Submillimeter Transmission at South Pole

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Abstract. Site testing measurements conducted by the Center for Astrophysical Research in Antarctica (CARA) have demonstrated that the South Pole is the best observatory site on Earth for submillimeter and millimeter astronomy. Skydip measurements taken at 492 GHz with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) throughout 1995 have provided the first systematic, long-term measurements of submillimeter-wave atmospheric transparency at an astronomical site. These data were taken concurrently with precipitable water vapor measurements; comparison shows that atmospheric constituents other than water vapor contribute to the opacity at submillimeter wavelengths at South Pole. Millimeter and submillimeter opacity and water vapor data for South Pole are compared with similar data for other observatory sites.

1. Introduction

Submillimeter astronomy can only be pursued from extremely cold and dry sites, where the atmosphere contains less than 1 mm of precipitable water vapor. Water vapor is usually the dominant source of opacity, although thousands of other molecular lines also contribute (Waters 1976; Bally 1989). Submillimeter sky opacity and noise depend on atmospheric temperature and pressure, as well as water vapor content. While the altitude of South Pole Station (2835 m) is lower than that of some other existing (e.g., Mauna Kea, Hawaii) or proposed (e.g., Atacama desert, Chile) mm/submm observing sites—resulting in higher atmospheric pressure and hence broader telluric lines—the polar atmosphere is significantly drier than anywhere else on Earth. Profiles of temperature, pressure, and water vapor above the Pole, measured by balloon-borne radiosonde at least once a day for several decades (Schwerdtfeger 1984), consistently show precipitable water vapor (PWV) values which are near saturation for air at the observed temperature and pressure. The PWV values which are consistent with saturation are extremely low because the polar air is dessicated by the frigid temperature (annual average: -49 C, minimum temperature: -82 C). Early evidence that South Pole would prove to be an excellent site for submillimeter astronomy was provided by skydip measurements over a broad bandwidth centered at $\lambda 700$ μm made on six days in 1987 by Dragovan et al. (1990).

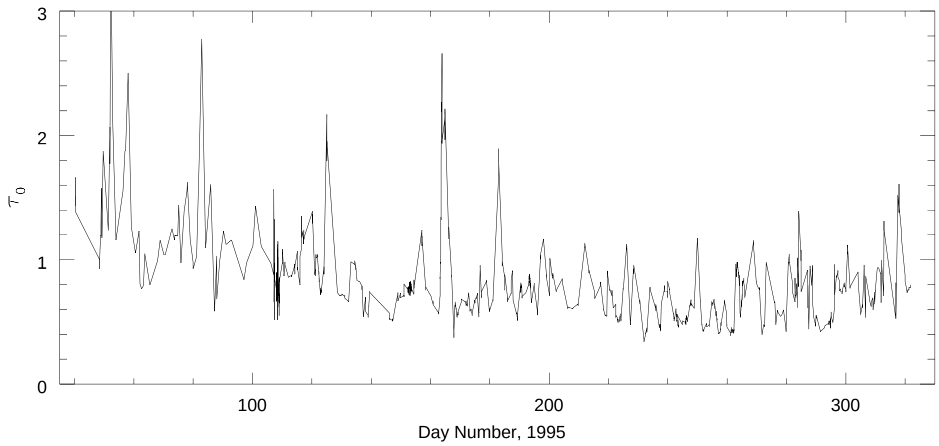

Figure 1. **South Pole 492 GHz Opacity during 1995** Shown is the measured 492 GHz zenith opacity, τ_0, at the South Pole plotted as a function of days elapsed since 1 January 1995 (Chamberlin, Lane, and Stark 1997). Prior to day 137, the local oscillator was set to 490.66 GHz; after day 137, the center frequency was 493.66 GHz. The minimum 492 GHz opacity at Pole is limited to 0.33 ± 0.02 largely by the wings of the O_2 line at 487 GHz.

