Atmospheric Opacity at the VLA

VLA Test Memo 232

Bryan Butler
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Introduction

It is important to quantify the atmospheric opacity at the VLA in order to aid in interpretation of data taken at high frequencies. In addition, in the near future it is envisioned that dynamic scheduling will be used in order to select observing programs. Atmospheric opacity will be an important input parameter into dynamic scheduling. In the absence of a dedicated instrument to measure the atmospheric opacity (e.g., a tipping radiometer), the VLA itself can be used to measure this quantity, via the TIP procedure (Butler 1996). Given that time is relatively expensive on the VLA (and, again, given the lack of existence of a dedicated opacity measuring device), one would also like to know if there are other ways of predicting the atmospheric opacity, from independent information. I investigate in this memo the measurements of atmospheric opacity at the VLA from C- through Q-bands, and methods of predicting that opacity given seasonal and surface weather information. Note that I use opacity in this memo to mean zenith opacity, and the symbol τ always represents this quantity.

Data

I consider all TIP data taken at the VLA in the period 1995May03 through 2002Apr17. There is TIP data taken prior to this, but some information is missing from the archival copies of these data (notably the assumed values of T_{cal}), and hence their interpretation is questionable. I consider only those TIPs whose fits are reasonably good, where this is defined subjectively by me (formally, I use all TIPs whose chi square is < 0.5). Table 1 shows the summary of the data. I do not distinguish between frequencies in the higher bands, except I only use data in Q-band at frequencies < 45 GHz. At higher frequencies, the antennas do not behave so well, and the system assumed T_{cal}'s are not very accurate, making the TIP data reduction much more questionable. I also do not consider TIP data at L-band, because the signature of atmospheric opacity is overwhelmed by the signature from the spillover (see, e.g., Bagri 1993; Lilie 1994). The histograms of the data for each band are plotted in Figure 1, while the mean and standard deviation are shown in Table 1.

