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Atmospheric conditions at a site for submillimeter wavelength astronomy

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ABSTRACT

At millimeter and submillimeter wavelengths, pressure broadened molecular spectral lines make the atmosphere a natural limitation to the sensitivity and resolution of astronomical observations. Tropospheric water vapor is the principal culprit. The translucent atmosphere both decreases the signal, by attenuating incoming radiation, and increases the noise, by radiating thermally. Furthermore, inhomogeneities in the water vapor distribution cause variations in the electrical path length through the atmosphere. These variations result in phase errors that degrade the sensitivity and resolution of images made with both interferometers and filled aperture telescopes.

To evaluate possible sites for the Millimeter Array, NRAO has carried out an extensive testing campaign. At a candidate site at 5000 m altitude near Cerro Chajnantor in northern Chile, we deployed an autonomous suite of instruments in 1995 April. These include a 225 GHz tipping radiometer that measures atmospheric transparency and temporal emission fluctuations and a 12 GHz interferometer that measures atmospheric phase fluctuations. A submillimeter tipping photometer to measure the atmospheric transparency at 350 μm wavelength and a submillimeter Fourier transform spectrometer have recently been added. Similar instruments have been deployed at other sites, notably Mauna Kea, Hawaii, and the South Pole, by NRAO and other groups.

These measurements indicate Chajnantor is an excellent site for millimeter and submillimeter wavelength astronomy. The 225 GHz transparency is better than on Mauna Kea. The median 225 GHz transparencies measured at Chajnantor and at the South Pole are comparable.

Keywords: atmosphere, site testing, radio telescopes

1. BACKGROUND

75 – 1000 GHz

Astronomy at short millimeter and submillimeter wavelengths, say 4 mm–300 μm, is primarily the study of cool thermal sources whose temperatures seldom exceed 100 K. For example, the rotational transitions of CO and other molecules, the fine structure lines of atomic carbon, and continuum radiation from optically thin dust are essential probes for the study of star formation, planet formation, late stage of stellar evolution, the chemical history and the structure of the interstellar medium, galactic structure, and the structure, evolution, and formation of other galaxies.

The proposed Millimeter Array will be a large, aperture sythesis radio telescope for observations in this wavelength range. In the current design, about 36 antennas, each 10 m in diameter, will be placed in ellipsoidal configurations from 95 m to 10 km in diameter. The instrument will have receivers that approach the noise limit set by quantum uncertainty and antennas with high precision surfaces and low spillover optics.

At millimeter and submillimeter wavelengths, however, the atmosphere is only partially transparent. Pressure broadened transitions of atmospheric molecules, particularly water vapor, both absorb and emit radiation. The absorption attenuates the astronomical signal and the emission adds to the inherent noise of the receiver. The signal-to-noise ratio is degraded, then, on two counts. Indeed, if the receivers are limited by quantum uncertainty and the antenna optics have low spillover, atmospheric emission can be the dominant source of system noise.

Moreover, turbulence in the atmospheric water vapor degrades the resolution of a telescope and further reduces its sensitivity. The electrical path length through the atmosphere varies because water vapor changes the index of refraction of air. Path length differences across the aperture of an individual antenna change the position of the beam on the sky, with deleterious effects on both the calibration of the observations and the resolution of the resulting

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Figure 1. Eastern skyline seen from San Pedro de Atacama, Chile (2400 m), showing (*left to right*) the road over the Paso de Jama (4850 m), Cerro Toco (5600 m), Cerro Chajnantor (5640 m), the Chajnantor site (5000 m), and Cerro Negro (5025).

