Submillimeter Array Technical Memorandum

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Atmospheric Opacity and Water Vapor

Summary

In comparing the qualities of submillimeter sites, the use of precipitable water vapor (PWV) can be misleading, since the opacity also depends on the atmospheric pressure. I tabulate what is known about opacity as a function of frequency in the submillimeter, including preliminary comparisons between measurements on Mauna Kea and the 225 GHz opacities from the NRAO radiometer. A good estimate of opacity at 225 GHz on Mauna Kea is $\tau(225) = 0.04$ PWV(mm). The opacity in the highest frequency windows is a factor of 20 higher than this.

Introduction

For the site decision for the SMA and for the planning of the observing strategy, one of the most important quantities is the atmospheric opacity. The atmospheric opacity in the millimeter and submillimeterwave regime is dominated by water vapor, except near a few oxygen lines. For a given site, the column of precipitable water vapor (PWV) is the most important parameter determining the opacity, (assuming that there are no water droplets). Ice has much lower absorption than water vapor and can be ignored.

In comparing different sites and, to a smaller extent, comparing different days at the same site, it can be misleading to rely simply on the value of PWV, for two reasons. First, in the submillimeter windows, the opacity depends on the wings of pressure-broadened lines. Therefore the effect of any water vapor depends on the pressure at the height of the water vapor. To a first approximation, since the water usually decreases rapidly with height, the opacity is proportional to the product of pressure at the site, p, and the PWV. Second, most measurements do not yield PWV directly, but rather an opacity at some observing frequency. In order to compare different measurements, particularly those made at different frequencies, it is necessary to ensure that the correct model was used to convert from observed opacity to PWV. For example, some papers in the literature erroneously use a calibration established at one altitude to relate PWV to opacity at a quite different altitude.

In view of these difficulties, I believe that we should put aside 'PWV' and cast our site shown as Figure 3. It can be seen immediately that there is good agreement with the Liebe model in the general character of the opacity.

More recently, with the advent of the NRAO 225 GHz radiometer on Mauna Kea, it has become possible to compare opacity measurements taken at various frequencies with the simultaneous 225 GHz values, providing a more accurate check of opacities at relatively low levels of PWV. At present only a few observations have been reduced, but more will become available as time goes on.

The other empirical question is the relation between measured opacity and PWV. Zammit and Ade (1981) present data from Tenerife, calibrated against an infrared radiometer which was, in turn, calibrated against humidity data from radiosondes. The NRAO 225 GHz data have also been checked against radiosonde data (Schwab and Hogg 1988).

Comparisons of Models and Data

In order to compare the spectral shapes of various models and datasets, I have tried to tabulate the predicted or measured opacities at various frequencies relative to that at 225 GHz. These ratios should be roughly independent of PWV, except near strong lines or at low frequencies and low values of PWV where the oxygen opacity is significant. Once the ratios are established it should be possible to estimate the opacity at any frequency from the measured value at, for example, 225 GHz. These ratios are listed below in Table I, and their derivations are explained in the text following the table.

TABLE I

RELATIVE OPACITIES

Source	225	270	345	405	460	680	880
Liebe (1989)	1.0	1.6	3.0	7	33	24	21
Schwab & Hogg(1989)	1.0	1.5	3.6	7	17	13	14
Hills (1979)	1.0		3	6		14	16
Zammit & Ade (1981)	1.0	1.37	3.3	6			
Mauna Kea vs radiometer	1.0		2.9		14	20	
Adopted values	1.0	1.4	3.0	7	20	20	20

The Liebe(1989) numbers are measured from his Fig. 2, which shows attenuation at sea level for 10% RH. The values are relatively high near the strong line at 550 GHz, which may be due to the increased effect of pressure broadening at sea level, compared with mountain tops.

comparisons simply in terms of the opacity at a standard frequency, which should be approximately proportional to the opacity at any other frequency in the submillimeter windows. The natural frequency to pick is that of the NRAO radiometer at 225 GHz. At this frequency, the opacity is dominated by water vapor, except on the very driest days. The dry component of opacity is typically ~0.01 at high mountain sites. All the sites we are considering have zenith opacities less than 0.05 for only 5 - 10 % of the time, so the error in neglecting it is almost always negligible.

