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Stability of the Submillimeter Brightness of the Atmosphere above Mauna Kea, Chajnantor, and the South Pole

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ABSTRACT. The summit of Mauna Kea in Hawaii, the area near Cerro Chajnantor in Chile, and the South Pole are sites of large millimeter- or submillimeter-wavelength telescopes. We have placed 860 GHz sky brightness monitors at all three sites and present a comparative study of the measured submillimeter brightness due to atmospheric thermal emission. We report the stability of that quantity at each site.

1. INTRODUCTION

Observations at submillimeter wavelengths are used to study molecular clouds, the Galactic center region, and high-redshift galaxies, among other sources. At submillimeter wavelengths, these astrophysical sources are more transparent than at optical or infrared wavelengths, allowing the study of the interiors of dense regions. However, despite the transparency of astronomical sources, Earth's atmosphere is largely opaque at these wavelengths.

Water vapor and other atmospheric gases absorb submillimeter radiation, attenuating astronomical signals. By Kirchoff's law, this absorption also leads to thermal radiation from the atmosphere itself, adding noise. Together, these effects degrade the signal-to-noise ratio, increasing the observing time necessary to reach a desired sensitivity. Worse, moving inhomogeneities in the water vapor distribution cause rapid fluctuations in the atmospheric radiation, called sky noise. In addition, slow variations of attenuation make calibration difficult. The uncertainty in astronomical flux caused by fluctuations due to the atmosphere often greatly exceeds that due to receiver noise.

Because of sky noise and attenuation, submillimeter astronomical observations can be made only at the driest, most stable sites. Three premier sites that have been used for millimeter or submillimeter observations and have also been chosen for large submillimeter telescopes are Mauna Kea in Hawaii (4100 m elevation), the area near Cerro Chajnantor in Chile (5000 m), and the Amundsen-Scott station at the South Pole (2800 m). We placed identical tipping photometers at these three sites to make automated measurements of sky brightness at 860 GHz (350 μm wavelength). These data are presented here in the form of values of the zenith optical depth of the atmosphere.

Previous measurements have shown that all three sites have very low *millimeter* wavelength (30–300 GHz) sky brightness. Identical radiometers operating at 225 GHz have been used for years to measure the brightness of the atmosphere. The median zenith optical depths derived from these measurement are Mauna Kea, 0.091; Chajnantor, 0.061; South Pole, 0.053 (Chamberlin & Bally 1994; Chamberlin, Lane, & Stark 1997; Radford & Chamberlin 2000).[7] Data from these instruments have not been analyzed to compare the atmospheric stability at the sites.

One previous study compared estimates of centimeter- and millimeter-wavelength sky noise at the South Pole and Chajnantor (Lay & Halverson 2000). An 11.2 GHz phase-difference monitor has been operated at Chajnantor for several years (Radford, Reiland, & Shillue 1996). This interferometer has a baseline of 300 m and measures phase fluctuations in a carrier wave broadcast by a geostationary satellite. These phase fluctuations are primarily due to turbulence in the water vapor above the site. At the South Pole, the Python telescope was used to study the cosmic microwave background at 90 GHz. The atmospheric emission fluctuations seen in the Python data are also due to water vapor variations. These data can be compared, but because the two instruments measure different spatial scales and different frequencies, models of atmospheric turbulence and the atmospheric emissivity spectrum are needed for comparison. In addition, to compare the two sites, an assumption must be made about the height of the turbulent layer at each site. Making reasonable assumptions, the analysis of Lay &

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[7] http://www.alma.nrao.edu/memos/html-memos/abstracts/abs334.html.

Halverson (2000) indicates that the sky noise at South Pole is lower than at Chajnantor by about a factor of 10.