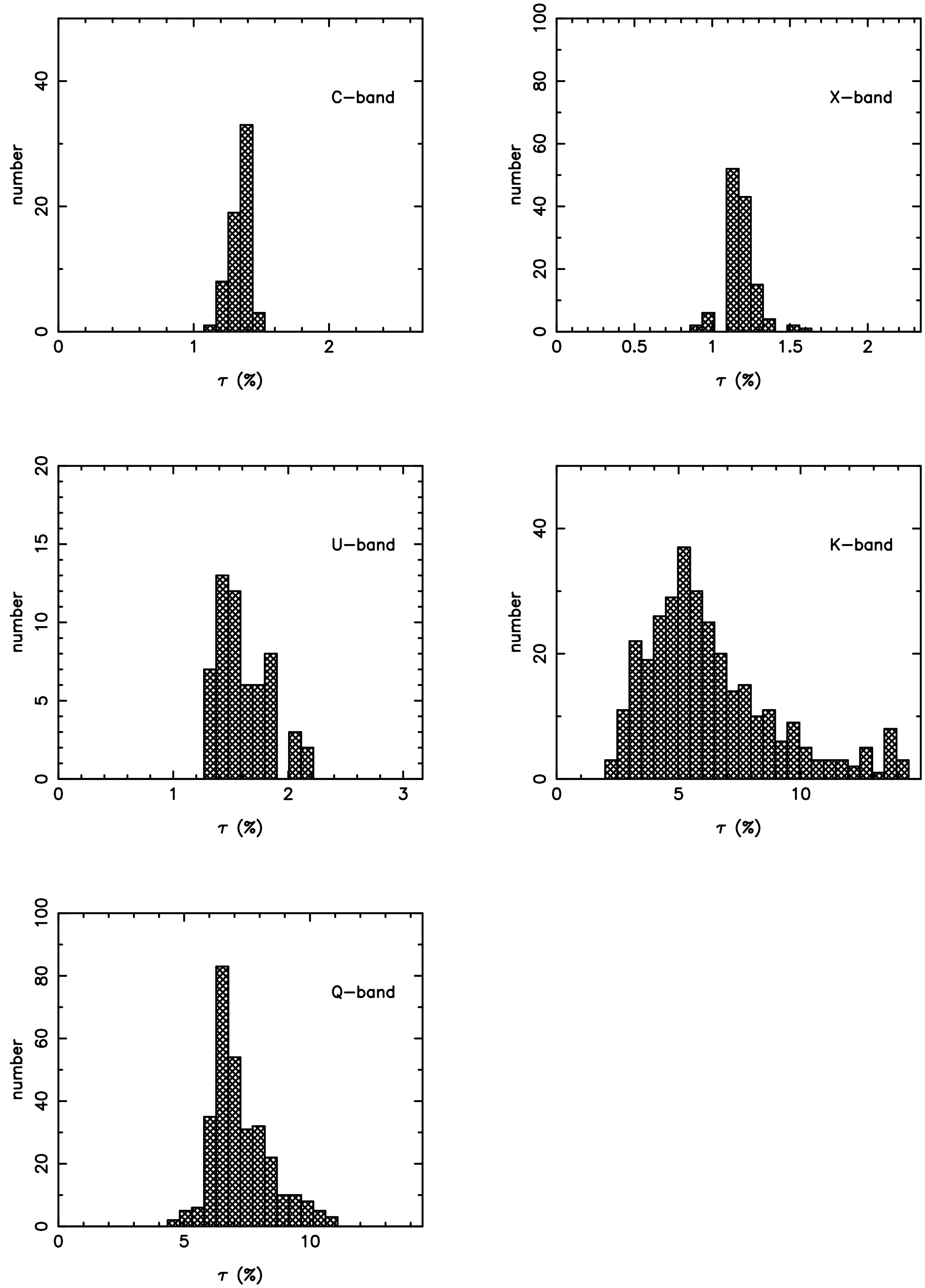

Figure 1: Histograms of calculated opacity at the VLA site from TIP data taken over the period 1995May03 through 2002Apr17.

Table 1: TIP data summary.

band	number	seasonal coverage	diurnal coverage	$\overline{\tau}$ (%)	σ_τ (%)	τ_{model} (%)
C	65	reasonable	poor	1.35	0.08	0.52
X	126	good	reasonable	1.17	0.11	0.59
U	58	reasonable	poor	1.58	0.24	0.88
K	355	good	good	7.46	4.45	5.68
Q	307	good	good	7.24	1.17	5.91

Atmospheric Modelling

How do the above mean opacities compare with those predicted from an atmospheric model for the VLA site? I use a model similar to the one described in Butler (1999), using the model of Liebe (1989). The only parameters necessary to construct the atmospheric model (and hence derive the predicted opacity as a function of band) are the surface ambient temperature, the atmospheric temperature lapse rate, the surface dewpoint, the scale height of water vapor in the lower troposphere, and the altitude of the site (a minor perturbation based on tropopause height is based on this). Table 1, in the last column, shows the predicted opacity based on the yearly median surface temperature (11.7 C) and dewpoint (-1.9 C) at the VLA over the period from 1990 to 1998 (Butler 1998). The estimated PWV from these surface temperatures is 6.1 mm (via the technique described in Butler 1998), and I use a water vapor scale height of 1.4 km and a temperature lapse rate of 6 K/km. The model predicts a lower opacity than what is actually measured. This might be attributed to one of several causes: 1) I don't have the right model atmosphere as input to the opacity model; 2) I don't have the right opacity model; or 3) there is a problem with the measurements. There is an immediate candidate for 3) - I have not considered spillover and the resultant increase in system temperature as a function of elevation when deriving the opacities from TIP data.

Spillover

As the VLA antennas go down in elevation, more and more ground emission is scattered into the feeds, increasing the system temperature. This is the well-known "spillover" effect. There is certainly some amount of spillover into the VLA antennas, but it has never been measured and quantified well. What is the effect of spillover on measurements of atmospheric opacity via TIP scans?