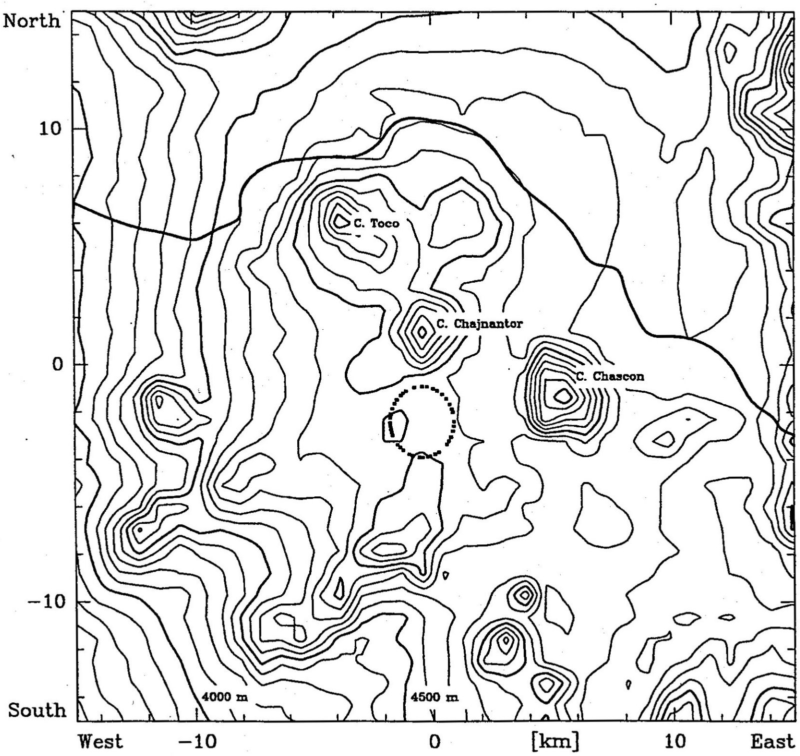

Figure 2. Environs of Cerro Chajnantor, showing approximate position of a possible 3 km diameter configuration of MMA antennas. Contour interval is 100 m. The highway over the Paso de Jama (*heavy line*) runs east–west just north of Cerro Toco.

Table 1. Site Characteristics

Longitude	67°45′ W
Latitude	23° 1′ S
Altitude	5000 m
Temperature:	
minimum	−21° C
median	− 4° C
maximum	+22° C
Wind:	
25 percentile	$3\,\mathrm{m\,s^{-1}}$
50 percentile	$6\,\mathrm{m\,s^{-1}}$
75 percentile	$10\,\mathrm{m\,s^{-1}}$
maximum	$35\,\mathrm{m\,s^{-1}}$

image. Path differences between different elements of an array decorrelate the signals on short time scales, reducing the measured amplitude, and introduce phase errors on long time scales that broaden the synthesized beam.

Since water vapor is the primary cause of atmospheric opacity, the best sites for millimeter and submillimeter wavelength astronomy will have exceptionally dry air. Although the scale height ($1/e$) of atmospheric water vapor depends on local conditions and weather conditions, it is typically 1–2 km.[1] Because water is trapped relatively low in the atmosphere, extremely dry air can be found above high altitude sites. Atmospheric turbulence is more complicated than the overall distribution of water vapor, as it can depend strongly on local effects and topography. Generally, turbulence is lessened if the air flow over a site encounters no upstream obstructions.

2. CANDIDATE SITE

Existing sites for submillimeter wavelength astronomy include Mauna Kea, Hawaii (4100 m), Mt. Graham, Arizona (3180 m), Gornergrat, Switzerland (3100 m), and the South Pole (2835 m). The highest, and by far the best developed site, is Mauna Kea, where the CSO, JCMT, and (soon) SMA are located together with numerous optical and infrared telescopes. Even though Mauna Kea has relatively gentle slopes, the mountain top topography limits the available land near the summit. A 3 km array configuration would only be possible at about the 3700 m level. Mt. Graham and Gornegrat are steep mountains with even more limited land area and, furthermore, seasonal variations in atmospheric conditions that preclude observations for large fractions of the year. Although the South Pole is situated in a very large expanse of flat terrain, the harsh operating environment and difficult logistics mean it presently could not support a large, multi-element, reconfigurable array. Moreover, maximum sky coverage is important for a general purpose facility. A site at a latitude less than 30° can view three times more sky at low airmass ($A < 2$) compared with a polar site. The median airmass is also lower at a low latitude site, 1.1 instead of 1.35 for observations at $A < 2$.