2. Submillimeter Opacity Measurements

CARA experiments have directly measured both millimeter and submillimeter-wave atmospheric opacity at the South Pole using skydip techniques. Over 1100 skydip observations were made at 492 GHz (λ609 μm) with the 1.7 m AST/RO telescope during the 1995 observing season (Chamberlin, Lane, and Stark 1997), in conjunction with Galactic survey observations of the [C I] $^3P_1 \rightarrow {}^3P_0$ line. The zenith opacity derived by fitting a single-slab atmospheric model to the data is shown in Figure 1 as a function of day number in 1995. Even though the observed 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 at any ground-based site. The stability was also remarkably good: the opacity remained below 1.0 for weeks at a time. Quartile values from the opacity cumulative distribution function are listed for both summer and winter in Table 1.

3. Precipitable Water Vapor

Radiosonde measurements made twice daily in summer and once daily in winter by the South Pole meteorology office have been used to derive values for the column of precipitable water vapor above the South Pole (Chamberlin, Lane, and Stark 1997; Chamberlin and Bally 1995). Quartile values from the PWV cumulative distribution function are listed in Table 1 and plotted in Fig. 2, where they are compared with corresponding values for Mauna Kea and for Atacama. The PWV values for the latter two sites were derived from an assumed relation between PWV and measured opacity at 225 GHz (Hogg 1992, Masson 1994; S.

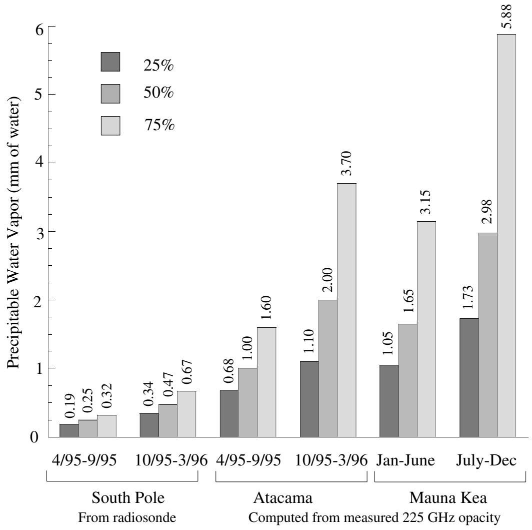

Figure 2. **Quartiles of Precipitable Water Vapor at Three Sites** The South Pole is a considerably drier site than Mauna Kea or Atacama (Chamberlin, Lane, and Stark 1997). During the wettest quartile at the South Pole, the total precipitable water vapor is lower than during the driest quartile at either Mauna Kea or Atacama.

Foster, private communication). For each site, the data are separated into the best 6-month period and the remainder of the year. Of the three sites, South Pole has by far the lowest PWV, during Austral summer as well as winter. In fact, the 75th percentile value for the *wetter* half of the year at the South Pole is less than the 25th percentile value for the *drier* half of the year at Mauna Kea or Atacama.

The correlation of 492 GHz opacity at South Pole with atmospheric water vapor (Chamberlin, Lane, and Stark 1997) is shown in Figure 3. For all points, the balloon sounding used to determine PWV was made within 6 hours of the associated skydip observation. A linear least squares fit to the solid circles (ν_{LO} = 493.66 GHz) gives:

$$\tau_0 = 0.33 + 1.49PWV,$$

showing that there is a significant contribution from dry air opacity at this frequency, more than is predicted by the Grossman atmospheric transparency model (see Chamberlin, Lane, and Stark 1997). Nonetheless, the atmosphere is sufficiently dry that 492 GHz observations are possible at South Pole over 90% of the time in Austral winter and spring.

4. Millimeter Opacity Measurements

Skydip data at 225 GHz (λ1.33 mm) for the Pole were obtained during 1992 (Chamberlin and Bally 1994, Chamberlin and Bally 1995) using a standard NRAO tipping radiometer similar to the ones used to measure the 225 GHz zenith opacities at Mauna Kea and Atacama. Quartile values for the three sites are listed in Table 1 (Mauna Kea data from Hogg 1992, averaged over the

PRECIPITABLE WATER VAPOR (mm of water)

	SOUTH POLE Winter (1) 4/95-9/95	*SOUTH POLE* Summer (1) 10/95-3/96	*MAUNA KEA* (2) Jan-June	*MAUNA KEA* (2) July-Dec	*ATACAMA* Winter (2) 4/95-9/95	*ATACAMA* Summer (2) 10/95-3/96
25%	0.19	0.34	1.05	1.73	0.68	1.1
50%	0.25	0.47	1.65	2.98	1.0	2.0
75%	0.32	0.67	3.15	5.88	1.6	3.7