Narrowband submillimeter sky brightness measurements have been made for several years using the AST/RO telescope at the South Pole (Chamberlin et al. 1997) at 461 and 492 GHz. This region of the spectrum is complicated by the wings of nearby O_2 and H_2O lines. The median winter zenith optical was found to be 0.70. Opacity at the South Pole has also been measured at 806 GHz with AST/RO and from 100 to 1800 GHz using a Fourier transform spectrometer (Chamberlin et al. 2003). The South Pole data have not been analyzed to study stability, and no similar data exist for Mauna Kea or Chajnantor.

To provide a set of site-quality measurements in a standard band used for submillimeter observations, we built a set of identical site-monitor instruments, called submillimeter tippers, which measure the sky brightness in the 860 GHz spectral window. These tippers overcome two of the problems of some of the previous site evaluation observations: dissimilar instrumentation and sporadic observation. The tippers are designed to be simple and compact. They require little electrical power and no cryogens. The tippers have the sensitivity to measure the zenith optical depth to about 3% every 12 minutes.

The 860 GHz atmospheric window lies between two strong pressure-broadened water lines. Because of the proximity to water lines, for most of the data presented here, water vapor is the component of the atmosphere that contributes most to opacity. At the South Pole, however, there is evidence of a dry-air component of opacity. After applying the window correction of Calisse (2002) to the data presented in Chamberlin (2001), we find $\tau_{\rm dry} \sim 0.3 \pm 0.1$. Since τ values as low as 0.5 are measured at all three sites, the dry air component is significant at times.

Broadband submillimeter astronomical observations are usually made by beam switching, that is, by rapidly (1–10 Hz) moving the telescope beam between points on the sky. By differencing the measured flux from two or more nearby points, much of the atmospheric emission can be subtracted from the data. It is the residual atmospheric emission after this subtraction that acts as the sky noise for these observations. Our submillimeter tipper instruments are not sensitive enough to detect variations of sky brightness at 10 Hz, and the beam width of our instrument (6°) is much larger than that of a large submillimeter telescope. To use the variations of optical depth reported below as an indication of sky noise in beam-switched observations would require an extrapolation by about 10^3 in both angular scale and fluctuation frequency. The uncertainty in that extrapolation exceeds the site-to-site differences in sky noise presented here.

To calibrate submillimeter observations, measurements of the atmospheric attenuation are needed throughout the course of the observation. The data presented here are taken in a manner and over a timescale similar to the attenuation measurements typically made during submillimeter observations. When interpreted as measures of attenuation stability, these results apply directly, with no need for extrapolation.

In this paper, we present data from all three sites for the period 1998 January to 2002 August.

2. INSTRUMENT DESCRIPTION

Radiation from the sky entering the tipper through a cylindrical window of woven expanded PTFE is then focused and redirected by an off-axis parabolic mirror. The sky flux is periodically interrupted at 0.75 Hz by a rotating chopper wheel. After the chopper, the radiation is filtered by a multilayer resonant mesh filter and then enters a compound parabolic concentrator (CPC) that illuminates a pyroelectric detector. The entrance aperture diameter of the CPC and the focal length of the parabolic mirror together determine the 6° beam width of the tipper.

The parabolic mirror is mounted on the shaft of a stepping motor so the mirror can be rotated about the axis of the CPC, allowing observations at various elevation angles. Rotating the mirror also allows the beam to be directed into either of two blackbody calibrators, which are held at approximately 300 and 340 K.

Approximately five times each hour, a set of observations, which we call a tip, are made. A tip consists of observations at elevation angles $\theta_i = 90°$, 41°.8, 30°, 23°.6, 19°.5, 16°.6, and 14°.5 (chosen to provide a linear progression of air mass) along with observations of both calibrators.

Further details on the design and operation of the instrument are presented in S. J. E. Radford et al. (2003, in preparation).

3. DATA REDUCTION

In the data reduction, brightness data from the tips are converted to values of slab-model zenith optical depth τ. This optical depth determines both the emission from and attenuation by the atmosphere.

