Site Characterization and Atmospheric Transparency in the mm/submm Range
ASP Conference Series, Vol. IAU SITE2000, 2000
Vernin, Munoz-Tunon, Benkhaldoun

Comparisons of saturated water vapor column from radiosonde, and mm and submm radiometric opacities at the South Pole

Richard A. Chamberlin

Caltech Submillimeter Observatory, 111 Nowelo Street, Hilo, HI 96720

Abstract.
The geographic South Pole is being developed as an outstanding site for submillimeter astronomy. In the 1990's, millimeter and sub-millimeter measurements of the atmospheric opacity were made throughout the winter months covering the wavelength range from 1.3mm to 0.35 mm. These ongoing opacity measurements span almost a decade. However, they are not continuous: there is very little information about the South Pole sub-mm opacity prior to 1992; and, not all wavelength ranges are covered by opacity measurements for each year. As part of characterizing the South Pole site quality, we made comparisons with saturated Precipitable Water Vapor ($PWVsat$) derived from concurrent radiosonde measurements and found significant correlations with mm and sub-mm opacity data sets. ($PWVsat$ is based on only the atmospheric temperature profile and represents the maximum water vapor that a saturated atmosphere could hold assuming coexistence with the ice phase. Using $PWVsat$ instead of PWV avoids problems associated with inconsistent hygrometer response sometimes found in different radiosonde instruments.) Since the record of radiosonde observations at the South Pole goes back to 1961, and since we can correlate our existing sub-mm opacity data sets with $PWVsat$, we are able to infer historical site quality. We find that the outstanding submillimeter site quality observed in the 1990's prevails for every year on record going back to 1961. We note that this year-to-year consistency of outstanding site quality is unusual when compared to middle-latitude high mountain sites.

It has long been noted by astronomers that the South Pole is a very dry site (Smythe & Jackson 1977; Lane 1998). Since submillimeter wavelength atmospheric opacity is a strong function of atmospheric water vapor abundance (Zammit and Ade 1981; Liebe 1985; Grossman 1989; Pardo 2001), the South Pole is an outstanding site for performing ground-based, submillimeter astronomy.

Observing programs to obtain direct measurements of millimeter and submillimeter South Pole atmospheric opacity and temporal stability are a fairly recent enterprise (Dragovan et al. 1990; Chamberlin & Bally 1994; Chamberlin, Lane, & Stark 1997; Lay & Halverson 2000; Chamberlin 2001; O'Kelly et al. 2001; Radford, Schartman, & Peterson 2001). These relatively recent results can be extrapolated back in time if we can observe correlation with atmospheric conditions recorded by concurrent upper air observations made with radiosonde.

South Pole radiosonde observations have been made routinely since 1957 and the data record from 1961 is available online from the NOAA Climate Monitoring and Diagnostics Laboratory.

We have made such comparisons (Chamberlin & Bally 1995; Chamberlin et al. 1997; Chamberlin 2001) and found that submillimeter zenith opacity has significant correlation with tropospheric integrated water vapor column density, PWV, derived from routine radiosonde observations. Studies of wintertime radiosonde soundings (Chamberlin 2001) have led us to the conclusion that the wintertime tropospheric PWV is typically about 90% of $PWVsat$, the saturated water vapor column. $PWVsat$, was calculated by using only the radiosonde ascent temperature profile and the assumption of coexistence with the ice phase.

Our studies span the submillimeter frequency range from 225 GHz to 860 GHz and include radiometer data from three different instrument types: a NRAO 225 GHz heterodyne site testing radiometer (Liu 1987); the AST/RO submillimeter radio telescope (Stark et al. 2001); and the NRAO/CMU 860 GHz broadband site testing radiometer (Radford, Schartman, & Peterson 2001). Radiosonde types we have made direct comparisons with include the A.I.R. Model 4A and model 5A, and NOAA Vaisala radiosondes. We have also provided validation of the absolute calibration of the A.I.R. Model 4A radiosonde for measuring tropospheric PWV by comparing its results with a limited set of measurements from the NOAA radiosondes equipped with frost point hygrometers (Chamberlin 2001). Our studies indicated that all types of radiosondes had hygrometers that were responding to integrated water vapor column density. However, we found that the response of the A.I.R. Model 5A, in use at the South Pole since February 22, 1997 was indicating a wintertime PWV about a factor two times too low based on PWV and submillimeter opacity relationships established earlier (Chamberlin 2001).

