MMA Memo 187: Modeling of the Submillimeter Opacity on Chajnantor

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Abstract

We have found two errors in NRAO's version of the Liebe 1989 atmospheric transmission model. These errors resulted in opacities at the Chajnantor site in the 650 and 850 GHz windows which were a factor of two lower than the corrected model or the Liebe 1993 predict. However, the Hills data set of 225 and 692 GHz opacities from Mauna Kea agrees with the old, buggy NRAO version of Liebe 1989, and not with any models which we now believe to be correct. This ambiguous situation requires more data from the Chajnantor site, but we should also be prepared for higher submillimeter opacities than those in the MMA project had been suggesting. Even so, Chajnantor should be a much better submillimeter site than Mauna Kea, due to the lower precipitable water vapor as inferred from the 225 GHz opacities.

1 Introduction

The atmospheric opacity is particularly important in estimating the fraction of the time observations can be made at a given frequency, and what the system temperature and telescope sensitivity will be. To quantify the opacity at what was once perceived as the MMA's workhorse frequency, the NRAO built the 225 GHz site testing radiometers. Now, we are looking toward much higher frequencies, all the way up to 900 GHz. Again, the obvious step to take is to measure the opacity in the submillimeter windows with a tipper or with a Fourier transform spectrometer (FTS), both of which are under way (see, for example Chamberlin *et al* 1997, Serabyn *et al* 1997). We can also combine our extensive opacity data at 225 GHz with an atmospheric transmission model to estimate the opacity at other frequencies of interest. NRAO has used a private version of Liebe's millimeter transmission model MPM (described in Liebe, 1989) to estimate the opacity at millimeter and submillimeter wavelengths (Schwab and Hogg, 1988, 1989; and numerous private MMA communications). However, the results from this model seem to be unrealistically optimistic in the submillimeter windows. Yet there are measured submillimeter data from Mauna Kea taken by Richard Hills which support our optimistic model. In this memo, we compare NRAO's version of Liebe 89 with Pardo & Cernicharo's ATM transmission code. Several defects in the NRAO version of Liebe's model have been revealed. Correcting them results in a less optimistic model in the submillimeter, but one which no longer agrees with the Hill's data.

2 History and Analysis of NRAO's Version of the Liebe Model

In the late 80's, a copy of Liebe's transmission model was obtained by Harry Lehto for transmission modeling at Green Bank. The numerical coefficients for the various atmospheric lines have been found to be somewhere between the published Liebe 1989 and Liebe 1993 models. A front end to Liebe's model was written to allow input of water vapor, temperature, and pressure profiles from radiosonde data, and the absorption through multiple slabs of atmosphere was calculated with Liebe's model and then integrated. The integration could be performed from any desired site elevation upward. At some point, Fred Schwab came to look after NRAO's version of the Liebe transmission code.

As the frequency range of the MMA grew to encompass the submillimeter, more and more pressure was put on NRAO's version of the Liebe model, though we really didn't realize it. In July 1997, we were able to perform a detailed comparison between the NRAO version of the Liebe model and the Liebe 1989 and Liebe 1993 models in the ATM package (Pardo, 1996). The initial comparison found that NRAO's version of the Liebe model disagreed markedly with either of ATM's Liebe models. Figure 1 shows the disagreement for the case of the Mauna Kea site with 1 mm PWV. The ATM models also have minor atmospheric absorption lines added, while NRAO's model does not. However, the bizarre shape of the submillimeter windows according to NRAO's Liebe model is striking. We found two problems in NRAO's Liebe model which have a minor effect on the millimeter opacity at typical sites, but a profound effect on the submillimeter opacity at extraordinary sites. After correcting these two problems, NRAO's model agreed very well with the ATM Liebe 89 in the submillimeter windows.

Liebe (1993) includes a plot of the opacity through a 1 km horizontal path of moist air at sea level. We compared the results of NRAO's Liebe model and ATM's Liebe 89 and Liebe

