Bull. Astr. Soc. India (2004) **32**, 99–111

Measurements of 220 GHz atmospheric transparency at IAO, Hanle, during 2000–2003

P.G. Ananthasubramanian[1], Satoshi Yamamoto[2], T.P. Prabhu[3] and Dorje Angchuk[4]

[1]*Astrophysics group, Cavendish lab., University of Cambridge, Cambridge CB3 0HE, UK & Raman Research Institute, Bangalore 560080, India*
[2]*Dept. of Physics, University of Tokyo, Tokyo-113, Japan*
[3]*Indian Institute of Astrophysics, Koramangala, Bangalore 560034, India*
[4]*Indian Astronomical Observatory, Indian Institute of Astrophysics, Skara, Leh 194101, (J & K), India*

Received 5 May 2004; accepted 18 May 2004

Abstract. A 220 GHz tipping radiometer was installed at the Indian Astronimcal Observatory (IAO), Hanle (Latitude 32°46′46″ N; Longitude 78°57′51″ E; Altitude 4500 m, above msl) towards the end of December 1999. The system is in continuous operation since early October 2000. A sky scan, *i.e.,* a forward and a reverse scan is taken once every 10 minutes and these data are averaged to fit for zenith opacity. We present in this report detailed results of zenith opacity measurements for a continuous 3-year period. The system was up and running to make these measurements for nearly 90% of the time during this period. In particular, we cover the opacity trends in three consecutive 6-month periods of 'winter' months (October to March, 2000–01, 2001–02 & 2002–03) and three 6-month periods of 'summer' months (April to September, 2001, 2002 & 2003). The fractional time for opacities less than 0.06 in the three winter periods mentioned are above 30% and the corresponding fractional time for opacities less than 0.1 are above 70%. The opacities show seasonal variations as normally expected and in general one month in summer (July or August) peaks in opacity values. Diurnal variations are not easily noticeable. These results indicate that Hanle is a very promising site for sub-mm and infrared astronomy during most of the year excluding the months of July–August.

Keywords : astronomical site characterisation, atmospheric water vapour, sub-mm astronomy

1. Introduction

There are several emission lines of astrophysical interest at sub-mm wavelengths (346 GHz (CO $J = 3$–2), 460 GHz (CO J=4–3), 492 GHz (C I), 660 GHz (^{13}CO J=6–5), 692 GHz (CO J=6–5), 806 GHz (CO J=7–6) and 880 GHz (^{13}CO J=8–7)) that lie in between strong absorption bands due to atmospheric water vapour. While it is very difficult to observe these from sea level, they become available easily from high-altitude, cold and dry sites.

A first feel for the suitability of a site can be obtained from surface weather parameters such as temperature and relative humidity, and derived parameter of partial pressure of water vapour at the surface. These parameters can be measured continuously using automated weather stations. Radiosonde techniques provide similar information on all the upper strata of atmosphere and hence the profile of atmospheric water vapour as a function of altitude above the site. However, such observations cannot be undertaken continuously. Once a site appears prospective, it is important to monitor the quality of atmospheric transmission in the windows of interest before a large investment is made for a major facility. Since sub-mm instrumentation is very expensive and requires considerable logistic support, it has been a general practice to monitor the atmospheric transmission at lower frequencies such as 183, 220 or 225 GHz in the mm-wave region. The transparencies in the higher frequency windows can be scaled using suitable models of earth's atmosphere. These measurements can also be scaled with somewhat lower accuracy to estimate absorption in the infrared region. The technique is discussed further by Radford (2002), Radford & Chamberlin (2000), Matsushita *et al.* (1999), Hirota *et al.* (1998), Matsuo. Sakamoto & Matsushita (1998), Chamberlin, Lane & Stark (1997), Holdaway *et al.* (1996), Sekimoto *et al.* (1996).