In the present work, we show that submillimeter opacity has some correlation with $PWVsat$. This result is not too surprising since the wintertime PWV was typically about 90% of saturation. Fig. 1 shows the 225 τ correlated with PWV in Panel A, and with $PWVsat$ in Panel B. In the plots the lines through the scatter plots are linear regression fits and A is intercept, B is the slope, and R is the linear-correlation coefficient (Bevington 1969). A is the dry air-opacity. Significant contributions to dry air opacity are caused by collision induced multipole moments in non-water vapor gas species. Accurately modeling of dry air opacity is a topic of ongoing research (Pardo, Serabyn, & Cernicharo 2001).

The data in Fig. 1 were acquired in 1992 using a standard NRAO 225GHz heterodyne site testing radiometer (Liu 1987) and PWV data derived from routine radiosonde observations performed with an A.I.R. Model 4A radiosonde (Atmospheric Instrumentation Research 1991). This radiosonde used resistive hygrometers made by VIZ manufacturing (Potts & Savitz 1990). The data directly comparing τ and PWV is well correlated with $R = 0.76$. τ is also correlated with $PWVsat$ with $R = 0.68$. As noted, some correlation should not be surprising since near saturation conditions prevailed most of the year, see above and also Fig. 2. The data in Fig. 1 sample more than 400 different radiosonde observations made concurrently with about 1000 different opacity observations. If τ and PWV, (& τ and $PWVsat$) were actually completely uncorrelated, obtaining R as large as 0.68 or higher would be very unlikely.

Fig. 1 demonstrates several features which are typical of all of the comparisons we have made: (1) The A coefficient which is the dry air-opacity, is not sensitive to absolute PWV. That is, rescaling PWV does not change the zero intercept very much. Rescaling PWV would be the same thing as applying a correction factor to the radiosonde water vapor response. The insensitivity A to rescaling PWV implies that our determinations of the dry-air opacity are quantitatively reliable indications. The wintertime PWV is typically so low that submillimeter opacity is dominated by dry-air. Therefore at extremely dry sites like the South Pole, it is important to model dry air accurately. We note that observed values of A are about an order of magnitude greater than predicted in Grossman's AT Model (Chamberlin & Bally 1995;Grossman 1989). (2) In every case studied which spans nine years, and many different instrument types and radiometer frequencies, correlation of submillimeter opacity and radiosonde derived PWV is always significant with R being found to be 0.76 or greater. Also, in every case studied, correlation with $PWVsat$ was always inferior, as in Fig. 1. This result showed that radiosonde hygrometer derived PWV did reflect real changes in integrated water vapor column density better than a method of estimating PWV based only on using the atmospheric temperature profile.

In the absence of reliable PWV data it is evident $PWVsat$ provides a useful upper limit on integrated water vapor column density. Additionally, since the wintertime PWV is probably about 90% of saturation (Chamberlin 2001), $PWVsat$ provides an approximate indication of wintertime PWV. Radiosonde observations at the South Pole are available going back to 1961 so we can use that 40 year record to infer wintertime water vapor conditions, see Fig. 3. This record implies that the favorable submillimeter observing conditions directly measured at the South Pole since 1992 are no aberration, rather they are characteristic. This long record of excellent year-to-year conditions which is found at the South Pole is in contrast to what has been observed on mountain top, lower latitude sites which have shown very large inter-annual variability.

References

Atmospheric Instrumentation Research 1991, Operations Manual, System IS-4A1-MET, Version 2.03 Atmospheric Instrumentation Research, Inc., Boulder, CO

Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences New York: McGraw-Hill

Chamberlin, R. A. 2001, JGR-Atmospheres, 106 (D17), 20101–20113

Chamberlin, R. A., Lane, A. P., & Stark, A. A. 1997, ApJ, 476, 428–433

Chamberlin, R.A. & Bally, J. 1995, International J. of Infrared and Millimeter Waves, 16(5), 907–920

Chamberlin, R.A. & Bally, J. 1994, Applied Optics, 33(6), 1095–1099

Dragovan, M., Stark, A. A., Pernic, R., & Pomerantz, M. A. 1990, Applied Optics, 29(4), 463–466

Grossman, E. 1989, AT Program Ver. 1.5 Air Head Software, 2069 Bluff St., Boulder, CO 80302

Kraus, J. D. 1986, Radio Astronomy 2nd edn. Powell, OH: Cygnus-Quasar Pages 3–32

Lane, A. P. 1998 Submillimeter Transmission at South Pole In: Novak, G., & Landsberg, R. H. (eds), Astrophysics from Antarctica ASP Conf. Ser. 141