225 GHz ZENITH OPACITY (NRAO tipper data)

	SOUTH POLE Winter (3) 4/93-9/93	*SOUTH POLE* Summer (3) 10/93-3/94	*MAUNA KEA* (3) Jan-June	*MAUNA KEA* (3) July-Dec	*ATACAMA* Winter (3) 4/95-9/95	*ATACAMA* Summer (3) 10/95-3/96
25%	0.040	0.052	0.052	0.079	0.032	0.046
50%	0.046	0.062	0.076	0.129	0.044	0.077
75%	0.055	0.076	0.136	0.245	0.066	0.138

492 GHz ZENITH OPACITY

	SOUTH POLE Winter (3) 4/95-9/95	*SOUTH POLE* Summer (3) 10/95-3/96	*MAUNA KEA* (2) Jan-June	*MAUNA KEA* (2) July-Dec
25%	0.55	0.84	0.84	1.38
50%	0.70	1.03	1.32	2.38
75%	0.81	1.33	2.52	4.70

(1) From radiosonde.
(2) Computed from measured 225 GHz opacity.
(3) Measured by skydips.

Table 1. **PWV, 225 GHz and 492 GHz Opacity: Comparison of Three Sites**

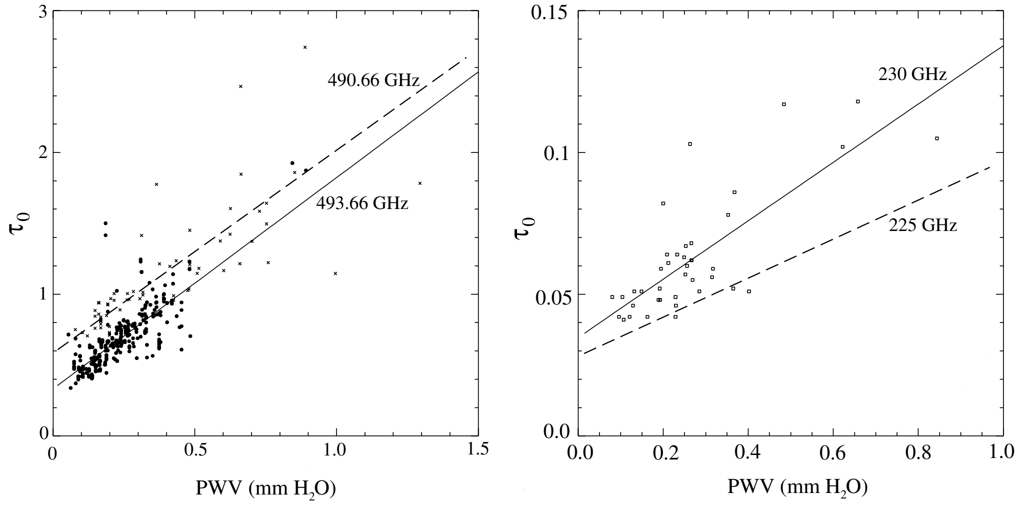

Figure 3. Zenith opacity, obtained from AST/RO skydip measurements, plotted as a function of precipitable water vapor, as determined by balloon radiosonde (Chamberlin, Lane, and Stark 1997). (*left*) Crosses (and dashed line): 490.66 GHz opacity. Solid circles (and solid line): 493.66 GHz opacity. (*right*) Squares (and solid line): 230 GHz opacity. Dashed line shows 225 GHz result from Chamberlin and Bally (1995). Note the two plots have different vertical scales.

period from 1989 October 1 to 1991 August 31; Atacama data from S. Foster 1996, private communication). There is a close linear relation between 225 GHz opacity data and balloon sonde PWV measurements at South Pole which is discussed in Chamberlin and Bally (1995) and Chamberlin, Lane, and Stark (1997). The latter paper finds:

$$\tau_0(225\ GHz) = 0.030 + 0.069PWV.$$

Additional skydip data were obtained at 230 GHz with the AST/RO telescope during 1995 (Chamberlin 1995). The resulting τ_0–PWV correlation is shown in Figure 3 and indicates a slightly larger dry air opacity (0.035) at this frequency due to the telluric CO line.