The Atacama desert of northern Chile is among the driest places on Earth. The combined effects of a high pressure belt over the southeast Pacific, the cold Humbolt current, and the moisture barrier of the Andean cordillera normally prevent both winter storms, from the ocean, and summer tropical convection, from the Amazon, from penetrating the area. The lack of glaciers, even on the highest peak in the region, Volcán Llullaillaco (6740 m), is unique in the world for these altitudes and attests to the aridity and the lack of precipitation.[2]

Over the past three years, the NRAO has explored an undeveloped site in the high Andes on the eastern edge of the desert near the oasis of San Pedro de Atacama. Japanese (LMSA) and European (LSA) groups have also been exploring sites in the region. East of this village (Fig. 1), the land rises smoothly for about 20 km from the Salar de Atacama (2400 m) to a large plateau at 5000 m. A paved highway runs over the Paso de Jama (4850 m) near the Bolivian border along the northern edge of this plateau (Fig. 2). About 10 km south of the road, near the base of Cerro Chajnanator (5640 m), NRAO installed a suite of autonomous test instruments in 1995 April (Fig. 3). This candidate site has a clear western horizon, so the prevailing westerly wind encounters no obstructions that generate turbulence. The site has space for 10 km (or larger?) arrays (Fig. 4). The nearby village provides a support base at moderate altitude (2400 m) only about 40 km away by road.

