center and the Magellanic Clouds;
2. support of observations of special interest, through observing proposals solicited from the worldwide astronomical community;
3. support of technology development, by making the telescope available for installation and trial of novel detectors, especially detectors at Terahertz frequencies.

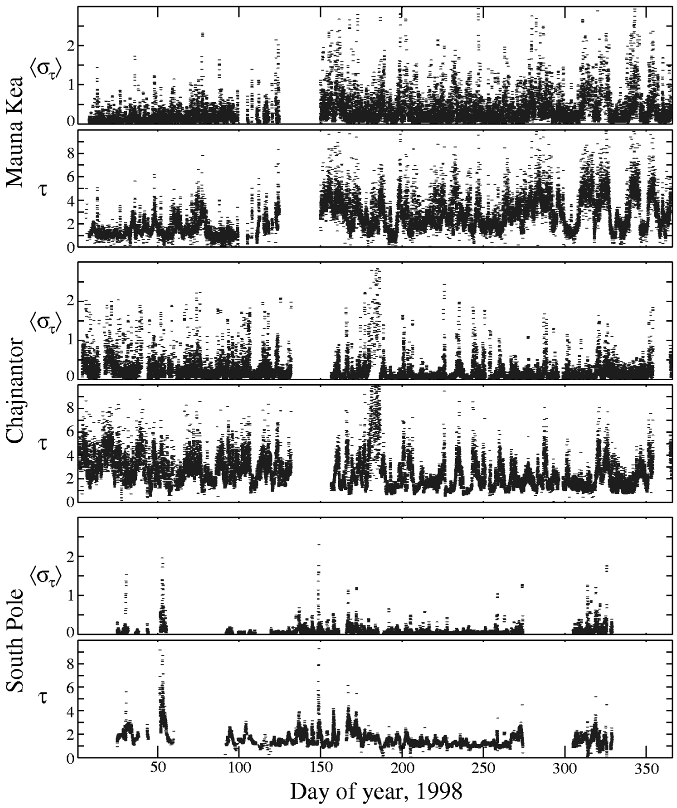

Fig. 1: **Sky Noise and Opacity Measurements at 350 μm from Three Sites.** These plots show data from identical NRAO-CMU 350 μm broadband tippers (Radford & Peterson, unpublished data) located at Mauna Kea, Hawaii; the ALMA site at Chajnantor, Chile; and South Pole during 1998. The upper plot of each pair shows $\langle\sigma_\tau\rangle$, the rms deviation in the opacity τ during a one-hour period—a measure of sky noise on large scales; the lower plot of each pair shows τ, the broadband 350 μm opacity. The first 100 days of 1998 on Mauna Kea were exceptionally good for that site. During the best weather at the Pole, $\langle\sigma_\tau\rangle$ was dominated by detector noise rather than sky noise.

II. Site Testing

The South Pole is an excellent millimeter- and submillimeter-wave site (Lane 1998, Chamberlin & Bally 1994, Chamberlin et al. 1997, Chamberlin 2002). It is unique among observatory sites for unusually low wind speeds, absence of rain, and the consistent clarity of the submillimeter sky. Schwerdtfeger (1984) has comprehensively reviewed the climate of the Antarctic Plateau and the records of the South Pole meteorology office. Chamberlin (2001) has analyzed weather data to determine the precipitable water vapor (PWV) and finds median wintertime PWV values of 0.3 mm over a 37-year period, with little annual variation. *PWV values at South Pole are small, stable, and well-understood.*

Submillimeter-wave atmospheric opacity at South Pole has been measured using skydip techniques. We made over 1100 skydip observations at 492 GHz (609 μm) with AST/RO during the 1995 observing season (Chamberlin et al. 1997). Even though this frequency is near a strong oxygen line, the opacity was below 0.70 half of the time during the Austral winter and reached values as low as 0.34, better than ever measured