5. Summary: South Pole as a Submillimeter Observatory Site

Of the three sites considered here—South Pole, Mauna Kea, and Atacama—South Pole consistently has the lowest water vapor and temperature but the highest pressure. This mixture makes the comparison between Pole and other sites more favorable at some wavelengths than at others; in particular, the transparency at frequencies between 600 and 1500 GHz (500 to 200 μm) is most sensitive to PWV, favoring the Pole. All three sites are excellent at millimeter-waves; the 225 GHz data for South Pole and Atacama are comparable, and both are superior to Mauna Kea. Similar 225 GHz opacity at Pole and Atacama, together with the higher atmospheric pressure at Pole, necessarily implies that

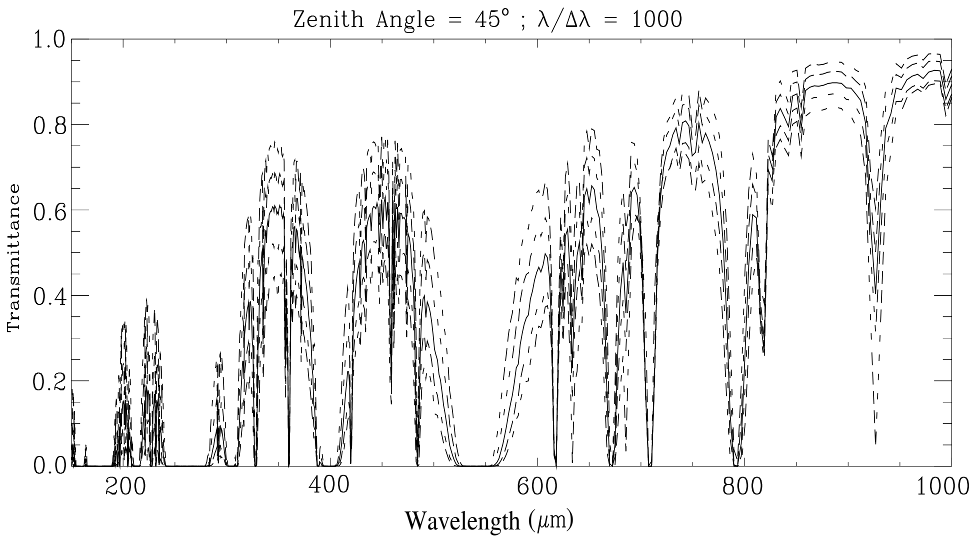

Figure 4. **Calculated Atmospheric Transmittance at South Pole** Atmospheric transmittance at 1.41 airmasses calculated by K. C. Yu using Grossman's AT code. Values near 609μm are consistent with AST/RO site testing. The upper four lines are for values of precipitable water vapor which are applicable 10%, 25%, 50%, and 75% of the time during winter (0.14 mm, 0.19 mm, 0.25 mm, and 0.32 mm, respectively). Also plotted (bottom dashed line) are values for the best 25% of the time during the better half of the year at Atacama (PWV = 0.68 mm).

the submillimeter-wave windows are more transparent at Pole than at Atacama (Chamberlin, Lane, and Stark 1997). High-frequency submillimeter tipper measurements are currently underway at the three sites to provide direct empirical comparison.

The South Pole PWV levels applicable 10%, 25%, 50%, and 75% of the time during winter have been used to compute values of atmospheric transmittance as a function of wavelength (Fig. 4). For comparison, the transmittance for excellent conditions on Atacama is shown by the lowest dashed line in the figure. If three identical background-limited instruments operating in the 350 μm window were placed at Pole, Atacama, and Mauna Kea to do identical observations over a long period of time, the observations at Pole would proceed 110× faster than Mauna Kea and 4.5× faster than Atacama.

The Antarctic Plateau is unique among observatory sites for unusually low wind speeds, absence of rain, and the consistent clarity of the submillimeter sky. The highest wind speed at the South Pole between 1957 and 1983 was only 24 m s^{-1}, and there are many months during which the wind speed does not exceed 12 m s^{-1}. Ice cores show no rain at the Pole for thousands of years. Schwerdtfeger (1984) has summarized the climate of the Antarctic Plateau.

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