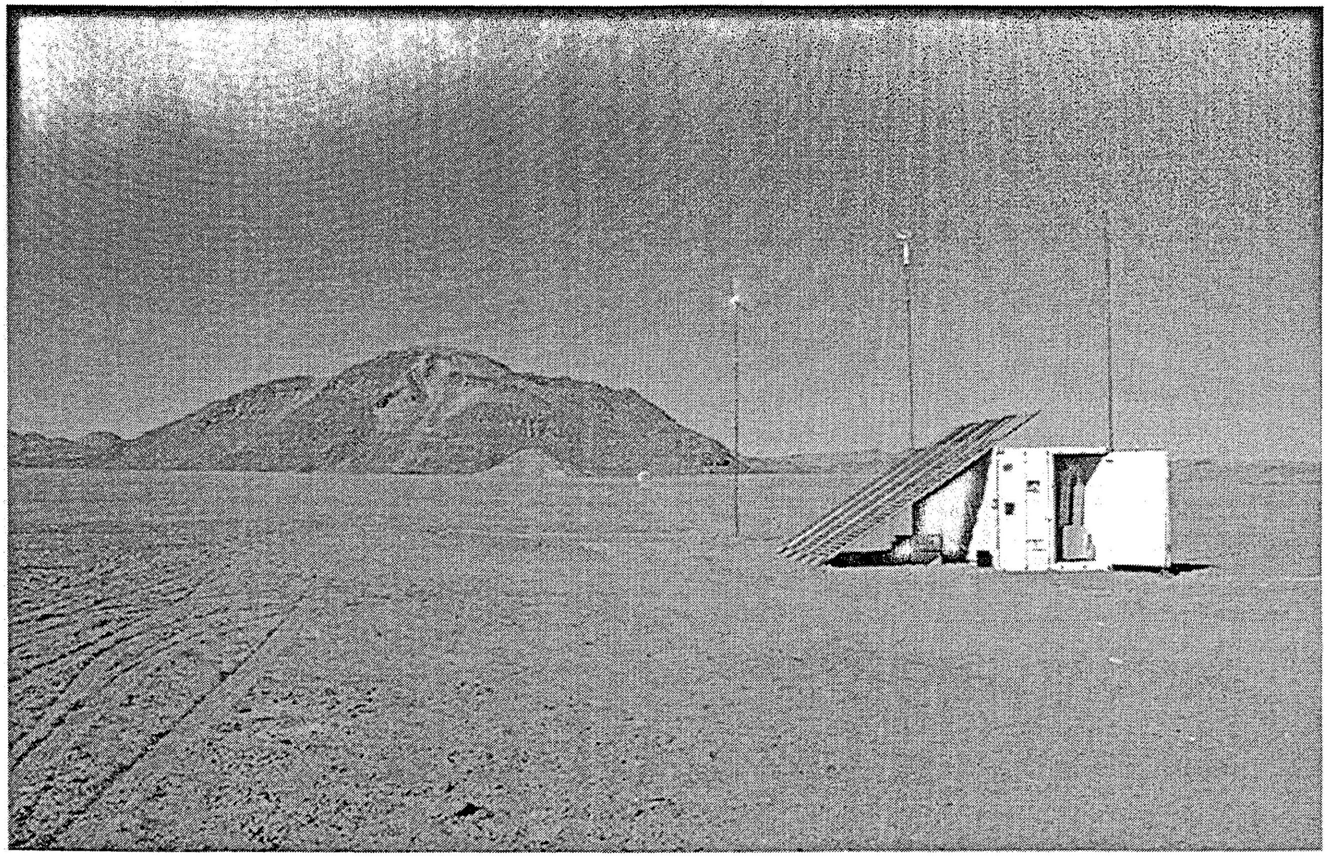

Figure 3. NRAO site test equipment at Chajnantor (5000 m) with moonrise over Cerro Chascon (5700 m) in the background.

The measured air temperature at Chajnantor shows the expected diurnal and seasonal variations (Fig. 5) about an overall median somewhat below freezing (Table 1). Especially in the afternoons, Chajnantor can be a windy site (Fig. 6). The diurnal variation of the wind speed is quite pronounced in all seasons. Although winters are windier than summers, westerly winds prevail almost exclusively during the winter, while easterly winds prevail 30–50% of the time during the summer.

3. TRANSPARENCY

3.1. 225 GHz measurements

Atmospheric transparency is determined every 10 minutes by measuring the 225 GHz sky brightness at different zenith angles with a tipping radiometer.[3] About one in five hours, the radiometer is pointed at the zenith to measure fluctuations in the sky brightness.

Diurnal variation in the measured optical depths is not prominent (Fig. 7), mostly occurring during summer. During the winters of 1995 and 1996, diurnal variation was especially weak. Seasonal and yearly variations, on the other hand, are quite pronounced. In particular, the "El Niño" winter of 1997 and the preceding, "La Niña" summer had higher optical depths than the previous summer and two winters. Nevertheless, even during the worst month on record, 1997 February, the median optical depth at Chajnantor, 0.28, was comparable to good conditions at many established millimeter wavelength observatories. There is no strong correlation of transparency with temperature or wind speed.