First, calibration measurements are used to convert the measured detector voltages to sky brightness temperatures. Then, data for each tip are least-squares fitted to an isothermal slab model of the atmosphere, $T_i = T(1 - e^{-\tau A_i})$. Here τ is the zenith optical depth, T is the effective temperature of the atmosphere, $A_i = \csc(\theta_i)$ are air mass values, T_i are sky brightness temperatures, and the index i counts through the seven elevation angles used in the tip. In addition to estimating the optical depth of the atmosphere and its effective temperature, the processing provides uncertainties in both parameters as well as the mean squared error and goodness of fit.

The window of the tipper has an average transmittance 0.81 ± 0.03 across the passband of the instrument, and the calibrators are inside the window. The window attenuates sky brightness signals and adds a window emission brightness component. We have corrected the τ values to remove the effect of window emission and attenuation following the procedure

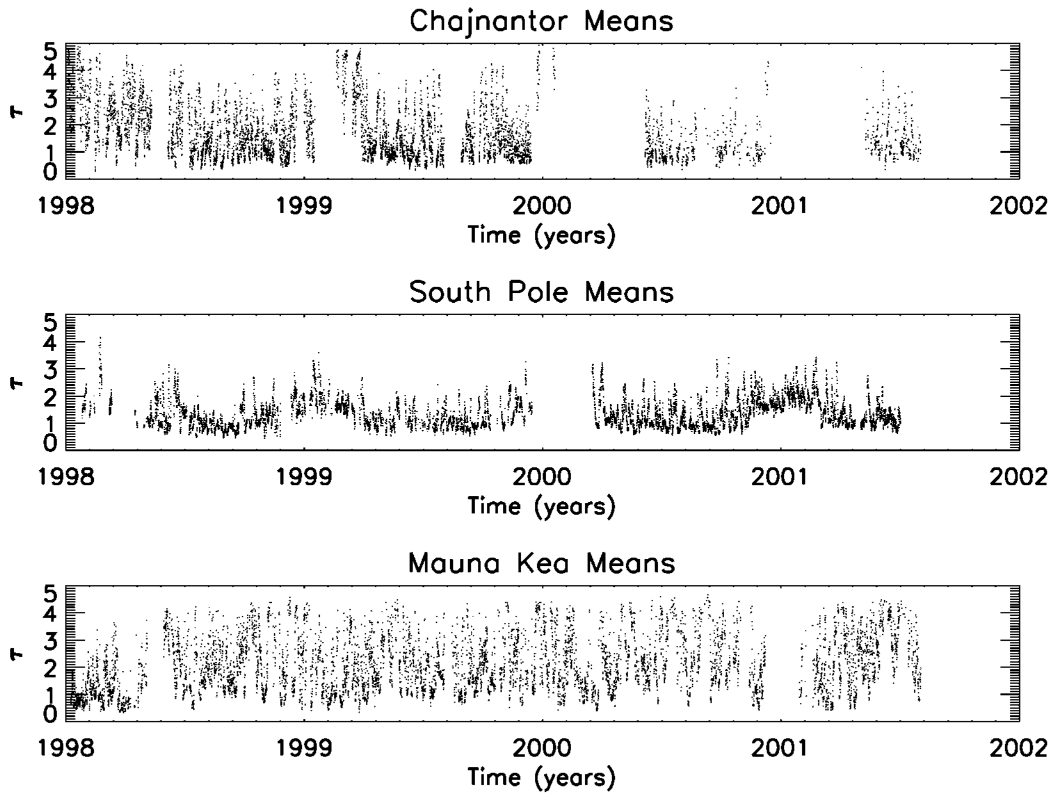

FIG. 1.—Zenith optical depth at 860 GHz. Mean values for 2 hr intervals are plotted. Intervals with no data are the result of tipper breakdowns or data cuts.

of Calisse (2002). Typical values of the correction are −0.25 at $\tau = 2$ and −0.32 at $\tau = 0.5$. To check this window correction, we temporarily added a second layer of window material to the South Pole tipper. Averaging five trials of this experiment, we find that the apparent value of τ was increased from 0.9 by 0.18 ± 0.07, consistent with the calculated correction. Note that all previous publications that make use of tipper results have not been corrected for window emission and should be updated.