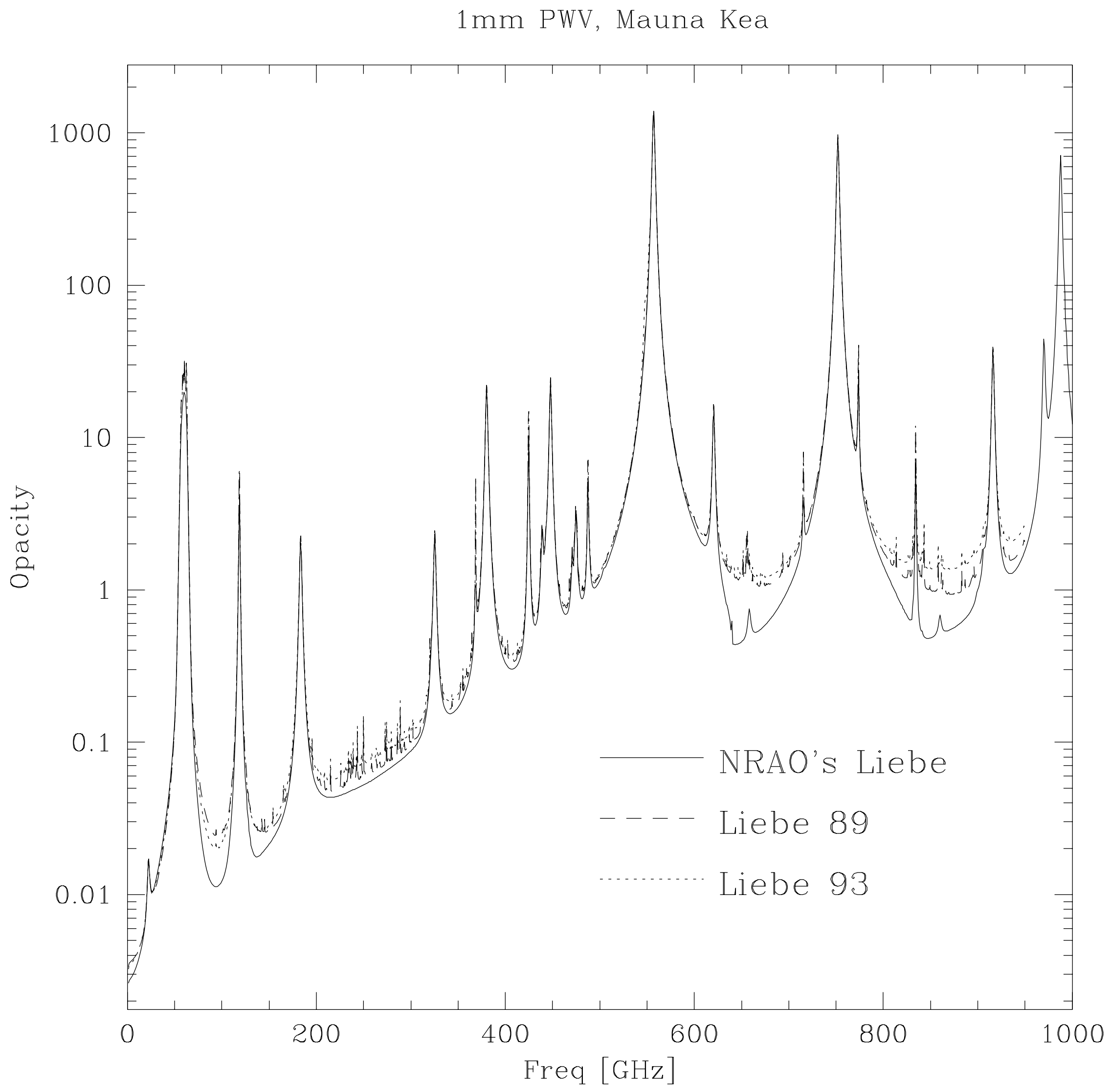

Figure 1: Opacity as a function of frequency with 1 mm PWV above Mauna Kea, for NRAO's Liebe model and the two Liebe models in ATM. In all models, the water vapor was distributed in an exponential profile with 2 km scale height.

93 models with Liebe's published plot and found a defect in the NRAO Liebe model. Figure 2 shows discontinuities about 135 GHz upwards from the 557 GHz and 752 GHz water vapor lines. Inspection of the code revealed that the line shape was truncated on the high frequency side at 40 γ above the line frequency. The parameter γ is a measure of the pressure broadening, so high altitude atmospheric layers would have smaller values of γ, which moved the cutoff to lower frequencies, opening up the submillimeter windows substantially. Because NRAO's Liebe model usually integrates through several atmospheric slabs with different elevations and pressures, the discontinuities were largely smoothed over, resulting in transmission or opacity profiles which did not look as obviously wrong as Figure 2 indicates. There was an interim report from Liebe which mentioned the 40 γ line shape cutoff, but it is obviously not in the final Liebe 1989 and Liebe 1993 models. After removing the cutoff from the code, the resulting test opacity profile looks much better and agrees with the published plot for Liebe's 1989 model (Liebe, 1993). (see Figure 3).