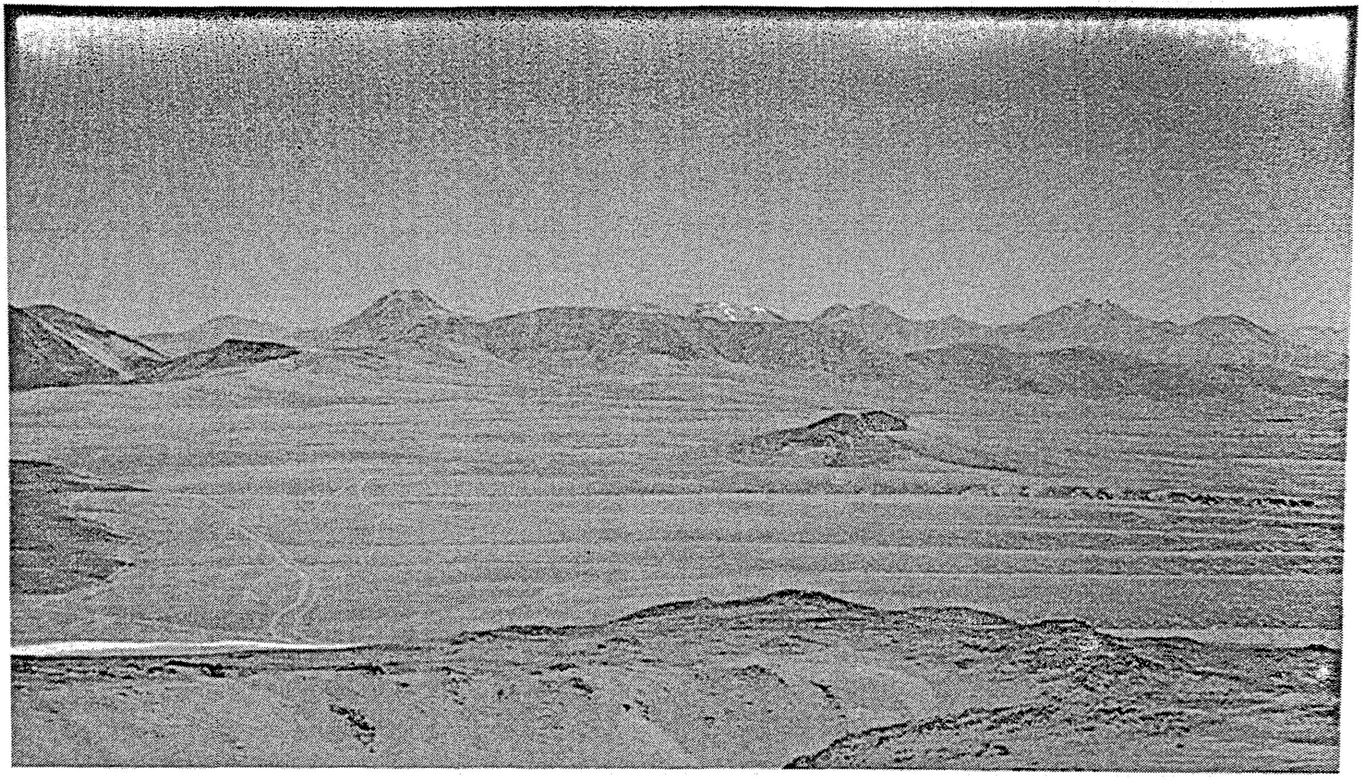

Figure 4. View south from Cerro Toco of the Chajnantor site, with Volcán Lascar on the horizon (M. Gordon).

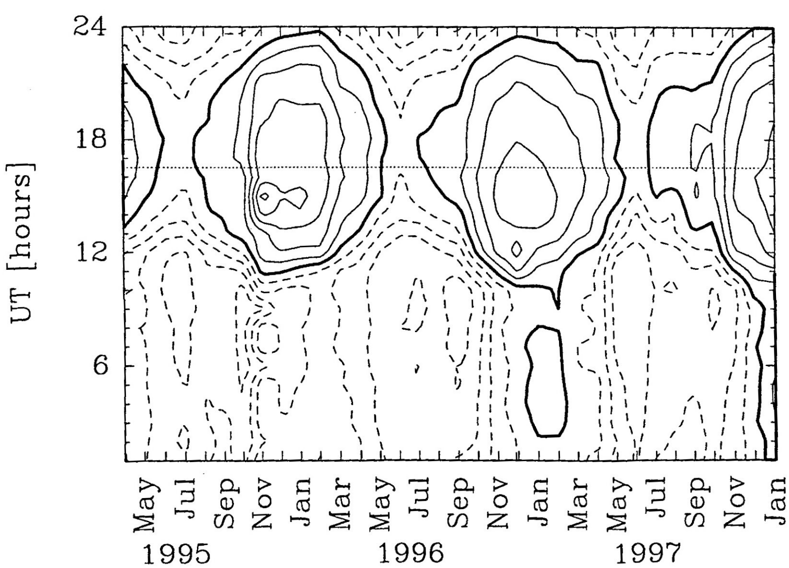

Figure 5. Diurnal variation of monthly median temperature measured at Chajnantor. Local solar time is UT$-4^h\ 30^m$ and the dotted line indicates local noon. Heavy contour is 0° C, contour interval is 3° C, and dashed contours are negative.