During 1999, instability of the chopping-wheel speed in the South Pole tipper caused increased and variable instrument noise. Because of this instability, variance values for the Pole in 1999 have been cut from the data set of variations of τ. The average values were not affected by the instability, so those values are included.

Some data fail to fit the slab model because of either cloud structure in the atmosphere or instrument malfunction. An observation was discarded if the best-fit value of τ was greater than 50 or equal to zero, the uncertainty in τ was greater than 1000 or zero, the estimated atmospheric temperature T_{atm} was greater than 1000 K, or the goodness of fit was zero. Samples with fit values of T_{atm} between 300 and 1000 K are also suspect, since the real atmospheric temperature is well below 300 K, but these samples were retained to avoid the possibility of biased removal of high-noise samples. Altogether, these data filters removed about 5% of the data.

The data filters might remove some legitimate data points with greater than average values of τ or σ_τ. For submillimeter astronomy, however, only the stable periods with low τ are usable. In any comparison of quiet sky periods, the bias resulting from the filtering process should be small and slightly favor a less-stable site. Considering the small fraction of data cut, the looseness of the cut parameters, and the tendency of the bias to affect mostly the high-τ segments of the data, we estimate that systematic bias from data cutting is less than 1% and make no correction for this effect.

4. QUALITATIVE COMPARISON

Figure 1 shows 2 hr means of optical depth for the three sites during the 4 yr beginning on 1998 January 1. Figure 2 shows the standard deviation of τ in 2 hr intervals for the same period. Figure 3 shows the most stable 2 week period in 1998 for each site. Successive points are typically taken 12–15 minutes apart.

Cumulative distributions of optical depth are shown in Figure 4, and quartiles from that distribution are shown in Table 1. All three sites have median optical depths between 1 and 2.