In this note, I try to summarize what is known about the relative opacities at different frequencies and their relation to PWV. I also include a preliminary report of the NRAO radiometer data from Mauna Kea.

Opacity models

One widely-used opacity calculation is that due to Liebe (1989), who gives a reduced list of the strongest water and oxygen lines up to 1000 GHz, with a prescription for calculating the resulting opacity at any frequency. The sum of these lines does not accurately predict the opacity in the spectral windows and empirical terms are added (Liebe 1989, Eq 15) to account for the effect of distant lines which can not be calculated individually. There are three empirical terms, depending on e^2, ep, and p^2, where e is the partial pressure of water vapor and p is the atmospheric pressure. Under dry, mountaintop conditions, the ep term is dominant. The opacity is assumed to be proportional to (frequency)^2, but the experimental data were taken primarily at 137.8 GHz. The results of some of Liebe's models are shown in his Figure 2, which is reproduced here as Figure 1. The lowest curve is for a dry atmosphere at sea level, and has only lines and continuum from the dry component. The next curve is the one closest to our conditions, showing the relative attenuation for air with 10 % relative humidity at sea level. Some other calculations incorporating Liebe's model have been presented by Schwab and Hogg (1989), who integrated the opacities deduced from radiosonde ascents under various weather conditions (Figure 2). While the general features are the same, the predicted opacity in the highest frequency windows is less than that shown in Figure 1, relative to the opacity at 225 GHz.

For the SMA we need predictions of opacity in the atmospheric windows, but these are just the places where the calculation is on its weakest ground. To check the model and supplement it, we must look for empirical data.

Opacity measurements

Until recently the best spectral measurements of opacity were made by Michelson spectrometers which observed the entire submillimeter window with a resolution of a few GHz. One of the more useful of these papers is by Hills *et al.* (1978), and their measurement of atmospheric emissivity is

The Schwab and Hogg(1989) values are measured from their curves at 3 mm PWV, based on a Liebe model applied to an actual distribution of water vapor, as measured by a radiosonde. The base altitude was 1.9 km, with a pressure of 790 mbar.

The Hills values are taken from the lines plotted in their Fig. 3, corrected to 225 GHz, using the value of $\tau(270)/\tau(225) = 1.37$, deduced from the data of Zammit and Ade (1981). These data were taken at a pressure of 850 mbar.

The Zammit & Ade values are interpolated between values in their table for low frequencies; These data were again taken at 850 mbar.

The Mauna Kea values are taken from fragmentary data thus far, although the correlations between opacities at 225 GHz and other frequencies appear to be good. The exact frequencies used were 344 GHz, 461 GHz and 691 GHz. The values should be regarded as provisional.

On the whole there is quite good agreement between the different values in the table, considering the slight differences in frequency between the different sources. The largest discrepancies are in the column at 460 GHz and these are likely to be due to the narrowness of the window there. In this case, the exact frequency and bandwidth of measurement are important, and the window shape changes significantly with PWV. The observations should improve significantly as we accumulate more direct data from Mauna Kea.

The adopted values are provisional values to be used for planning. They are biased towards round numbers and empirical values. Frequencies far from the bottoms of windows must be adjusted according to the curves presented in Figures 1 and 2.

The calibrations in terms of PWV are summarized in Table II. The first column shows the relation between the 225 GHz opacity and PWV and the second column shows the pressure at the altitude of the observations. In the third column, the relation has been adjusted to the altitude of Mauna Kea simply by scaling it in proportion to atmospheric pressure.

TABLE II
CALIBRATION OF OPACITY vs PWV

Source	$\tau(225)$/mm	pressure	adjusted to 616 mbar	
Zammit & Ade	0.056	850	0.041	
Schwab & Hogg(3mm)	0.047	790	0.037	
Adopted value		616	0.04	Mauna Kea
		680	0.045	Mt Graham

The Zammit and Ade value is interpolated between the numbers quoted in their paper. The Schwab & Hogg number is based on an opacity of 0.142 for PWV = 3 mm. This is not exactly appropriate, since there is a small dry contribution to the opacity (~0.01 from Mauna Kea at 225 GHz), but the error is fairly small.