The second error we found in NRAO's version of the Liebe model was an error in converting the measured relative humidity into water vapor density. Figure 4 shows the opacity for a 1 km horizontal test path through totally dry air. Even though we edited a fake radiosonde file to indicate 0.00 relative humidity, the code was inserting a small amount of water vapor. This error was traced to the relative humidity conversion, which assumed any dew point below some nominal value was not realistic, and the dew point was set to that nominal value. The radiosonde data usually extends to elevations of about 15 km, and the dew point would dip below the assumed minimum realistic value at about 8 km. Hence, between 8 and 15 km, water vapor was added to the radiosonde data. This extra water vapor was included in the total PWV calculation, but since it was at the highest altitudes and the lowest pressures, it did not suffer from much pressure broadening, and hence did not contribute much to the opacity in the submillimeter windows. Figure 5 shows the opacity for a 1 km horizontal dry test path after the error had been corrected.

After correcting these two errors (the nonphysical line shape cutoff and the erroneous conversion between relative humidity and water vapor density), NRAO's version of the Liebe code actually agreed fairly well with ATM's Liebe 89 model (see Figure 6).

3 Empirical Relationship Between Millimeter and Submillimeter Opacity

Richard Hills has made simultaneous measurements of the opacity at 225 GHz and at 692 GHz in Millimeter Valley near the Mauna Kea summit. The 225 GHz observations were made with the NRAO/MMA site testing radiometer at the CSO site, and the 692 GHz measurements were made with the JCMT. The data were taken before the CSO took over maintenance of the 225 GHz radiometer. The data have been posted in various public places and given to different people. We got our digital copy of the data from Bob Brown. These data are reproduced in Figure 7. We expect a linear relationship between the two opacities, but not a simple scaling since there are wet and dry opacity terms at both frequencies. The best fit line for these data