Lay, O. P. & Halverson, N. W. 2000, ApJ, 543, 787

Liebe H. J. 1985, Radio Science, 20 (5), 1069–1089

Liu, Zhong-Yi 1987 225GHz Atmospheric Receiver - User's Manual Electronics Division Internal Report 271 National Radio Astronomy Observatory, Charlottesville, VA

O'Kelly, M. J., Peterson, J. B., Radford S. J. E., Schartman E., Chamberlin R. A., Ade P. A. R. 2001, in preparation

Pardo, J. R., Serabyn, E., & Cernicharo, J. 2001, IEEE Trans. on Ant. & Prop., in press

Potts, L. & Savitz, L. 1990, Humidity Sensor Equations Tech. Pub. No. 80415(C) VIZ Manufacturing Co., Philadelphia, PA

Radford, S. J. E., Schartman, E., & Peterson, J. B. 2001, in preparation

Smythe, W. D. & Jackson, B. V 1977, Applied Optics, 16(8), 2041–2042

Stark, A. A., Bally, J., Balm, S., Bania, T. M., Bolatto, A. D., Chamberlin, R. A., Engargiola, G., Huang, M., Ingalls, J. G., Jacobs, K., Jackson, J. M., Kooi, J. W., , Lane, A. P., Lo, K.Y., Marks, R. D., Martin, C. L., Mumma, D., Ojha, R., Schieder, R., Staguhn, J., Stutzki, J., Walker, C. K., Wilson, R. W., Wright, G. A., Zhang, X., Zimmermann, P., & Zimmermann, R. 2001, PASP, 113, 567–585

Zammit, C.C. & Ade, P.A.R. 1981, Nature, 293, 550

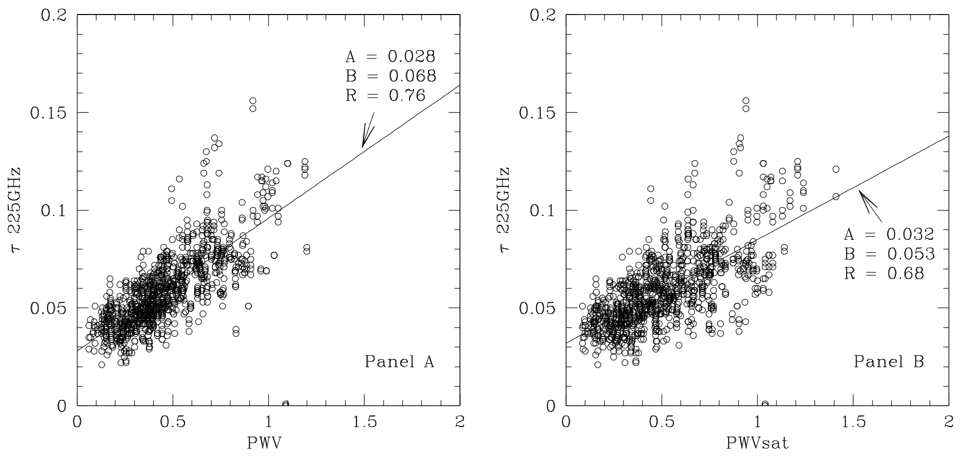

Figure 1. Panel A is τ 225 GHz opacity versus PWV from radiosonde. Panel B is τ 225 GHz opacity versus $PWVsat$ from radiosonde. The straight line is from linear regression fits to the data. A is the zero PWV intercept, or "dry-air opacity"; B is the slope; R is the linear-correlation coefficient. In this case, and in every case studied, submillimeter opacity has a significant correlation to radiosonde derived PWV and the correlation is always better than when PWV is estimated based on temperature versus elevation profiles (eg. $PWVsat$). This type of data indicates that standard radiosonde types used at the South Pole are sensitive to tropospheric integrated water vapor column density despite the fact that they are operating in very low temperatures regimes, typically below -40°C. The PWV data in this plot was derived from the A.I.R. Model 4A radiosonde. Elsewhere (Chamberlin 2001) it is shown that the magnitude of tropospheric PWV derived from the A.I.R. Model 4A agreed well with PWV derived from NOAA radiosondes flying a frost point hygrometer. Panel A in this figure is reproduced from data first presented in Chamberlin & Bally (1995). Panel B has not been previously published.