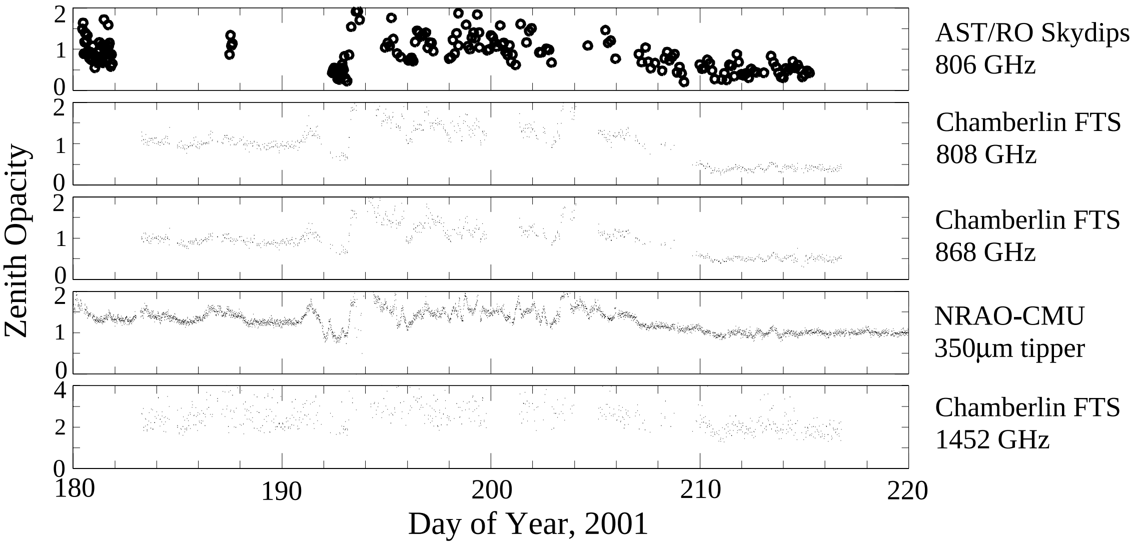

Fig. 2: **Simultaneous Opacity Measurements from Three Instruments at the South Pole.** These plots show data from AST/RO skydips, the NRAO-CMU 350 μm broadband tipper (Radford & Peterson, unpublished data), and a submillimeter-wave Fourier Transform Spectrometer (FTS, Chamberlin 2002) in July and early August of 2001. The AST/RO data are from skydips taken for calibration purposes during observations; they agree well with the FTS measurements at 808 GHz. The FTS measurements at 868 GHz are shown for comparison with the NRAO-CMU broadband measurements, which are centered at that frequency. Note that the NRAO-CMU tipper values are monotonically related to the FTS measurements, but show an offset and compression of scale. The bottom plot shows a preliminary reduction of FTS measurements at 1.452 THz, and indicates $\tau < 2$ for a significant fraction of the time. Usually August and September are the best months at the Pole; these observations unfortunately had to be stopped early because of insufficient liquid helium supplies.

at any ground-based site. The stability was also remarkably good: the opacity remained below 1.0 for weeks at a time. From early 1998, the 350μm band has been continuously monitored at Mauna Kea, Chajnantor, and South Pole by identical tipper instruments developed by S. Radford of NRAO and J. Peterson of Carnegie-Mellon U. and the Center for Astrophysical Research in Antarctica (CARA). Results from Mauna Kea and Chajnantor are compared with South Pole in Figure 1. *The 350μm opacity at the South Pole is consistently better than at Mauna Kea or Chajnantor.*

A new Fourier Transform Spectrometer developed by R. Chamberlin and collaborators was operational at the Pole during some of the winter of 2001. This instrument measures a broadband spectrum covering 300 GHz to 2 THz as a function of airmass