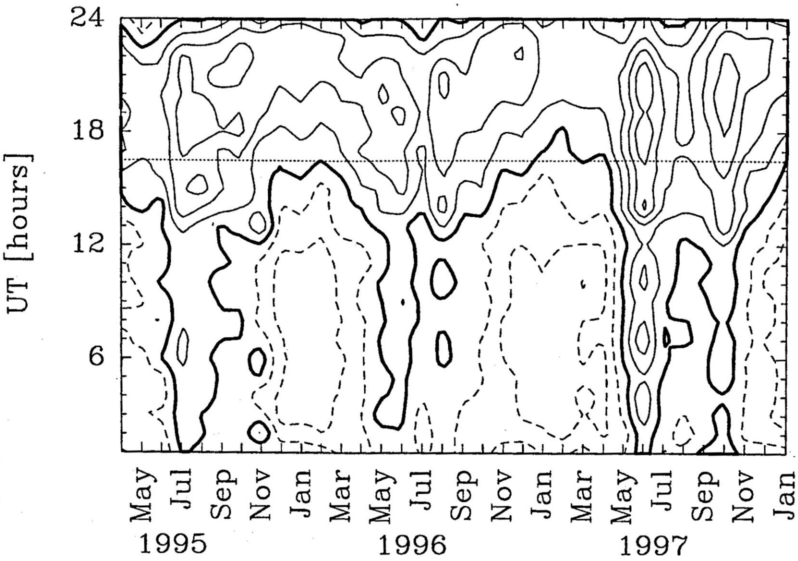

Figure 6. Diurnal variation of monthly median wind speeds measured at Chajnantor. Local solar time is UT$-4^{\mathrm{h}}\,30^{\mathrm{m}}$ and the dotted line indicates local noon. Heavy contour is $6\,\mathrm{m\,s^{-1}}$, contour interval is $2\,\mathrm{m\,s^{-1}}$, and dashed contours are $\leq 4\,\mathrm{m\,s^{-1}}$.

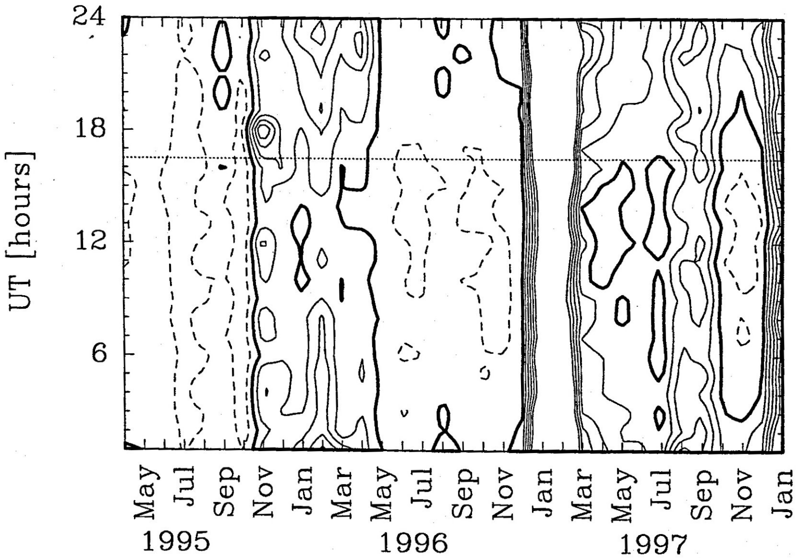

Figure 7. Diurnal variation of monthly median 225 GHz zenith optical depths measured at Chajnantor. Local solar time is UT $-\ 4^{\mathrm{h}}\,30^{\mathrm{m}}$ and the dotted line indicates local noon. Heavy contour is 0.06, contour interval is 0.02, and dashed contours are ≤ 0.04.

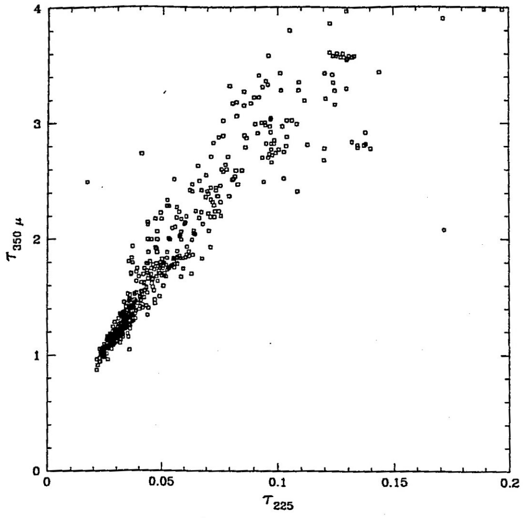

Figure 8. Correlation of broadband 350 μm ($\tau_{350\,\mu}$) and narrowband 225 GHz (τ_{225}) zenith optical depths measured on Chajnantor at night during 1997 November. (The tipper calibration was not working properly during daytime.)