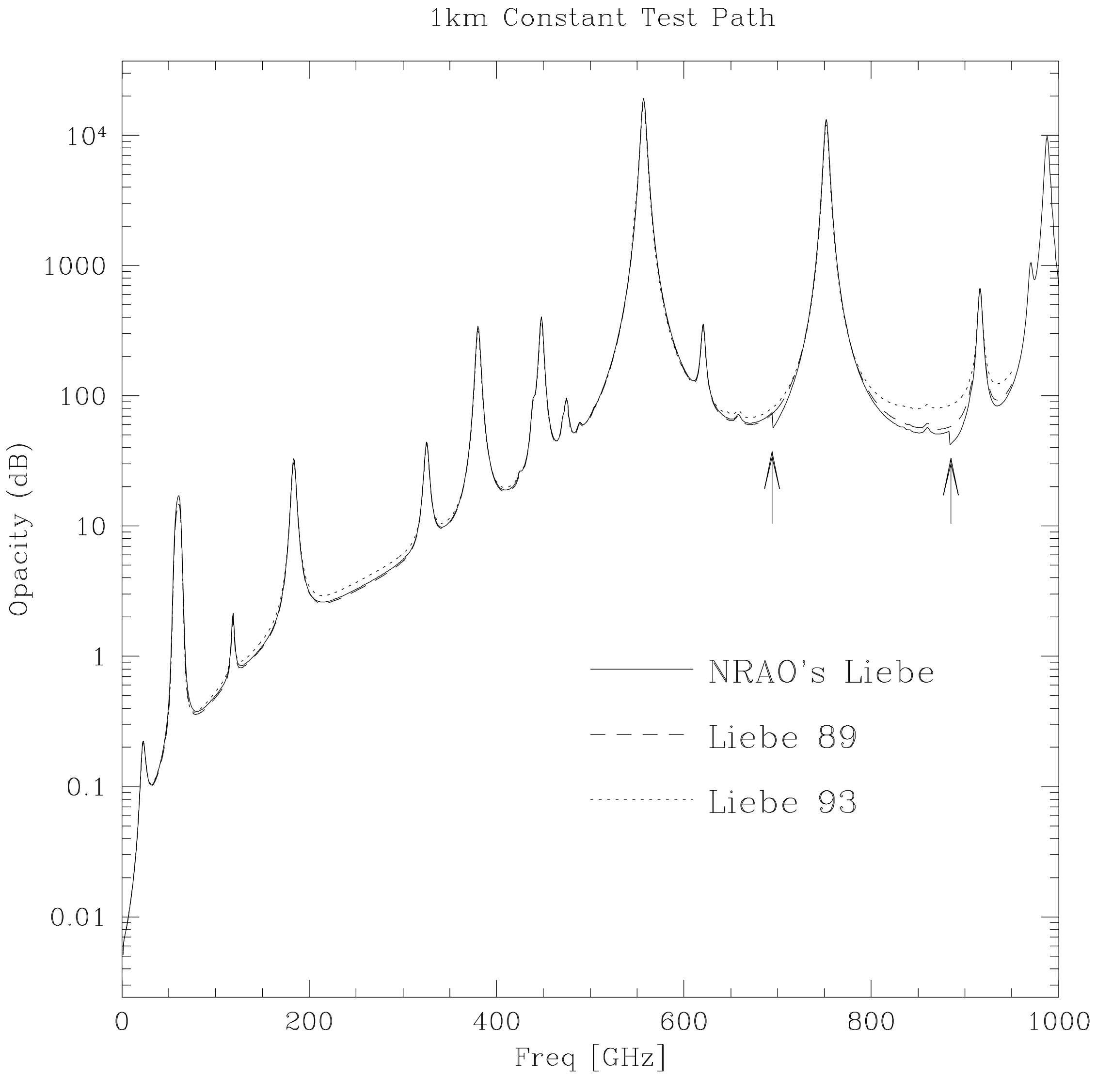

Figure 2: Opacity as a function of frequency for a 1 km horizontal test path through moist air. The plot is in dB for easy comparison with Liebe 1993. NRAO's version of the Liebe model suffers from a nonphysical cutoff in the line shape of the water vapor lines. Minor lines have been removed to more clearly identify problems.

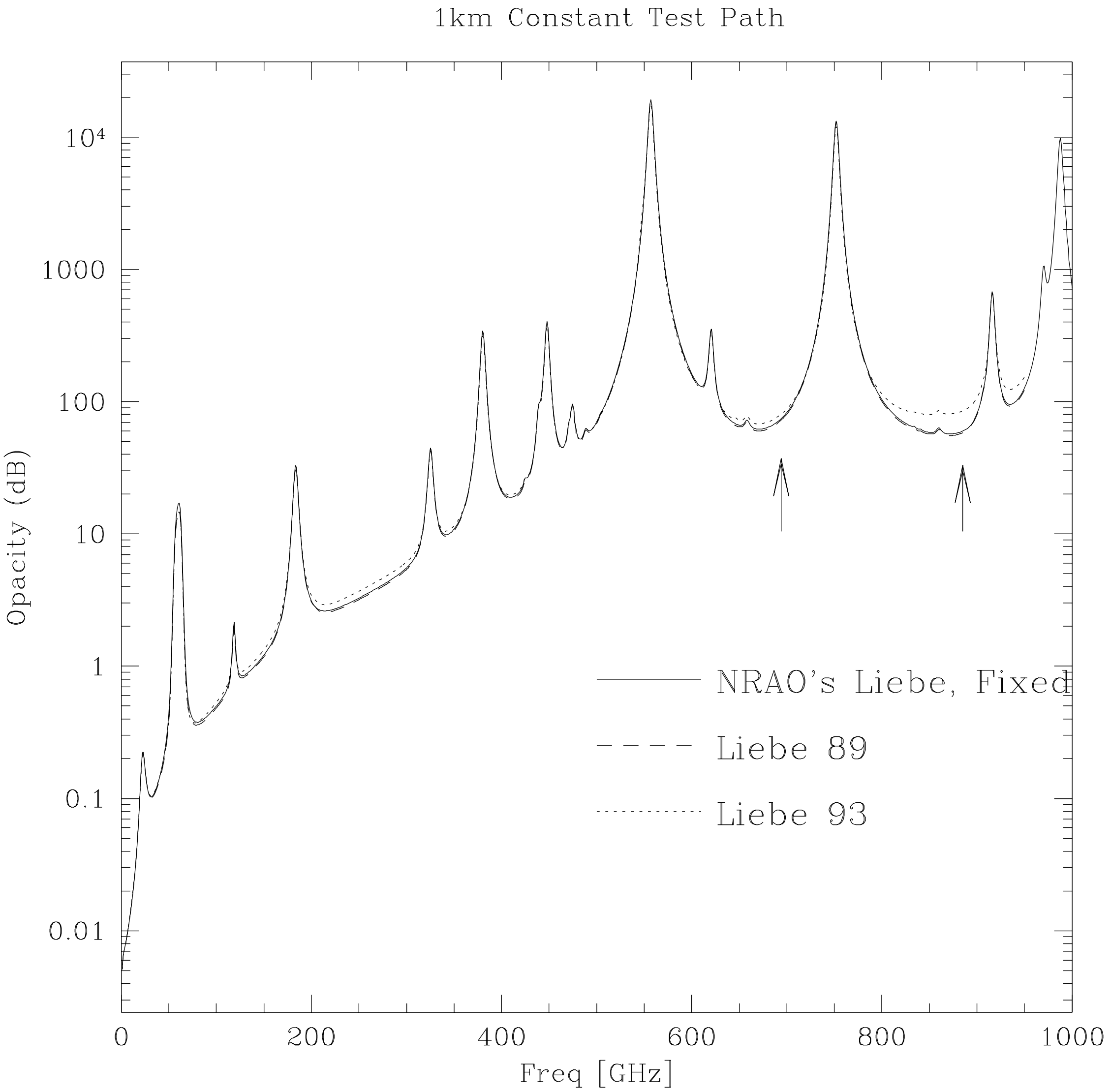

Figure 3: Opacity as a function of frequency for a 1 km horizontal test path through moist air, after correcting for the nonphysical line shape cutoff.