Because there is always a distribution of water vapor in the atmosphere, there is no single conversion factor between opacity and PWV, even at one site. However, it is clear that the available data agree quite well once a first-order correction is made for the pressure. The adopted values are for the elevations of Mauna Kea and Mount Graham. Since our site measurements are directly in terms of opacities, this calibration factor is not directly significant for our site choice.

The value of 0.04 nepers/mm at Mauna Kea is lower than values which have been used in some papers (e.g. de Zafra *et al.* 1983), sharply reducing the calculated number of nights where the actual PWV is less than 1mm. On the other hand, this revision affects all frequencies nearly equally, and does not cause any change in the fraction of time expected to be useful for submillimeter observing.

A graph of preliminary and unedited results from the first few months of the NRAO radiometer on Mauna Kea are shown in Fig. 4. These data cover all 24 hours of the day for a period of about 4 months. On the basis of these results, we may expect to have a zenith opacity <0.1 at 225 GHz approximately 50 % of the time, and <0.05 for <10 % of the time, when all 24 hours of the day are included. The corresponding figures for an annual average at S. Baldy are about 20 % and 5 % (Hogg, Owen and McKinnon 1988).

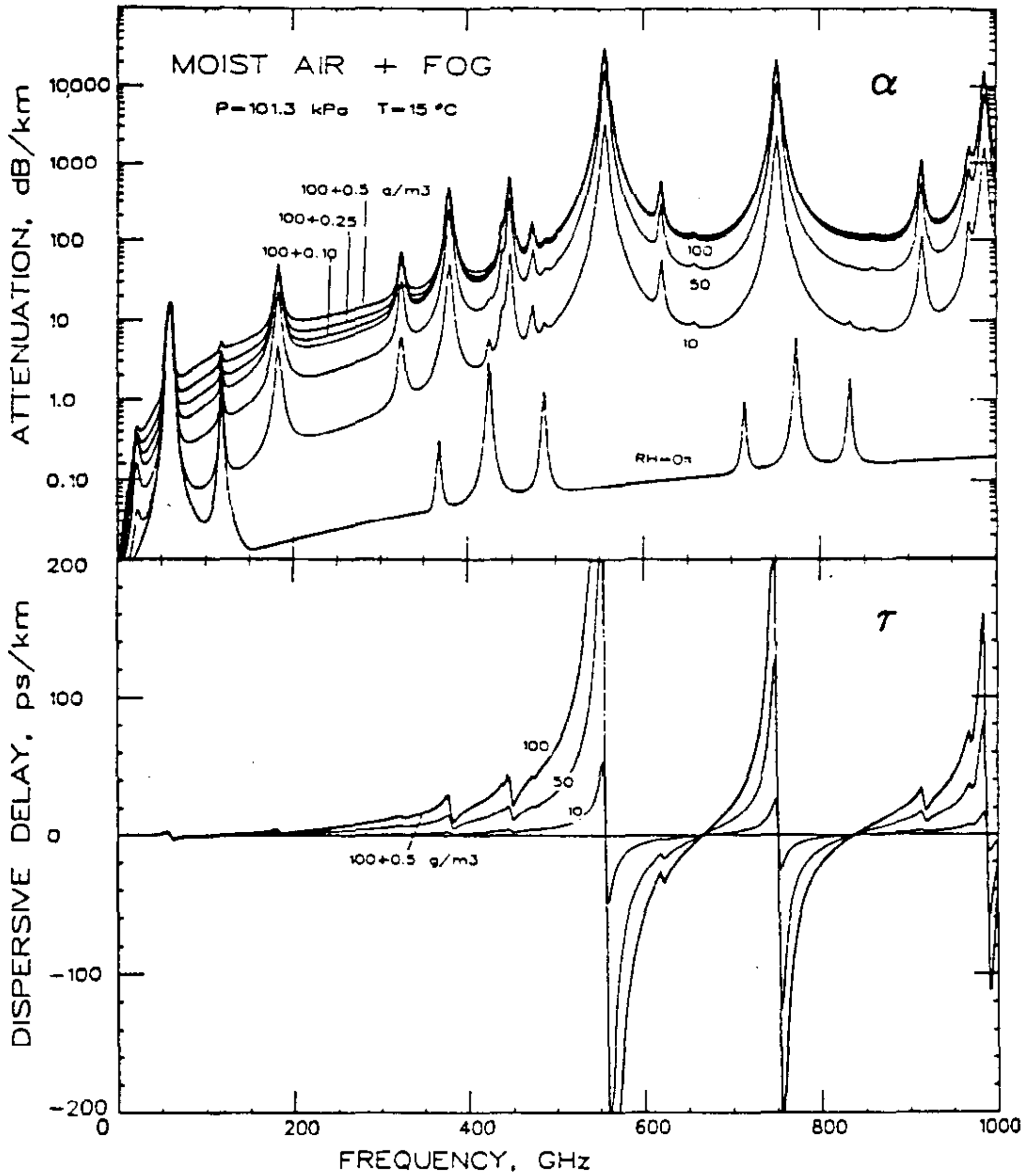

Figure 1. Opacity vs frequency from Liebe (1989). The lowest curve shows the dry atmosphere at sea level, and the second curve shows the effect of 10% humidity at sea level.