Consider two cases of spillover: 1) small effect, taken as equivalent to what is assumed for VLBA antennas at long wavelengths (C. Walker, personal communication); 2) large effect, taken as equivalent to what is assumed for VLBA antennas for 7mm (Lepännen 1993). Table 2 shows the additional system temperature for these two cases, at the elevations for the standard system TIP.

Now, can the discrepancy between the measured and modelled opacity be due entirely to

Table 2: Possible system temperature increase due to spillover.

Case	Elevation						
	23.6	25.9	28.8	32.5	37.4	44.2	55.1
1 (VLBA C-band)	2.3	1.4	0.35	0	0	0	0
2 (VLBA Q-band)	7.1	6.2	5.3	4.1	2.6	1.5	0.64

this additional system temperature from spillover? Take as the estimated system temperature:

$$T_{sys} = T_o + T_{atm}\left(1 - e^{\tau A}\right) + T_{spill}(A) \quad , \tag{1}$$

where T_o includes all contributions to system temperature which are not a function of elevation (mostly receiver temperature), T_{atm} is the effective atmospheric temperature, A is the airmass ($A \sim 1/\sin E$ for elevations that are not too low), and T_{spill} is the spillover contribution (taken from Table 2). If this equation for T_{sys} is used to create system temperatures for a simulated TIP, and those temperatures are fit in the same way as the normal TIP data, the results in Table 3 are obtained. I use model opacities as indicated in Table 3 (the same as the opacities derived from the atmospheric model), a value of $T_{atm} = 275$ K, and values of T_o as shown in Table 3. This shows that, indeed, the discrepancy between the atmospheric model and measured opacities could be due to spillover. It also shows that values of T_o estimated from TIP fits which ignore spillover are probably underestimates by a few K. Lastly, these results indicate that the VLBA high frequency spillover is not a good model for the VLA spillover — it yields fitted opacities which are much too high.

Table 3: Effect of ignoring spillover on fitted τ.

band	T_o (K)	spillover model	assumed τ	fitted T_o	fitted τ
C	44.3	1	0.52	41.7	1.15
C	44.3	2	0.52	38.1	3.22
X	30.8	1	0.59	28.2	1.22
X	30.8	2	0.59	24.5	3.29
U	114.0	1	0.88	111.4	1.51
U	114.0	2	0.88	107.7	3.61
K	40.0	1	5.68	37.1	6.43
K	40.0	2	5.68	32.6	9.00
Q	71.0	1	5.91	68.1	6.67
Q	71.0	2	5.91	63.5	9.26

How can I test this with the data currently in hand? If I take all of the TIP data considered above, and only use the data with $E > 30°$ (where spillover should really be minimal), what is the result? I expected to obtain results which were closer to what the model atmosphere predicted, or at least to obtain results which were lower than the fitted opacities which included the low elevation data. Surprisingly, this was not the case. I get

Table 4: TIP data summary, using only data at $E > 30°$.

band	$\overline{\tau}$ (%)	σ_τ (%)
C	1.35	0.16
X	1.28	0.11
U	1.67	0.29

mean fitted opacities for C-, X-, and U-bands shown in Table 4, which are nearly identical to those in Table 1. I do not claim to understand this, but it indicates that more investigation is needed into spillover effects on the VLA antennas.

Fits to Opacity Data

Ignoring the complication of spillover discussed above, is there some known quantity that allows us to predict the measured opacities? I argued in Butler (1998) that you could do this from measurements of the surface ambient and dew point temperatures. If the assumption that the atmosphere is well-behaved above the site is correct, then this is in fact a good way to get a prediction for opacity. However, often the atmosphere is certainly not strictly exponential in distribution of water vapor, or the scale height is different from assumed, and hence the derivation of predicted opacity from surface measurements often doesn't work (see historical references in Butler 1998 for a discussion of this). Frazer Owen suggested to me that it might be just as good to assume a simple model based on season (or, equivalently, day of year). Are predictions based on either of these premises good proxies for the measured opacities? Note that I only consider U-band and higher frequencies, since the measured opacities at C- and X-bands are nearly constant, and can be taken as such.