The most prospective cold desert sites in the world suitable for sub-mm and infrared astronomy are in the Atacama desert of Andes mountains in northern Chile, Changthang Ladakh in India and adjoining Changthang Tibet in China. The development of Indian Astronomical Observatory (IAO) at Hanle (Latitude 32°46′46″ N; Longitude 78°57′51″ E; Altitude 4500 m, above msl), by the Indian Institute of Astrophysics (IIA), Bangalore, amidst a vast cold desert landscape, where the ambient temperatures go down to $-25°$ C during winter nights, opens up possibilities for setting up large observing facilities in the sub-mm and shorter wavelength bands as well as in the infrared, in the northern hemisphere. Hence, the University of Tokyo, Raman Research Institute and IIA, decided to operate a 220 GHz radiometer continuously at the site initially for a 2-year period. The period was extended further since the instrument continued to work well without much manual intervention. The first results of the 220 GHz opacity measurements at IAO are already presented by Ananthasubramanian, Yamamoto & Prabhu (2002, hereinafter Paper 1). In this paper, we present results based on continuous measurements over a 3-year period.

2. The System

Detailed description of the system, measurement method and data reduction procedure can be found in Paper 1. We list here a few of the system parameters in Table 1 for completeness.

Table 1. List of a few system parameters

Beam size on sky	$\sim 1^\circ$
Angular samples on sky	every 0.72°
Total angular sky covered in a scan	$\sim 90^\circ$
System temperature	$\sim 13,000$ K
Predetection half power bandwidth	500 MHz
Integration time per point on sky	90 ms
System sensitivity	~ 2 K rms
Fit errors on opacity	$\sim \pm 0.01$, under clear sky conditions.
Total time taken for a sky scan	~ 50 s

3. Results

Our data set consists of 220 GHz opacities (τ) derived every ten minutes of the day and the night for a continuous three-year period since October 2000. The instrument has functioned consistently and continuously over the whole period under discussion. The system has not been in operation for relatively short periods of time of about 10% in total, due to a failure of the control and data acquisition PC power supply, and due to occasional power outages. The fractional negative opacity values rejected in the computation of quartiles are less than 1.0%. As in Paper 1 where results of the first year measurements were presented, high values of opacity have not been rejected. High values of opacity may have large errors but the number of points above 1.0 are not large. These high values indicate that possibly the sky was not so uniformly clear over the 1 degree strip in the quadrant being scanned.

The monthly quartiles of the 220 GHz opacity values for the three years of continuous operation of the radiometer are shown in Fig. 1. The year is reckoned from October to September since the continuous operation of the instrument began in October 2000. For completeness, the quartiles for about the six-month period between December 1999 and May 2000 are also plotted. The instrument developed problems in May 2000 which could be set right only towards the beginning of October 2000.

It may be noted that the opacity values generally reach a minimum during the coldest