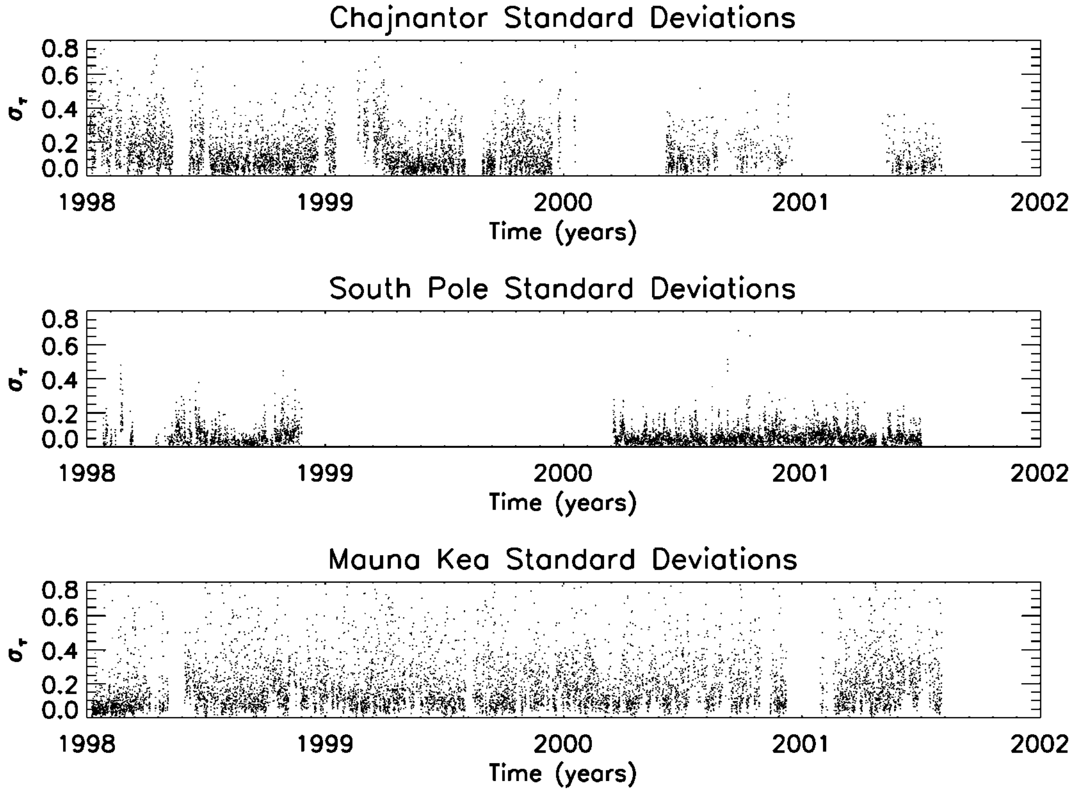

FIG. 2.—Variations of optical depth. The standard deviation of τ during 2 hr intervals is plotted. Instrument noise has been subtracted from the measured variance to produce the values plotted.

Because the transparency of a slab is exp $(-A\tau)$, only 24% of the radiation from a source at 45° elevation reaches the telescope when $\tau = 1$. These measurements demonstrate the challenge of submillimeter astronomy, even from superb sites. Below the median, the South Pole and Chajnantor have similar distributions of opacity, while Mauna Kea has higher opacity.

Our measurements demonstrate that the atmosphere at the South Pole is more stable than at the other two sites (Figs. 1 and 2). This is particularly evident in Figure 3. At the South Pole, variations due to noise intrinsic to the tipper usually exceed real variations of atmospheric optical depth for averages over periods less than a few hours. For Chajnantor, the sequence of τ-values follows monotonically increasing or decreasing trends for periods of several hours. The point-to-point variations in the Chajnantor data are mostly due to real changes of optical depth rather than instrumental noise. Much of this variation is diurnal. Mauna Kea has hardly any periods of stability comparable to the other sites.

5. QUANTITATIVE STABILITY ANALYSIS

To quantitatively compare the atmospheric stability at the three sites, we studied the fluctuations in optical depth during 2 hr intervals. This choice of interval, during which nine observations were typically made, represents a compromise. Integration periods longer than an hour are needed to average out instrumental noise sufficiently so that variations of optical depth can be measured in the South Pole data. Integrations longer than a few hours, on the other hand, would be dominated

TABLE 1
QUARTILES OF MEASURED ATMOSPHERIC ZENITH OPTICAL DEPTH

τ (860 GHz)	25%	50%	75%
South Pole	0.91	1.20	1.64
Chajnantor	0.91	1.39	2.22
Mauna Kea	1.20	1.88	2.73

TABLE 2
QUARTILES OF OPTICAL DEPTH VARIATION AFTER REMOVAL OF INSTRUMENTAL NOISE

$\sigma(\tau)$	25%	50%	75%
South Pole	<0.01	0.03	0.07
Chajnantor	0.05	0.10	0.18
Mauna Kea	0.08	0.13	0.24