Fits Using Surface Weather Data

Here, I use a variant of the technique used in Butler (1998). I now use a more accurate expression for the vapor pressure of water given the surface measurements (from Buck 1981). Figure 2 shows scatter plots of the estimated PWV vs. the measured opacity, and polynomial fits to them, for all of the considered bands. The fit is given by:

$$\tau_{pred} = a_0 + a_1 P + a_2 P^2 \quad , \tag{2}$$

where P is the estimated precipitable water vapor in mm, and τ_{pred} is the predicted opacity, in %.

The fits are reasonably good, but there are clearly times when the difference is large. Table 5 shows the polynomial fit coefficients and the rms absolute difference (rms of $\tau_{pred} - \tau$, which I call $\sigma_{\Delta\tau}$), rms relative difference (rms of $|\tau_{pred} - \tau|/\tau$, which I call $\sigma_{\Delta\tau'}$), and maximum absolute deviation (maximum of $|\tau_{pred} - \tau|$, which I call d_τ) for the fits.

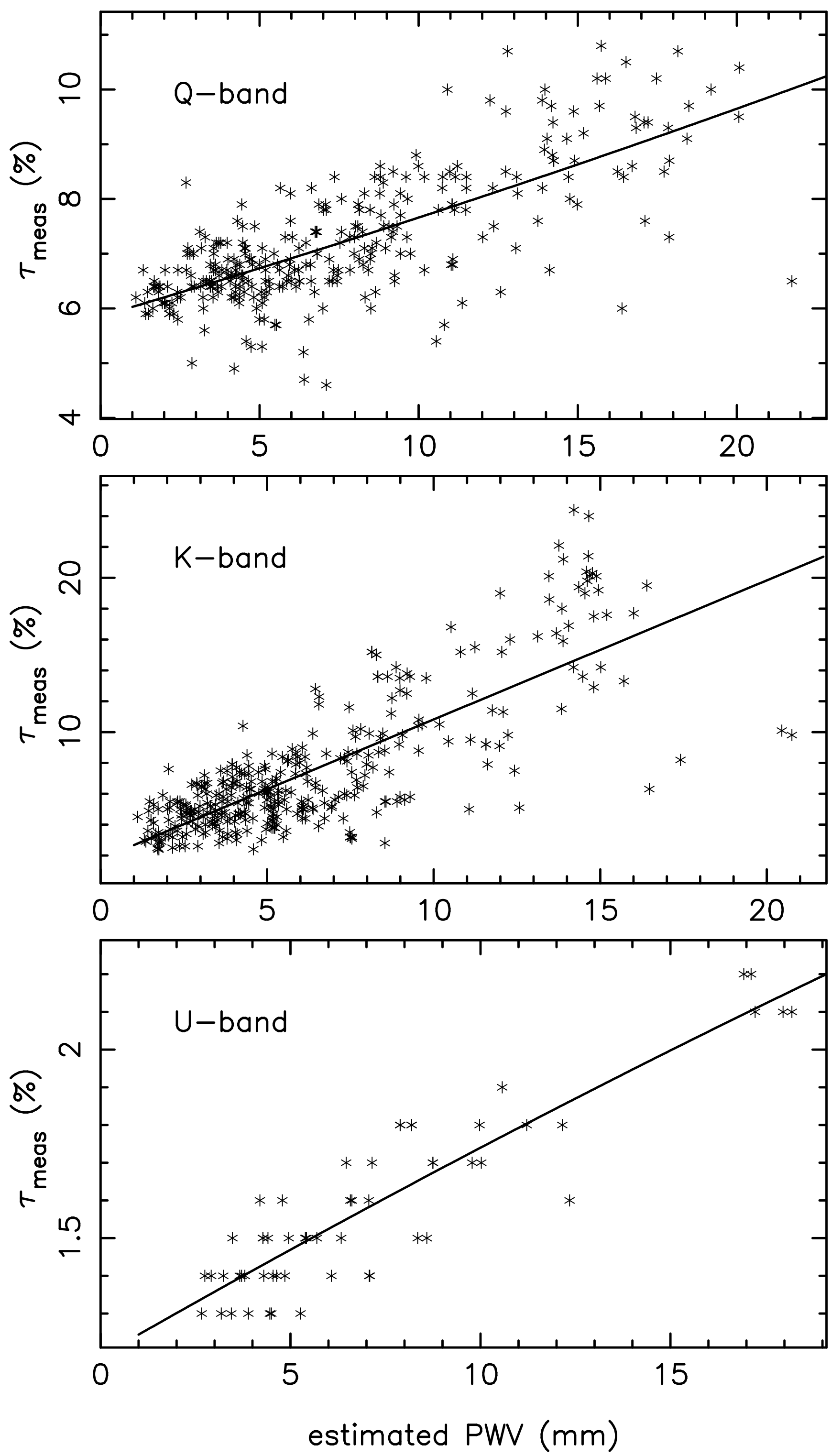

Figure 2: Plots of estimated PWV vs. measured opacity. Polynomial fits are shown as solid lines.

Table 5: Fits of measured opacity from estimated PWV.

band	a_0	a_1	a_2	$\sigma_{\Delta\tau}$ (%)	$\sigma_{\Delta\tau'}$ (%)	d_τ (%)
U	1.19	0.0578	-0.000249	0.10	4.2	0.3
K	1.77	0.906	-0.000138	2.79	32.8	10.7
Q	5.86	0.171	0.000920	0.79	8.5	3.5

Fits Using Season (Day of Year)