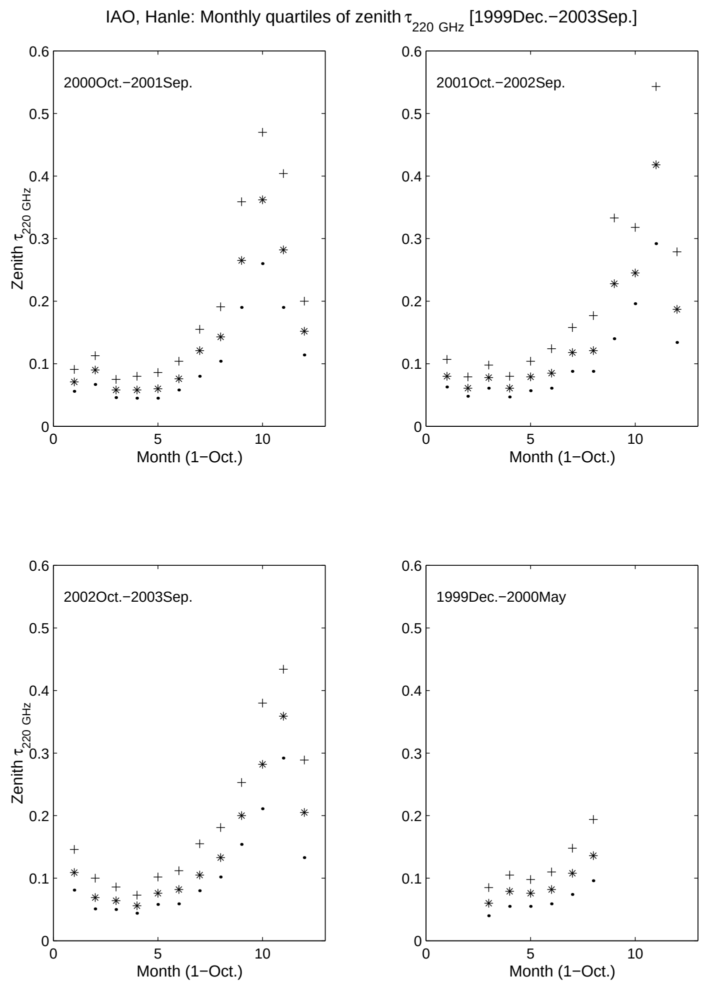

Figure 1. A plot of the monthly opacity quartiles for continuous 36 months shown for each "opacity year". For completeness, the quartiles for the 6 months from late December 1999 to early May 2000 are also shown. Symbols – ".": 25%, "*": 50%, "+": 75%.

month of January and a maximum during the warmest (July) or wettest (August) month. The median values are seen to be below 0.1 for the period October – March, and above 0.3 only for the July-August months.

The frequency distributions of opacities are shown in Fig. 2 for each of the three years. Distributions for the six colder months (October – March) are plotted separately. We refer to these as winter months and the period between April – September as summer months as if there are only two seasons in a year. The peaks of the frequency distributions

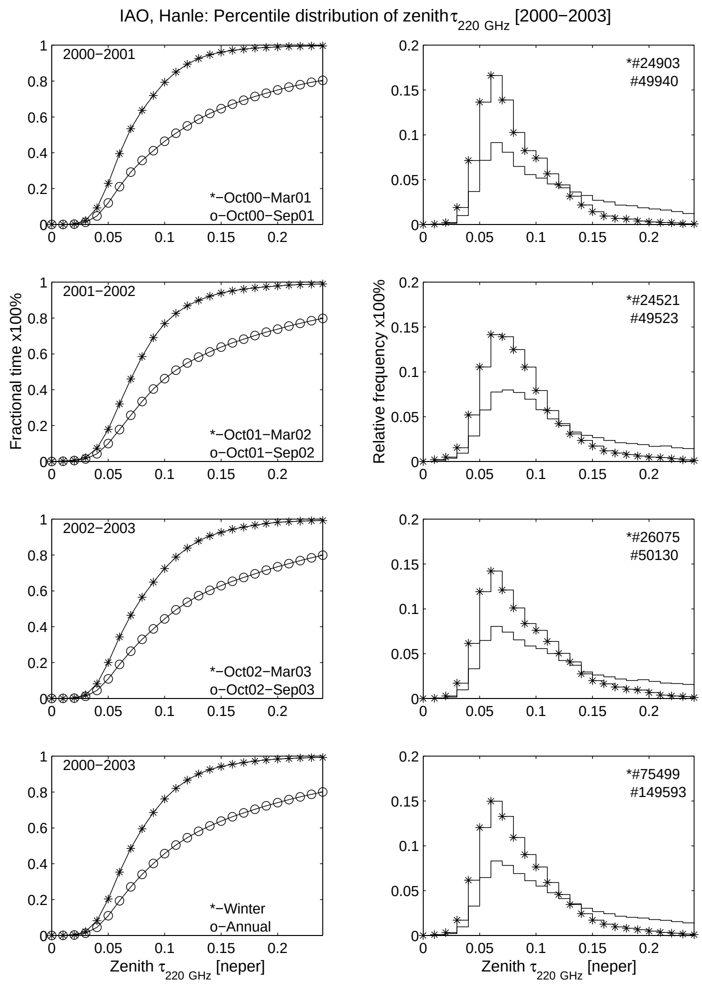

Figure 2. Cumulative distribution of 220 GHz opacities at Hanle (left) for the three years 2000 – 2003. The distribution for six colder months is shown by the symbol "*" and the annual distribution with open circles. The frequency distributions are plotted on the right. Data with "*" represent the winter season, whereas data without "*" represent the annual ones. The number of total sky samples used to generate these plots are also marked.

are around $\tau = 0.06$ to 0.07 for all the three full years and also for the winter months. The 75% quartile is at or below 0.1 for the winter months for all the three years. The median opacities for all the years (summer + winter) are around 0.10.