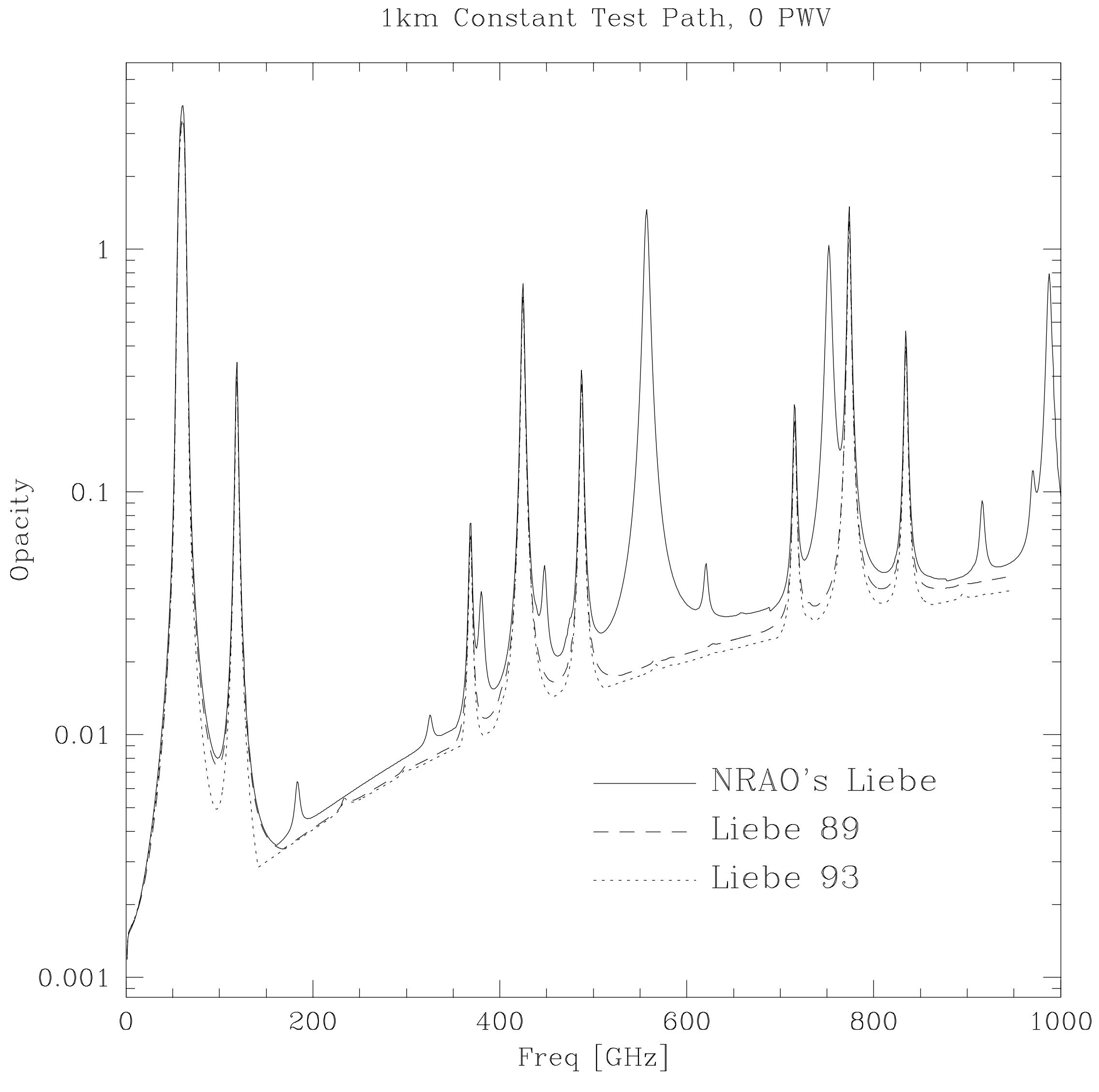

Figure 4: Opacity as a function of frequency for a 1 km horizontal test path through completely dry air. NRAO's version of the Liebe model falsely inserts water vapor anyway.