Here, I simply use the day of year as the 'observable' quantity. Since I want a function which can be represented by a simple polynomial, and I know that the opacity will reach its peak in the summer, I choose to use a 'modified day of year', equal to:

$$m = d + 165 \tag{3}$$

where d is the true day of year if it is < 200, and is the day of year minus 365 otherwise. This effectively gives a variable that starts at 0 on day of year 201 (July 19 or 20), and progresses through to 365. Figure 3 shows scatter plots of the modified day of year vs. the measured opacity, and polynomial fits to them, for all of the considered bands. The fit is given by:

$$\tau_{pred} = a_0 + a_1 m + a_2 m^2 \quad . \tag{4}$$

The fits are reasonably good, with differences between the fit/model and the measurements similar to the PWV case. Table 6 shows the polynomial fit coefficients and the differences. Similar to the PWV fit/model, there are times when the difference is large.

Table 6: Fits of measured opacity from modified day of year.

band	a_0	a_1	a_2	$\sigma_{\Delta\tau}$ (%)	$\sigma_{\Delta\tau'}$ (%)	d_τ (%)
U	2.19	-0.00851	0.0000201	0.12	4.9	0.3
K	1.77	-0.178	0.000440	2.62	26.3	9.8
Q	5.86	-0.0357	0.0000940	0.75	6.9	2.6

Diurnal Variation

One might expect that adding a diurnal variation term on top of the seasonal variation would actually improve the fits. In fact, this is not the case — the improvement is modest at best. Figure 4 shows a plot of all of the K-band measured opacities vs. time of day. There is no clear trend, which explains why adding that to the model does not improve the fits.