The atmospheric transparency measured at Chajnantor is better than that measured at the CSO on Mauna Kea with the same instrument.[4] There is less diurnal variation in transparency on Chajnantor than on Mauna Kea. The transparency measured at Chajnantor in 1995-96 is comparable to that measured at the South Pole in 1992 with the same instrument.[5] The 1992 summer and winter median optical depths at the Pole, 0.080 and 0.046, respectively, are quite similar to the 1995-96 summer and winter medians at Chajnantor, 0.087 and 0.042.

3.2. 350 μm measurements

Enticed by the scientific interest in high frequency observations and by the low 225 GHz optical depths measured at Chajnantor, we have developed in collaboration with Carnegie Mellon University a tipping photometer to directly measure the atmospheric transparency at 350 μm wavelength. This instrument is based on an ambient temperature, pyroelectric detector. The spectral response is defined by a resonant metal mesh. A compound parabolic (Winston) cone and offset parabolic scanning mirror together define the 6° beam on the sky. The detector is internally calibrated with two temperature controlled loads and views the sky through a woven Gore-tex window. Identical instruments have been deployed on Chajnantor (1997 October), at the CSO on Mauna Kea (1997 December), and at the South Pole (1998 January).

Although the results are still very preliminary, the broadband 350 μm ($\tau_{350\,\mu}$) and narrowband 225 GHz (τ_{225}) zenith optical depths measured on Chajnantor are well correlated. The correlation can be fit linearly as $\tau_{350\,\mu} = 28\tau_{225} + 0.38$ for $\tau_{225} < 0.1$. There is also a hint of curvature to the correlation, in the sense that the slope is steeper and the intercept lower for low optical depths.

Since it is an average over the atmospheric window, the broadband optical depth is larger than the peak optical depth in the center of the window. The difference depends on the shapes of the broadband filter passband and of the atmospheric spectrum. From model calculations, we expect $\tau_{350\,\mu} = 1.1\tau_{850} + 0.31$, where τ_{850} is the narrow band optical depth at 850 GHz.

3.3. Spectroscopy

To measure the atmospheric emission spectrum at Chajnantor, the Smithsonian Observatory is deploying a Fourier transform (polarizing Martin-Pupplet) spectrometer with support from NRAO. This cryogenic instrument covers 200–5000 GHz with 3 GHz resolution and a 3° beam. Initial results are expected in the first half of 1998. In late