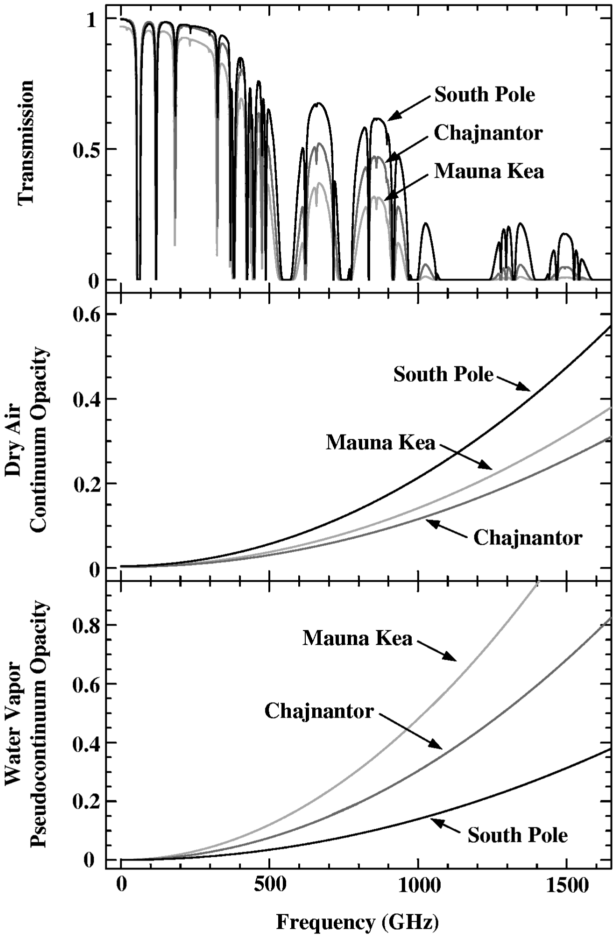

Fig. 3: **Calculated atmospheric transmittance at three sites.** The upper plot is atmospheric transmittance at zenith calculated by J. R. Pardo using the ATM model (Pardo et al. 2001). The model uses PWV values of 0.2 mm for South Pole, 0.6 mm for Chajnantor and 0.9 mm for Mauna Kea, corresponding to the 25$^{\text{th}}$ percentile winter values at each site. Note that at low frequencies, the Chajnantor curve converges with the South Pole curve, an indication that 225 GHz opacity is not a simple predictor of submillimeter wave opacity. The middle and lower plots show calculated values of dry air continuum opacity and water vapor pseudocontinuum opacity for the three sites. Note that unlike the other sites, the opacity at South Pole is dominated by dry air rather than water vapor.

several times each hour. Some of these data are shown in Figure 2. The zenith transparency at 1.452 THz (near an important [N II] line) exceeded 10% for almost the entire first week of August 2001. *The observed relation between the NRAO-CMU tipper and the 1.452 THz measurements indicates that it will be possible to observe the* $\lambda 205\,\mu$m [N II] *line about 30 days each year.*

The South Pole 25% winter PWV levels have been used to compute values of atmospheric transmittance as a function of wavelength which are plotted in Figure 3. For comparison, the transmittances for 25% winter conditions at Chajnantor and Mauna Kea are also shown.

Sky noise is caused by fluctuations in total power or phase of a detector caused by variations in atmospheric emissivity and path length on timescales of order one second. Sky noise causes systematic errors in the measurement of astronomical sources. Lay & Halverson (2000) show analytically how sky noise causes observational techniques to fail: fluctuations in a component of the data due to sky noise integrates down more slowly

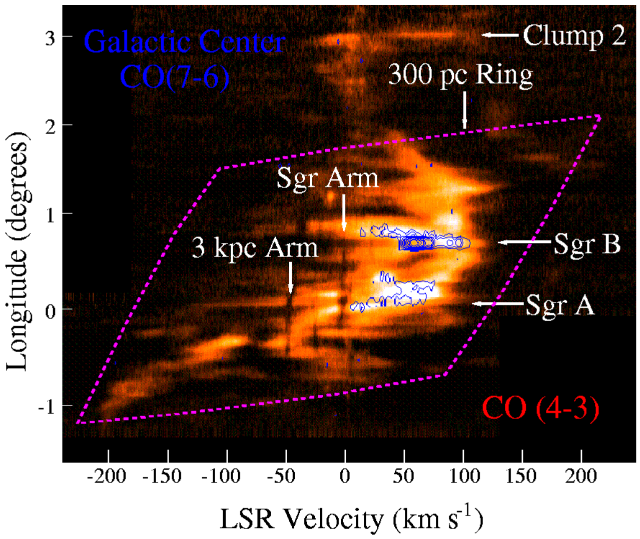

Fig. 4: **AST/RO observations of the Galactic Center Region** (from Kim et al. 2000). The CO $J = 4 \rightarrow 3$ (pseudo-color) and $J = 7 \rightarrow 6$ (blue contour) lines observed in an $l - v$ strip, sampled every $1'$, at $b = 0$. These data have been used in conjunction with CO and ^{13}CO $J = 1 \rightarrow 0$ data to determine the the density and temperature in the features shown here.

than $t^{-1/2}$ and will come to dominate the error during long observations. Sky noise at South Pole is considerably smaller than at other sites, even comparing conditions of the same opacity. The PWV at South Pole is often so low that the opacity is dominated by the *dry air* component (Chamberlin & Bally 1995, Chamberlin 2001, cf. Figure 3); the dry air emissivity and phase error do not vary as strongly or rapidly as the emissivity and phase error due to water vapor.

III. 810 GHz Observations at AST/RO

AST/RO has detected the isotopic [^{13}C I] $^3P_2 \rightarrow {}^3P_1$ fine-structure transition in three galactic regions: G 333.0-0.4, NGC 6334 A, and G 351.6-1.3. This is only the second time that this line have been successfully observed, the previous detection being a single spectrum obtained with the Caltech Submillimeter Observatory toward the Orion Bar (Keene et al. 1998). The [^{13}C I] line was observed simultaneously with the CO $J = 7 \rightarrow 6$ line emission at 806 GHz (Tieftrunk et al. 2001).