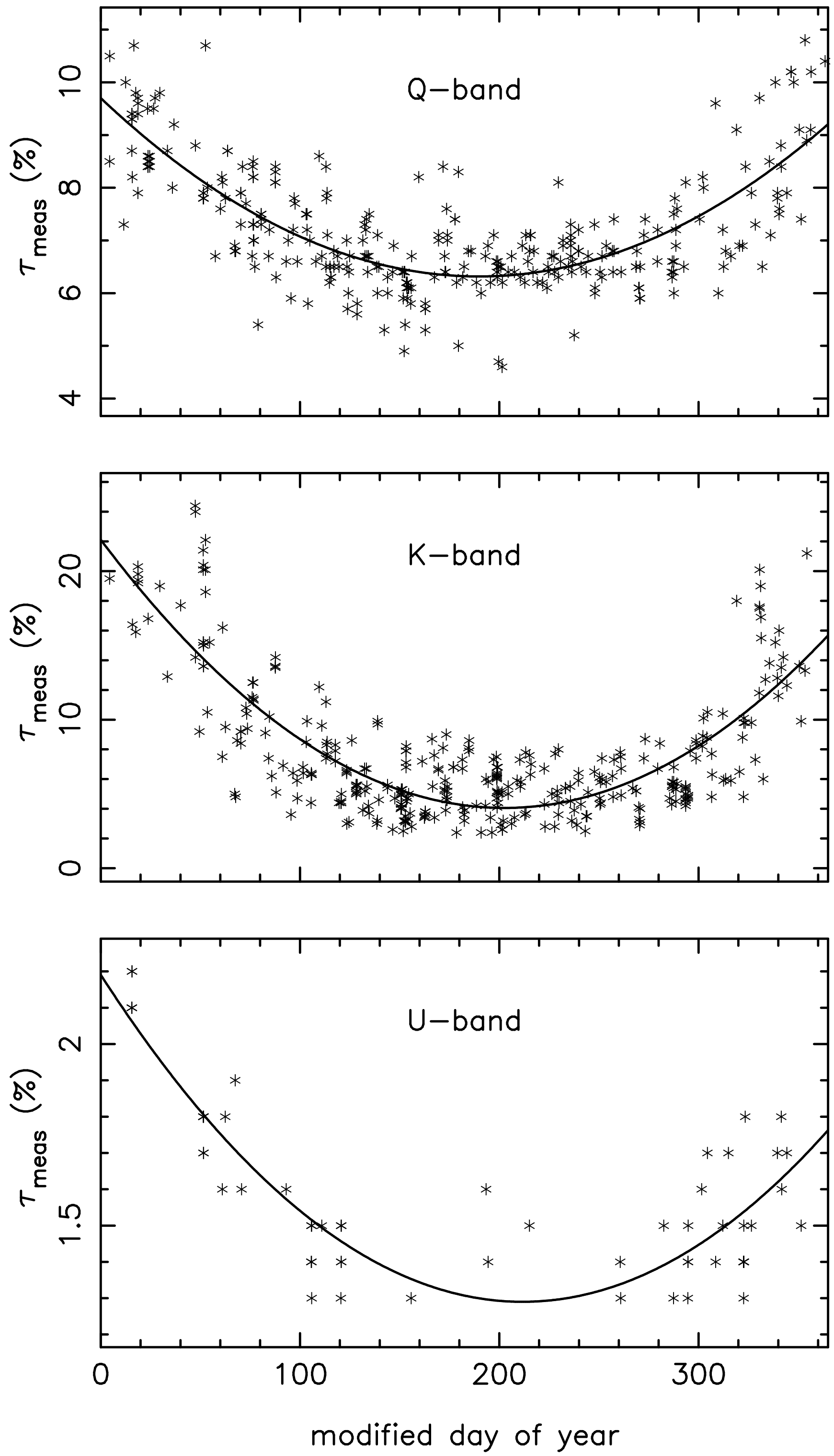

Figure 3: Plots of modified day of year vs. measured opacity. Polynomial fits are shown as solid lines.