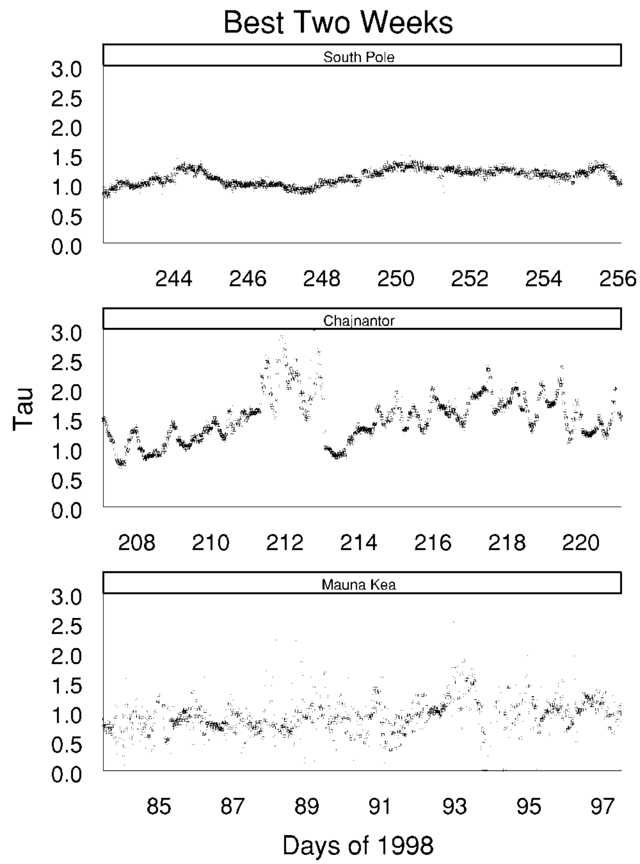

FIG. 3.—Zenith optical depths at 350 μm are shown for the most stable 2 weeks during 1998 at each site. The point-to-point variations in the South Pole data are due to instrumental noise. The tippers at the other sites have similar noise levels. Strong diurnal variation is evident in the Chajnantor data. Mauna Kea has only occasional short periods of stability.

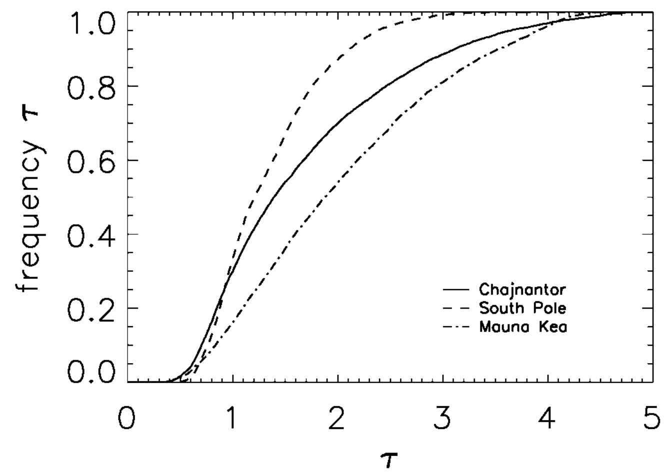

FIG. 4.—Cumulative distributions of 860 GHz zenith optical depth.

by the diurnal variations present at Chajnantor. Also, submillimeter observations tend to last a few hours.

We determined the instrumental noise using the calibration data. During calibration, the detector voltage, measured while the mirror is turned toward the warm or hot calibrator, is compared with the calibrator temperature, measured using a thermometer attached to the calibrator. To determine the instrumental noise, we calculated the variance of the detector voltage. The instrument noise level is typically $\sigma_\tau \sim 0.04$

To test whether the noise in the South Pole data during quiet periods is due to the instrument, we calculated the set of differences of successive observations of τ for the South Pole during the best 2 weeks of 1998. The resulting distribution of differences is an excellent fit to the Gaussian distribution expected from instrumental noise alone. Atmospheric variations of optical depth would have a broader distribution with long tails. We conclude that instrumental noise is dominant during the most stable periods, and we proceed to subtract its variance from the total variance to estimate the variance due to atmospheric fluctuations. Because the South Pole is so stable, the variance difference is negative about 40% of the time. In these cases, the atmospheric variation is too small to measure precisely with our instrumental noise, and we assign a value of σ_τ in the range 0–0.01 to these samples.

Cumulative distributions of optical depth variation are shown in Table 2 and plotted in Figure 5.