The diurnal variations of opacities are shown in Fig. 3 for each of the full year, as well as for the summer and winter halves of the year. The diurnal variation is seen to

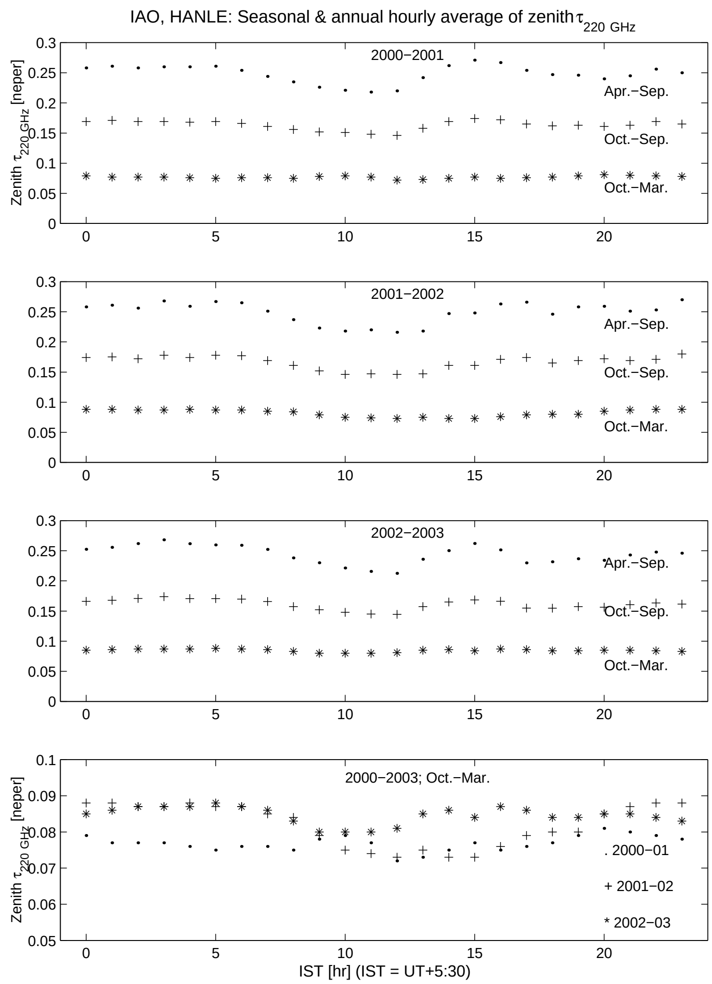

Figure 3. Diurnal variation of the opacities averaged hourly for the winter, summer months; the annual average is also shown for each year. In the lowermost panel only the three winter trends are shown with an expanded y-scale to bring out the small variations clearly. Local mean solar rime is IST-0:13.

be very low, with a small improvement in transparency early in the morning and again around noon.

A better estimate of diurnal variation can be obtained by comparing the median opacities of 12 day-light hours and 12 dark-night hours (Fig. 4). The day and night opacities are not significantly different and the diurnal variation is small.