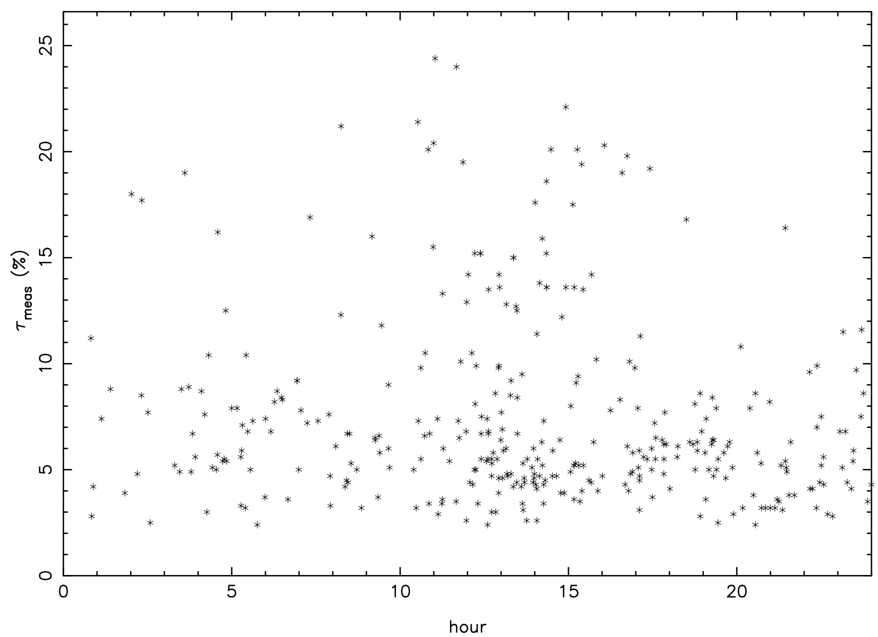

Figure 4: Plot of measured opacity vs. hour, for K-band TIPs on the VLA.

Weighted Combinations of the Two Fits

Is there some weighted combination of the two fits (PWV and seasonal) which gives better results than either one by itself? Figure 5 shows the relative rms difference error (scaled by the minimum value) for the three upper bands, using a straight linear weighting of the two models (the sum of the two weights equals 1.0). For all three of these bands, better fits are obtained if nearly equal weights are given to the two models.

Summary

Derived opacities at the VLA (from TIP data) for the period 1995May03 through 2002Apr17 are shown in Table 1. These measured opacities are probably slight overestimates of the true opacities, based on model atmospheric opacity arguments, and the fact that I ignore spillover when deriving opacity from TIP data. Spillover is currently poorly quantified for VLA antennas — this should be remedied by conducting tests designed to measure it. The opacity can be predicted nearly equally well (in a stastical sense) using either a model based on surface weather measurements or one based only on day of year. A weighted combination of the two (with weights near 0.5 for each) gives a better fit. However, the predictions are still sometimes seriously in error. Given that we probably don't want to be spending lots of time doing TIPs with the VLA antennas themselves to determine atmospheric opacity (a necessary input for dynamic scheduling), this argues for a stand-alone device to measure atmospheric opacity. A clone of the GBT 90 GHz tipping radiometer (see the description at: http://www.gb.nrao.edu/~jbraatz/Tipper/tipper.html) might do nicely in that respect.

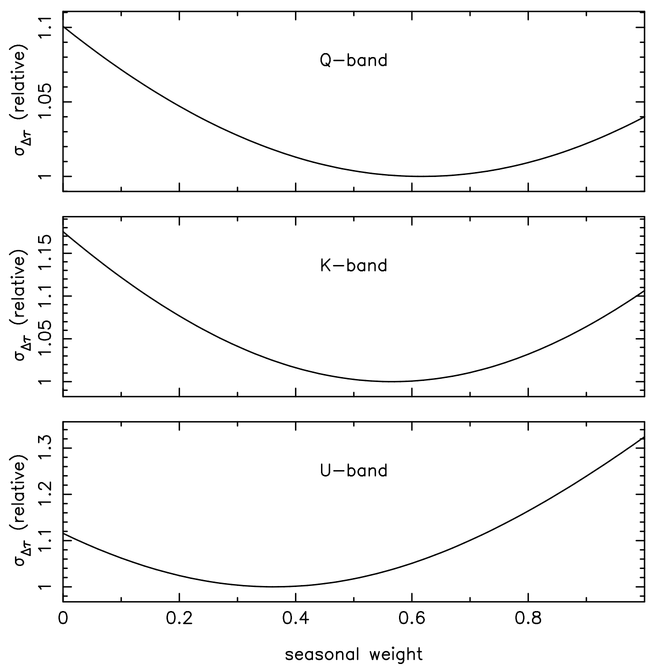

Figure 5: Plot of relative rms difference between the measured values of opacity and a weighted sum of the two models vs. the weight for the seasonal model (the weight for the PWV model is 1 minus the seasonal model weight) for the upper 3 bands on the VLA.

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