We also calculated the power spectrum of the optical depth variations for the best 2 weeks of 1998 segments (Fig. 6). The power spectrum falls with frequency at all three sites. The level

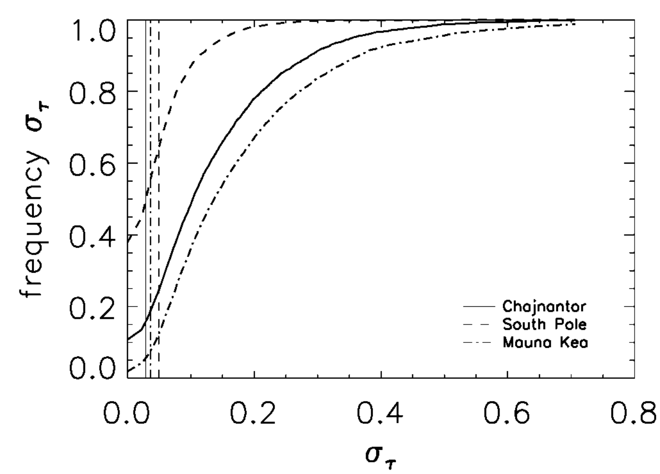

FIG. 5.—Cumulative distribution of 860 GHz zenith optical depth variations. These distributions are the result of subtraction in quadrature of instrumental noise variance from the total measured variance. Negative resultant variances are accumulated in the bin at zero standard deviation. We estimate that these variation estimates should be reliable for σ_τ values greater than 0.01. The vertical lines show the instrumental noise that has been subtracted.

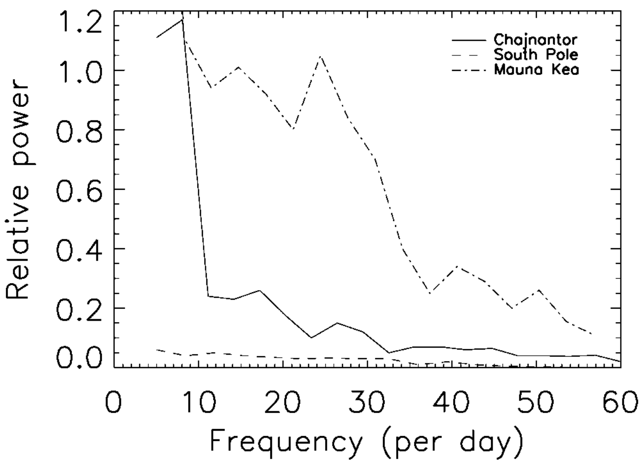

FIG. 6.—Binned power spectra of zenith optical depth. The irregularly sampled data for each site's best 2 weeks were converted to a regularly sampled stream by linear interpolation and the spectrum was calculated. The data were binned in frequency and medians of each frequency range are shown. The approximate Nyquist frequency is 60 day^{-1}. The lowest frequency bin of the Mauna Kea power spectrum is off scale with a relative power of 2.53 at 5 day^{-1}.

of optical depth fluctuation power is much lower at the South Pole than at the other sites.

6. CONCLUSIONS

The median opacity at the South Pole (1.20) is lower than that at Chajnantor (1.39) and at Mauna Kea (1.88). Since all these values are above 1, rare, low-opacity periods are of special interest. During these periods, observations may be possible that would not usually succeed. Below the median, the opacity distributions at the South Pole and Chajnantor are similar. At the South Pole, the low ambient temperature maintains a low water vapor density. In contrast, at Chajnantor, the low surface pressure is expected to produce the lowest dry-air opacity of the three sites. Apparently, these differences offset each other, producing similar opacity distributions below the median.

At the median, the standard deviation of the zenith optical depth at the South Pole is 3 times lower than at Chajnantor and 4 times lower than at Mauna Kea. In agreement with Lay & Halverson (2000), we find that the submillimeter atmospheric opacity at the South Pole is substantially more stable than at Chajnantor. We also find that Chajnantor has better stability than Mauna Kea.

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