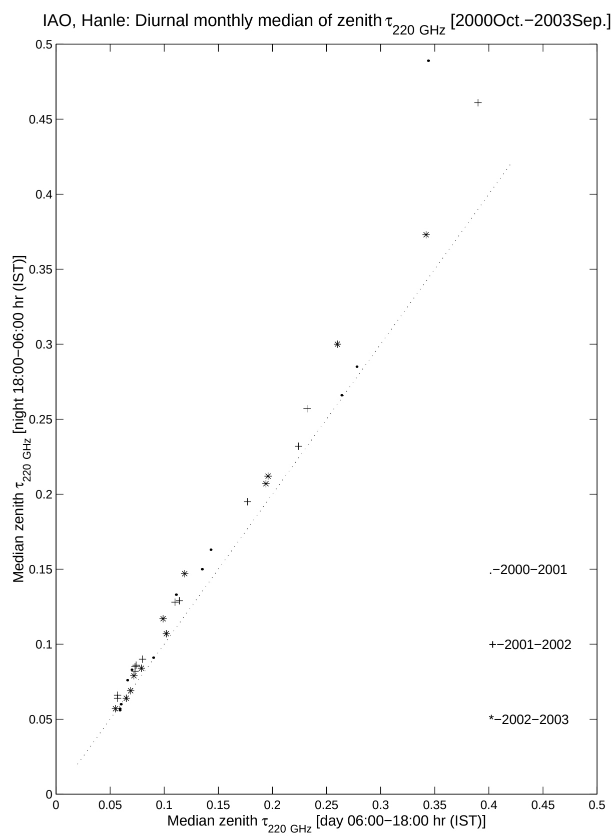

Figure 4. The median diurnal opacity plots. The night monthly median values plotted against the day median values; the dotted line represents the locus of points when these two values are equal. IST=UT+5:30 and local mean solar time is IST-0:13.

The lack of significant diurnal variation in opacity suggests that the atmosphere is stable and behaves almost like a closed box, the relative humidity varying as the temperature changes to keep the total water vapour constant. The small reduction in the opacity in daytime noticeable in Figs. 3 and 4 may be due to the reduction of absorption coefficient of water vapour with temperature (Pardo, Cernicharo & Serabyn 2002).

The runs of opacities for the best month (November, December or January) and the worst month (July or August) are shown for each year in Fig. 5. The best months are reasonably stable giving continuous good stretches with less than 20% variation. This trend holds good for all the six winter months. There is considerable fluctuation in the opacities during the worst months with short good stretches interspersed. Such high fluctuations occur only during the worst month of the year.

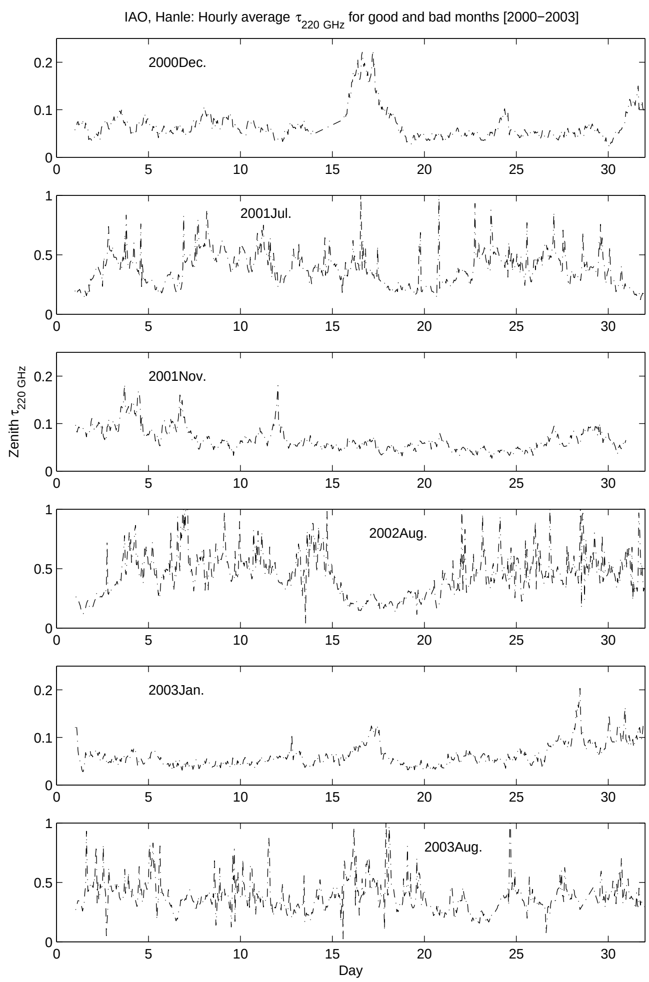

Figure 5. A plot of running hourly averaged opacity for six months in three years. Trends during both the best and the worst month in each of the three years are shown for comparison. Note that the ordinate scales are not the same for the best and the worst months.