Essentially all of the NGC 6334 Giant Molecular Cloud was mapped in 492 and 810 GHz [C I] and the CO $J = 7 \rightarrow 6$ and $J = 4 \rightarrow 3$ spectral lines. The data show that high excitation temperatures exist throughout most of the cloud volume. Detailed modeling is in progress to account for the observed line intensities and ratios (Yan et al. in preparation).

An up-to-date bibliography of AST/RO publications can be found at the AST/RO website `http://cfa-www.harvard.edu/~adair/AST_RO`.

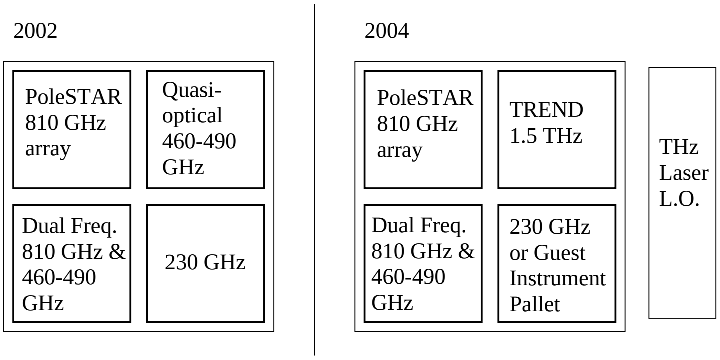

Fig. 5: **AST/RO Receiver Room Configurations.** On the left is the current configuration of pallets in the AST/RO receiver room, looking downwards to the Coudé focus. At right is a proposed configuration circa 2004, with the TREND 1.4 THz HEB mixer and its laser local oscillator installed. A "Guest Instrument Pallet" would permit testing of high-frequency prototypes.

IV. Terahertz Initiative

Two new short wavelength instruments are in development for use on AST/RO:

- Dr. G. Stacy and collaborators have developed the South Pole Imaging Fabry-Perot Interferometer (SPIFI, Swain et al. 1998), a 25-element bolometer array preceded by a tunable Fabry-Perot filter. This instrument was successfully used on the JCMT in May 1999 and April 2001 and is being modified with new instrumentation, cryogenics, and detectors for South Pole use. SPIFI is frequency agile and can observe many beams at once, but has limited frequency resolution ($\sim$ 100 km s^{-1}) and scans a single filter to build up a spectrum.

- Dr. S. Yngvesson and collaborators (Gerecht et al. 1999, Yngvesson et al. 2001) are developing a 1.5 THz heterodyne receiver, the Terahertz Receiver with Niobium Nitride Device (TREND). TREND has only a single pixel and is not frequency agile. Its HEB device requires high local oscillator power levels; we will use a laser local oscillator source which requires that the gas be changed in order to change frequencies. The frequency resolution of TREND is high ($\sim$ 2 MHz), limited by the stability of the laser.

In addition, Dr. D. Prober and collaborators are developing a low-noise, low-power 1.5 THz heterodyne receiver based on aluminum and tantalum HEB technology which may be tested on AST/RO.

Deployment of these technologies on a ground-based telescope is a path of technological development that has exciting prospects. On AST/RO, the $\sim 35''$ beam size and high spectral resolution (~ 0.4 km s^{-1}) of Terahertz receivers will allow the study of galactic star-forming regions and large-scale studies of nearby galaxies. In future, these detectors could be used on the South Pole Submillimeter Telescope (SPST), an 8-meter telescope (see NRC 2001), which would have a beamsize of $\sim 7''$.

V. Conclusion

We hope to begin ground-based Terahertz observations with AST/RO in 2003. Routine observations have been carried out in the 350 μm window over the past two years, and our experience has been that such observations are possible more than 100 days each year. Site testing with a new Fourier Transform Spectrometer, combined with long-term measurements from the NRAO-CMU tipper, indicates that observations in the 200 μm window should be possible about 30 days each year. Two Terahertz detector systems, SPIFI and TREND, are scheduled for installation in the next two years. We expect that after initial tests and observations these instruments will become available for astronomical use on a proposal basis. AST/RO is also open to proposals for tests of other prototype Terahertz instruments in the coming years.

We thank Simon Radford of NRAO and Jeff Peterson of CMU for the data shown in Figure 1. We thank Juan R. Pardo of Caltech for discussions on atmospheric modeling and for carrying out the calculations shown in Figure 3. The AST/RO group is grateful for the logistical support of the National Science Foundation, Antarctic Support Associates, Raytheon Polar Services Company, and CARA during our polar expeditions. This work was supported in part by United States National Science Foundation grant DPP88-18384, and by the Center for Astrophysical Research in Antarctica and the NSF under Cooperative Agreement OPP89-20223.

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