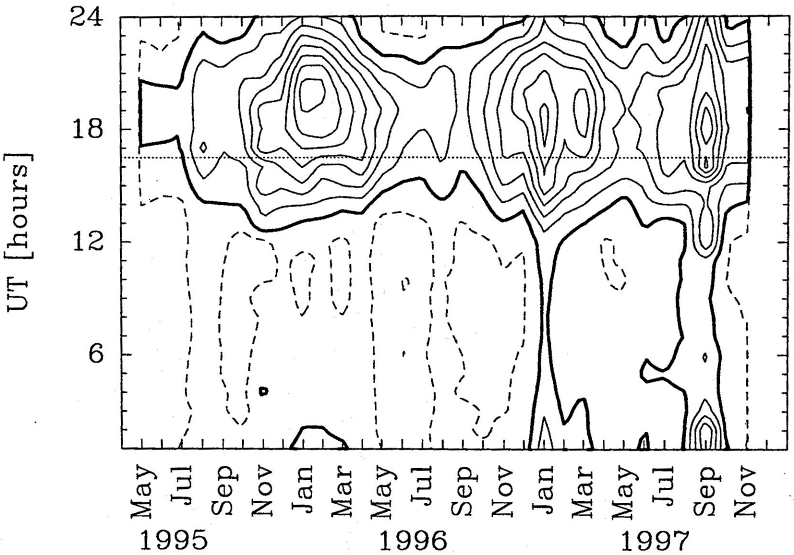

Figure 9. Diurnal variation of monthly median path length fluctuations measured at Chajnantor, scaled to zenith. Local solar time is UT $- 4^h 30^m$ and the dotted line indicates local noon. Heavy contour is 400 μm, contour interval is 100 μm, and dashed contour is 200 μm.

1997, a Japanese team made spectroscopic observations with a similar FTS at the neighboring Pampa la Bola site, about 10 km northeast from Chajnantor.[6] Our photometric results agree well with their spectroscopic measurements.

4. STABILITY

Because radio waves travel more slowly in wet air than in dry air, fluctuations in the water vapor content will cause variations in the electrical path length through the atmosphere. Path length variations across an array aperture will degrade both image quality and array sensitivity. Path length fluctuations, which are independent of observing frequency, correspond to phase fluctuations that scale linearly with frequency. Numerical simulations show phase fluctuations of less than 10° rms at the observing wavelength will have little impact upon most imaging. Phase errors of 30° rms will permit imaging with up to 200:1 dynamic range, but will result in a 13% sensitivity loss due to signal decorrelation. Image reconstruction becomes all but impossible for phase errors higher than 60° rms. Although active calibration schemes are under consideration to reduce the effects of most phase fluctuations, these correction schemes will work better if the underlying atmospheric phase fluctuations are smaller.[7,8]

Atmospheric phase stability is measured continuously with a 300 m baseline, 11.2 GHz interferometer observing a geostationary communications satellite.[9] Because the atmosphere is non-dispersive away from line centers, low frequency measurements can be extrapolated to characterize the atmospheric phase stability at least up to 350 GHz. This test interferometer senses atmospheric structures on 300 m and smaller scales. Because the satellite is viewed at larger zenith angle (54°) than the median zenith angle (25°) for uniformly distributed sources at low airmass ($A < 2$), we scale the phase fluctuations to the expected value at the zenith.[10] The effective baseline of the test interferometer is then about 200 m. We characterize the phase stability by the r.m.s. phase fluctuations calculated over 10 minute intervals. This interval is twenty times longer than the time it takes an atmospheric feature to move the length of the baseline at $10\,\mathrm{m\,s^{-1}}$, which is a typical wind speed aloft. Thermal instrumental phase noise is on the order of 0.1° r.m.s. at 11.2 GHz, while the smallest phase fluctuation seen to date—after allowing for instrument noise—is 0.3° r.m.s. at 11.2 GHz.[7]

Like the windspeed (Fig. 6), the measured phase stability (Fig. 9) shows marked diurnal variation. The phase stability deteriorates in the afternoons just when the windspeed increases. There is seasonal variation in the phase stability as well, but note the seasonal variations in the windspeed and phase stability are anticorrelated. Even though the windspeed is often higher in the winter, the phase stability tends to be better. Moreover, in winter the wind is predominantly westerly, where the horizon is unobstructed. In summer, however, the wind blows from the east 30-50% of the time. On those occasions, the wind flows over and around Cerro Chascon, which presumably generates substantial turbulence.[11]

5. CONCLUSIONS

Water vapor is the primary atmospheric impediment to astronomical observations at millimeter and submillimeter wavelenghs, degrading both telescope resolution and sensitivity. Because water vapor is largely confined to the lower atmosphere, however, extremely dry air can be found at high altitude sites.

NRAO has explored a candidate site for the Millimeter Array at 5000 m altitude near Cerro Chajnantor in the high Andes on the eastern edge of the Atacama desert. Measurements of the atmospheric transparency and stability show this is an excellent site for millimeter and submillimeter wavelength astronomy. The 225 GHz transparency is better than on Mauna Kea, with less diurnal variation. The median 225 GHz transparencies measured at Chajnantor and at the South Pole are comparable.

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