Finally, the observed opacities do not show any trend with respect to the reference load temperature (Fig. 6) indicating that the system was stable and the diurnal as well as seasonal trends seen are not instrumental in origin.

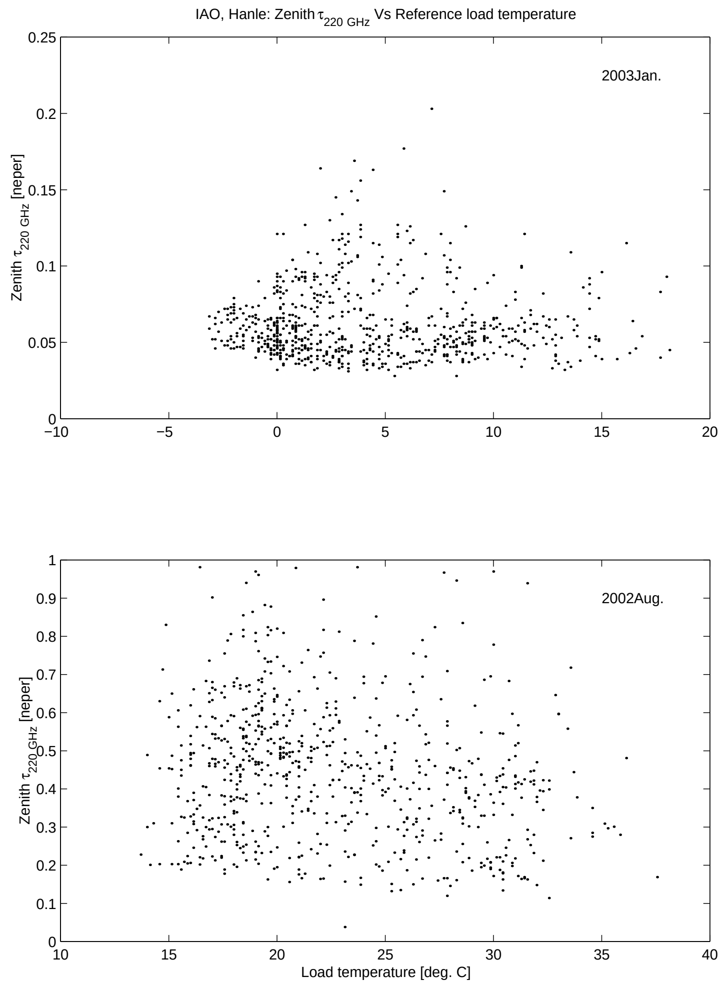

Figure 6. A plot of zenith optical depth as a function of the temperature of the reference load. Averages of 7 data points are used to obtain hourly values of both opacity and temperature.

4. Discussion

This longer term study reinforces the earlier conclusion based on data for one year: that Hanle is one of the good sites for sub-mm astronomy. The statistics for the three-year period listed in Table 2 may be compared with the 225 GHz opacities at Mauna Kea, a site at similar altitude, but closer to the equator and surrounded by ocean. Radford & Chamberlin (2000) provide the quartiles of 225 GHz opacities at Mauna Kea for the period of 1997 January to 2000 October as 0.058, 0.091, 0.153. The 220 GHz opacities are expected to be 19% lower in the range of opacities 0.06 - 0.12 (see paper 1). Thus the annual median at Hanle is about 40% higher than at Mauna Kea. On the other hand, the opacities at Hanle for the colder 6 months (October – March) are very similar to the opacities at Mauna Kea during its best 6 months (January – June quartiles of 0.052, 0.076, 0.136: Lane 1998). In fact, the third quartile at Hanle is better by about 10%.

Table 2 also lists the fractional time over which the opacities are below 0.06 or 0.10. $\tau_{220} = 0.06$ sets the upper limit for observations in the 492 GHz and 675 GHz bands. The conditions are good for observing in these bands for a third of the colder six months. Annually, about a quarter of the time is useful if one excludes the wettest months of July and August.

Table 2. Quartiles of 220 GHz opacities and the fraction of time below the given opacity value.