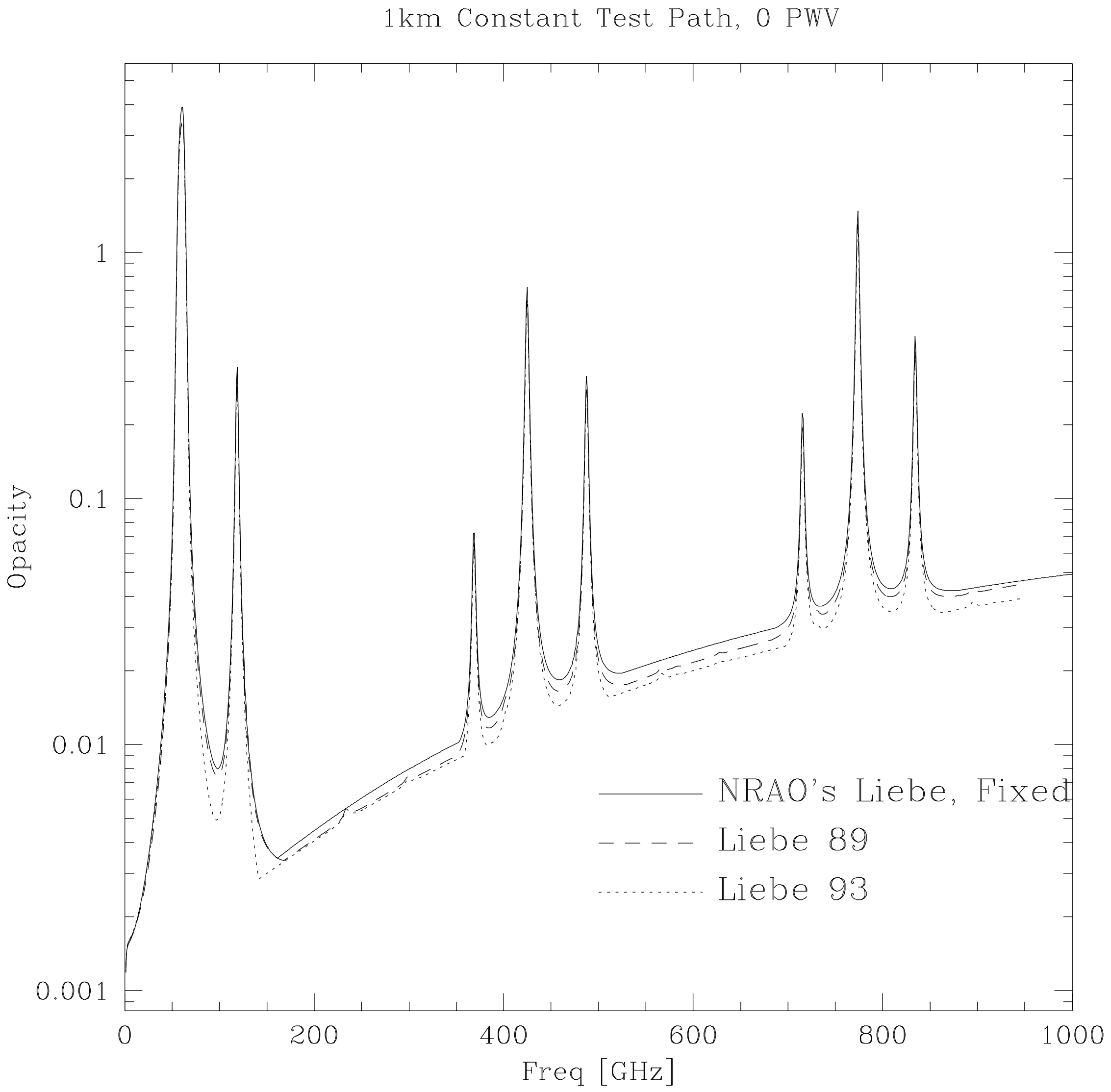

Figure 5: Opacity as a function of frequency for a 1 km horizontal test path through completely dry air after correcting the NRAO code.