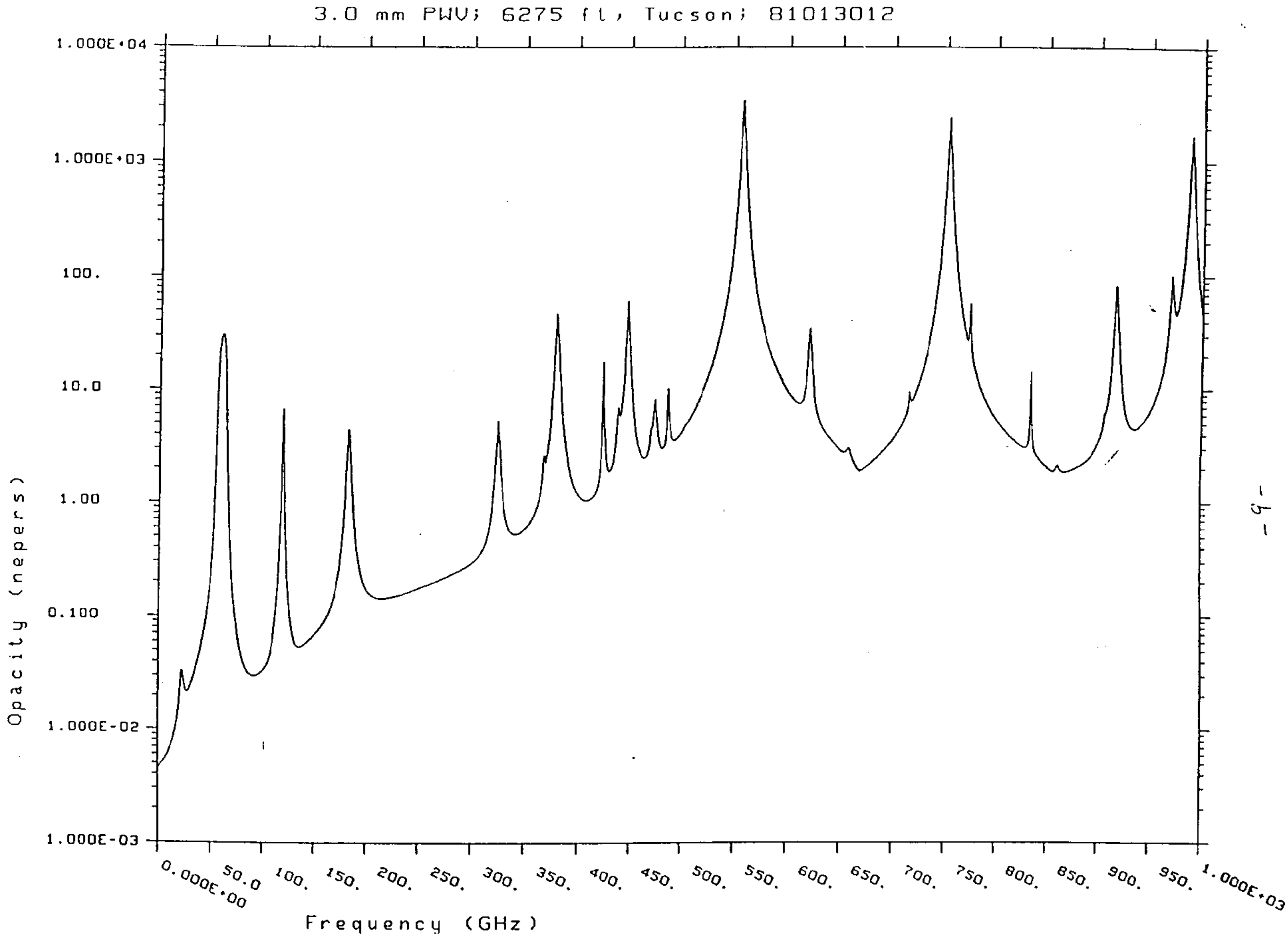

Figure 2. Opacity vs frequency from Schwab and Hogg (1989). This curve is for 3 mm PWV, above a base altitude of 6275 ft.

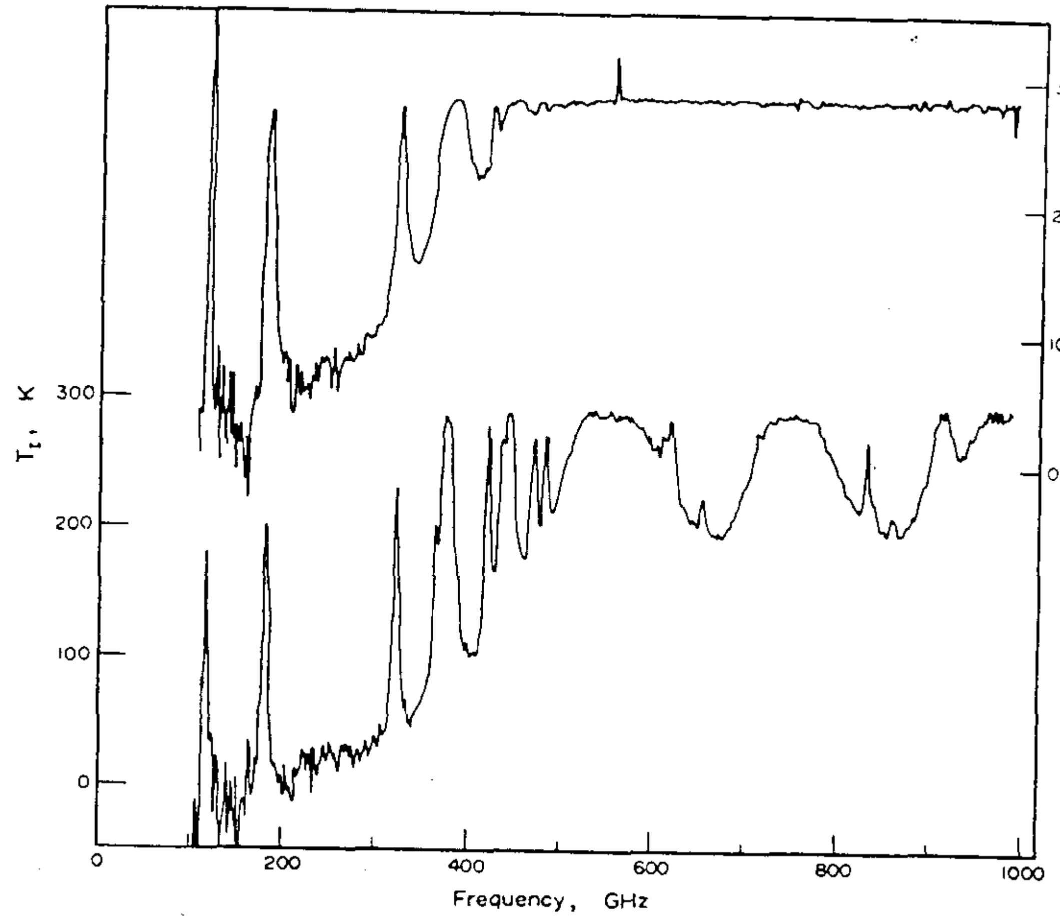

Figure 3. Atmospheric emission vs frequency from HIlls *et al.* (1978). The frequency resolution is 2.4 GHz and the two curves (which are vertically offset) refer to dry and wet conditions.