Year Oct-Sep	Quartiles winter Oct-Mar			Annual Oct-Sep			10 months Sep-Jun		
	25%	50%	75%	25%	50%	75%	25%	50%	75%
2000-01	0.051	0.068	0.094	0.065	0.108	0.200	0.060	0.090	0.145
2001-02	0.055	0.073	0.098	0.069	0.108	0.207	0.064	0.091	0.144
2002-03	0.054	0.074	0.104	0.068	0.111	0.209	0.063	0.095	0.150
2000-03	0.053	0.071	0.098	0.067	0.109	0.205	0.062	0.092	0.146
	$\tau < 0.06$ %	$\tau < 0.10$ %		$\tau < 0.06$ %	$\tau < 0.10$ %		$\tau < 0.06$ %	$\tau < 0.10$ %	
2000-01	39.5	79.3		21.1	46.4		25.6	55.9	
2001-02	32.1	76.9		17.8	46.2		21.6	56.2	
2002-03	34.3	72.5		19.0	44.4		22.8	53.3	
2000-03	35.3	76.2		19.3	45.6		23.3	55.1	

We mentioned in the beginning that the surface weather parameters provide a first estimate for the water vapour column at the site. We had derived in Paper 1, zenith precipitable water vapour (*pwv*) using the water vapour partial pressure at the surface and an assumed scale-height of 1.5 km for the water vapour column. The partial pressure of water vapour at the surface was derived using the relative humidity and temperature recorded by an automated weather station, and empirical relations for saturation water vapour pressure as a function of temperature. A comparison of opacities with the *pwv* derived from the weather station data during the 1-year period resulted in a correlation

$$\tau_{220} = 0.0281 + 0.0462pwv$$

This implies that the opacities of about 0.03 in the absence of any contribution due to water vapour above the site. This offset is in excess of opacity due to oxygen (~ 0.01).

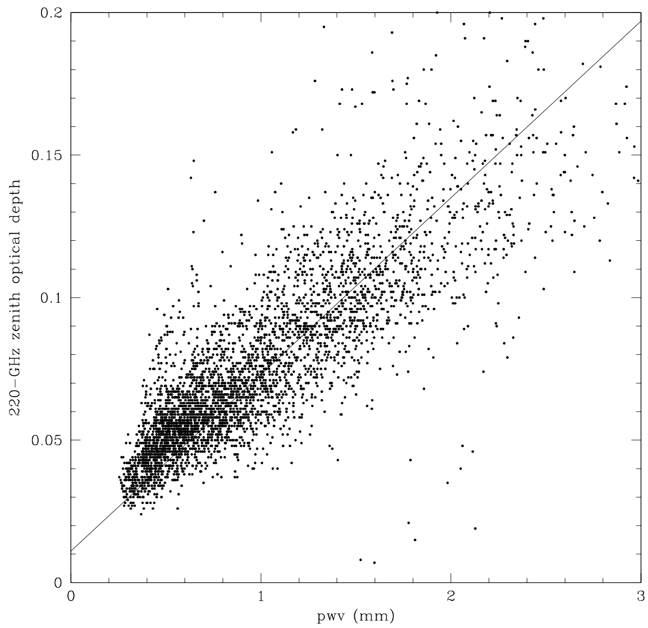

Figure 7. A plot of zenith optical depth against *pwv*; the linear fit shown is obtained by assuming errors in both opacity and *pwv*.

We had earlier derived the regression based on medians of *pwv* and medians of opacities assuming that all the errors are in the opacities. Since there can be significant errors in the derived *pwv* due to departures from the assumption of a constant scale height, we have now reanalysed the raw data assuming errors in both the variables. We used the SIXLIN program of Isobe *et al.* (1990) and used the OLS bisector following their advice. This yields,

$$\tau_{220} = (0.000 \pm 0.001) + (0.062 \pm 001) pwv$$

with an rms scatter of 0.072. There is some non-linearity at high values of *pwv* leading to an underestimate of the intercept. If we restrict to pwv < 3.0 mm, we obtain,

$$\tau_{220} = (0.011 \pm 0.002) + (0.062 \pm 002) pwv$$

with an rms scatter of 0.032, (Fig. 7). This intercept agrees with the opacity due to oxygen.