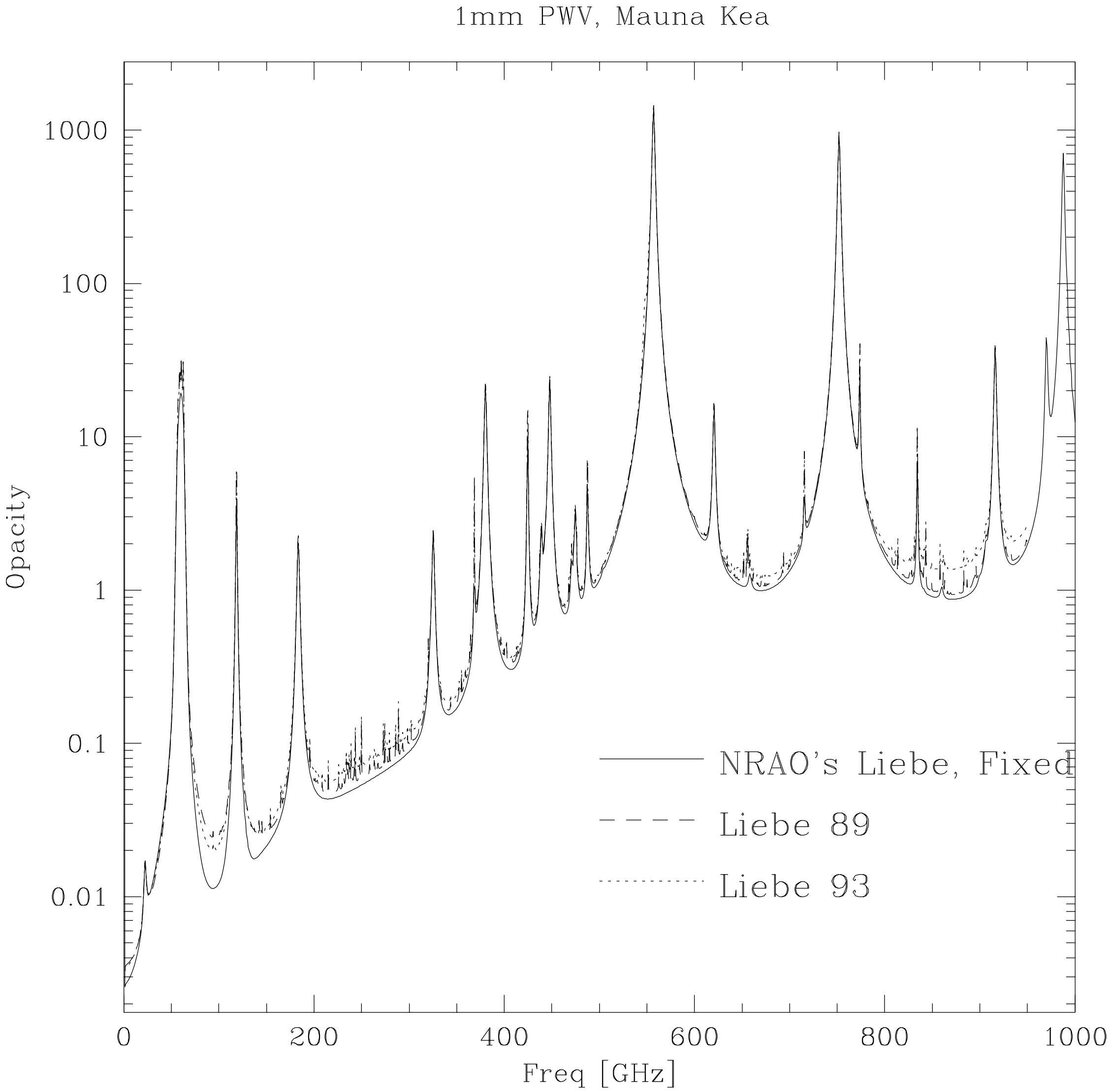

Figure 6: Opacity as a function of frequency with 1 mm PWV above Mauna Kea, for NRAO's Liebe model after the two errors were corrected, and the two Liebe models in ATM.