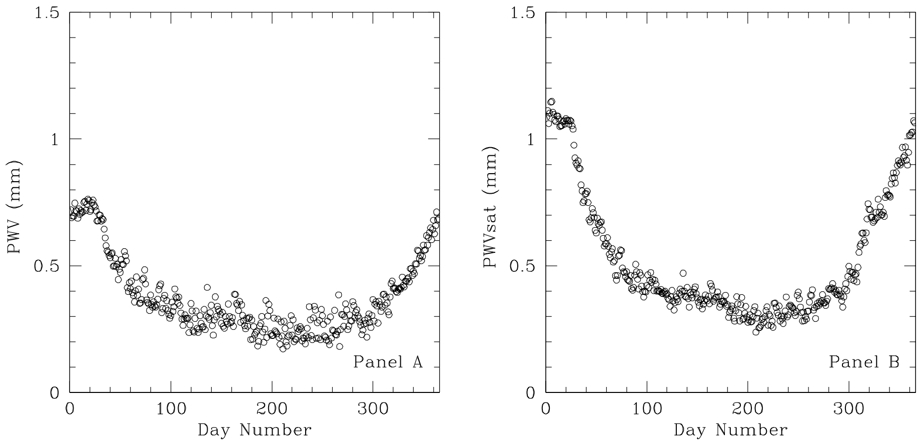

Figure 2. Panel A is the average daily PWV from all accepted radiosonde ascents for all years from 1961 to 1999. Panel B is the average daily $PWVsat$ from 1961 to 1999. As can be seen, the lowest water vapor period is from about Day 100 to Day 300. In this figure Day 1.0 starts at 00 UT on Jan 1. An overlay of the two plots shows that PWV is near to saturation from about Day 30 to Day 310. In Panel A, no attempt has been to adjust the calibration of radiosonde data from the A.I.R. Model 5A, and PWV data prior 1991 is not well sampled in some years due to many periods of unreported humidity data. In contrast $PWVsat$ which relies on only the temperature versus altitude profile, is well sampled for most years. Comparison of A.I.R. Model 4A derived PWV data to $PWVsat$ shows that from Day 100 to Day 300 the troposphere was typically about 90% of saturation. The A.I.R. Model 4A was used for routine daily observations for six years, from 1991 through 1996. This figure is reproduced from Chamberlin (2001).

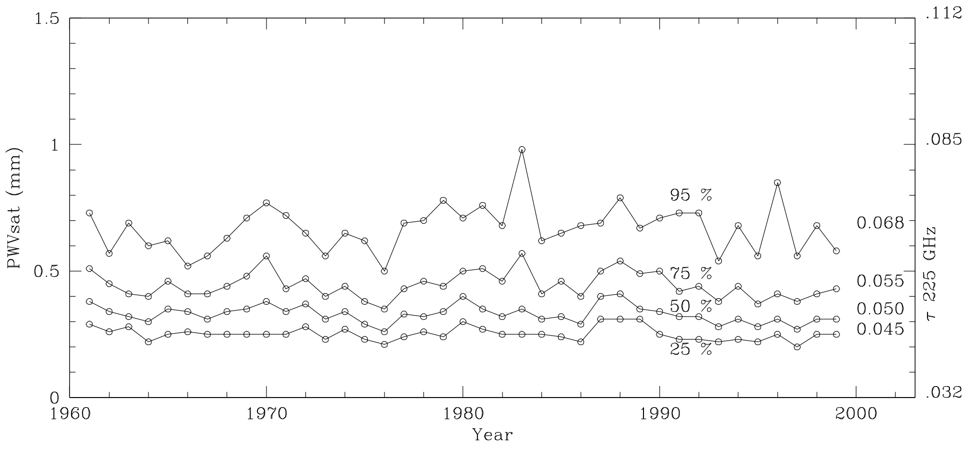

Figure 3. Average wintertime $PWVsat$ cumulative distribution versus year. In wintertime, typically $PWVsat$ is less than 0.25 mm 25% of the time; less than 0.33 mm 50% of the time; less than 0.44 mm 75% of the time; and, less than 0.67mm 95 % of the time. Here "winter" is defined as the lowest water vapor period which is from Day 100 to Day 300. On the right hand side of the plot, the $PWVsat$ values are expressed in terms of equivalent 225 GHz opacity using the quantitative relationship established in Fig. 1, Panel B. The 225GHz zenith opacity is less than 0.045 nepers/airmass 25% of the time; less than .050 nepers/airmass 50 % of the time; etc. In this context, the neper unit is used to describe power extinction. For example, the power transmitted through the atmosphere from a celestial source is $Power_{transmitted} = Power_{incident} * \exp(-\tau * Airmass)$. The argument of the exponent, $\tau * Airmass$, is in nepers (Kraus 1986; Zammit & Ade 1981) and $Airmass \approx 1/\cos(ZA)$ where ZA is zenith angle of the celestial source with respect to the observer on the earth's surface. τ is the zenith opacity. $PWVsat$ data in this figure is from Chamberlin (2001).