The sharp rise in the opacities for one month in a year is due to the summer rains during this period. Several days with low opacity are seen during these months also (e.g. 16-20 August 2002) since the relative humidity drops sharply whenever there is no precipitation. On the other hand, a lack of significant diurnal trend in the opacities and long stretches of stable opacities over the colder months have specific advantages for continuous observations at sub-mm frequencies.

Hanle, being an inland site, has larger annual variations in ambient temperature compared to Mauna Kea. While higher opacities in the summer months can be understood from this, one expects lower opacities at Hanle during the winter months. The monthly quartiles presented by Masson (1992) shows that the best months at Mauna Kea are January – May, worst months are October-November and the remaining months have intermediate opacities. At Hanle, the best months are October – March, the worst June – August and the remaining 3 months have intermediate opacities. The higher opacities during the month of August are primarily due to the southwest monsoon winds which bring in moisture from the Indian Ocean and the Arabian Sea. The ambient temperatures reach their highest value at the end of July which helps in retaining the moisture in the atmosphere. Additional sources of water vapour during the summer months could be due to melting of snow in high peaks and evaporation of water from the glacial streams. The best months appear to be similar to Mauna Kea, though we expect lower opacities due to much lower temperatures and low relative humidity. More sensitive instruments may be used in future to check if this is due to poorer sensitivity of the present instrument at lower opacities.

It will be useful to check if better sites exist at slightly higher elevations, away from major sources of liquid water such as the Hanle stream. It would be possible to compare the qualities of such sites with Chajnantor in Atacama desert of Chile.

It is found from site characterisation studies at other high-altitude sites that there is no strong correlation between low opacity and phase stability. For setting up any large sub-mm observational facility, it will be worthwhile characterizing the site for its phase stability.

Acknowledgements

We appreciate the efforts of Tashi Thsering and Phunchok Dorje for continued upkeep of the radiometer, its uninterrupted power supply and data gathering during this period.

References

Ananthasubramanian P.G., Yamamoto S., Prabhu T.P., 2002, *Intl. J. IR & MM Waves*, **23**, 227 (Paper 1).

Chamberlin R. A., Lane P. A., Stark A. A., 1997, *ApJ*, **476**, 428.

Hirota T., Yamamoto S., Sekimoto Y. Kohno K., Nakai N., Kawabe R., 1998, *PASJ*, **50**, 155.

Holdaway M. A., Ishiguro M., Foster S. M., Kawabe R., Kohno K., Owen F.N., Radford S. J. E., Saito M., 1996, *MMA Memo No.* 152.

Isobe T., Feigelson E.D., Akritas M.G., Babu G.J., 1990, *ApJ*, **364**, 104.

Lane A.P., 1998, in Astrophysics from Antarctica, ASP Conf. Ser., **141**, 289.

Masson C., 1992, Submillimeter Array Technical Information No. 60.

Matsuo H., Sakamoto A., and Matsushita S., 1998, *PASJ*, **50**, 359.

Matsushita S., Matsuo H., Pardo J. R., Radford S. J. E., 1999, *PASJ*, **51**, 603.

Pardo J., Cernicharo J., Serabyn E., 2002, in proc. IAU Technical Workshop Astronomical Site Evaluation in the Visible and Radio Range, Eds, J. Vernin, Z. Benkhaldoun, C. Muñoz-Tuñón, ASP Conf. Ser., **266**, 188.

Radford S. J. E., and Chamberlin R. A, 2000, *ALMA Memo No. 334*, 1.

Radford S., 2002, in proc. IAU Technical Workshop Astronomical Site Evaluation in the Visible and Radio Range, Eds, J. Vernin, Z. Benkhaldoun, C.Muñoz-Tuñón, ASP Conf. Ser., **266**, 148.

Sekimoto Y., Yoshida H., Hirota T., Takano Y., Furuyama E., Yamamoto S., Saito S., Ozeki H., Inatani J., Ohishi M., Cardiasmenos A. G., Hensel S. L., 1996, *Intl. J. IR & MM Waves*, **17**, 1263.