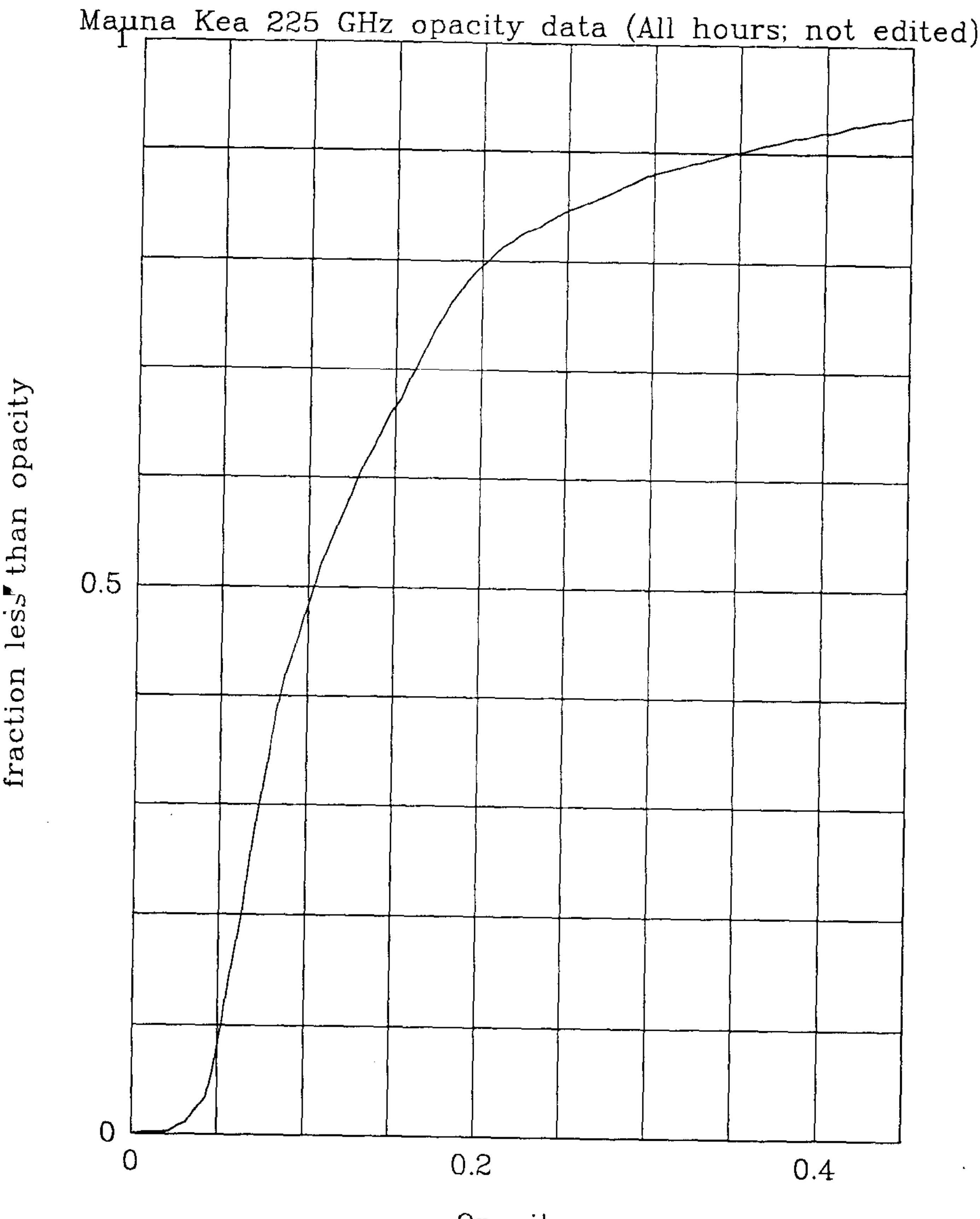

Figure 4. Preliminary 225 GHz opacity data from Mauna Kea. The data span about 4 months of observations in winter 1989-90 and have not been edited.

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