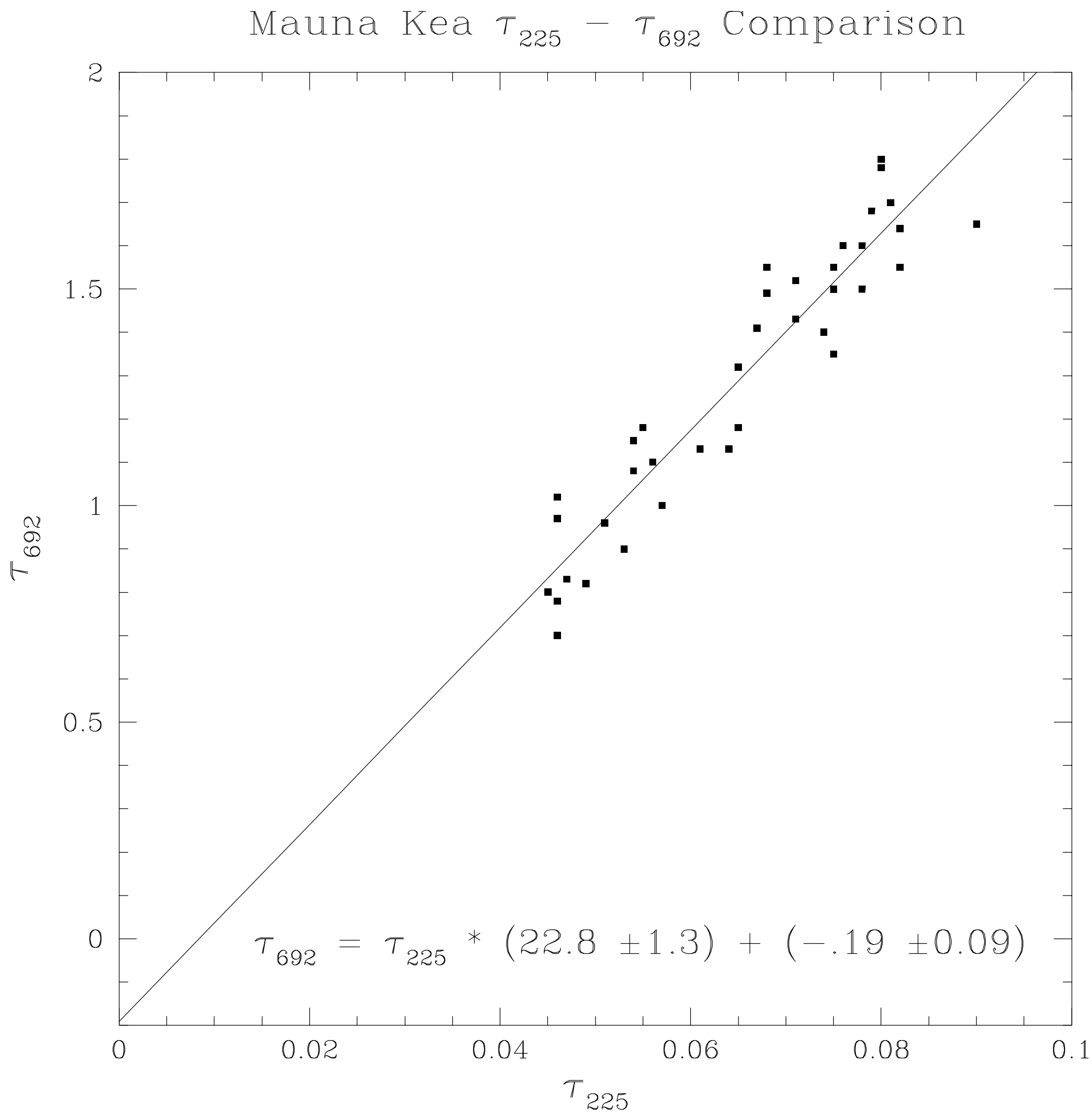

Figure 7: Comparison of the opacity at 225 GHz and at 692 GHz near the Mauna Kea summit.

are

$$\tau_{692} = \tau_{225} * (22.8 \pm 1.3) + (-0.19 \pm 0.09). \tag{1}$$

4 Comparison Between the Empirical Relationship and the Models

We would like very much to finish our story in a nice and tidy fashion by saying that the empirical relationship derived from Hills' data agrees with one of our fixed up models, but it doesn't. Hills' relationship actually agrees perfectly with the old (ie, buggy) NRAO version of the Liebe model.

Assuming that the form of the water vapor distribution above the site does not change, the transmission models produce, for each frequency requested, dry opacity terms due to atmospheric constituents which do not change with time, and wet opacity terms, which scale with the amount of precipitable water vapor (PWV) in the atmosphere, which is highly variable:

$$\tau(\nu) = \tau_d(\nu) + \tau_w(\nu) * PWV. \tag{2}$$

For Mauna Kea, the NRAO's buggy version of the Liebe model yields:

$$\tau_{225} = 0.0120 + 0.0285 * PWV, \tag{3}$$

$$\tau_{692} = 0.0910 + 0.6273 * PWV, \tag{4}$$

which results in the relationship:

$$\tau_{692} = \tau_{225} * 22.0 - 0.17, \tag{5}$$

which compares *very favorably* with Hill's empirical result. ATM's Liebe 89 predicts that

$$\tau_{692} = \tau_{225} * 31.8 - 0.31, \tag{6}$$

and ATM's Liebe 93 predicts that

$$\tau_{692} = \tau_{225} * 28.1 - 0.26, \tag{7}$$

both in significant disagreement with Hill's empirical result.

5 What Might the Submillimeter Opacity at Chajnantor Be?

To summarize our predicament:

- NRAO's version of the Liebe model was definitely wrong.
- By fixing two bugs in NRAO's Liebe model, we can make it produce results that agree with published results from the Liebe model and with ATM's Liebe models.

	Measured	650 GHz τ			850 GHz τ		
Quartile	225 GHz	Old NRAO	ATM	ATM	Old NRAO	ATM	ATM
	τ	Liebe 89	Liebe 89	Liebe 93	Liebe 89	Liebe 89	Liebe 93
.10	0.028	0.25	0.49	0.44	0.29	0.47	0.51
.25	0.036	0.35	0.72	0.65	0.38	0.66	0.73
.50	0.054	0.56	1.24	1.21	0.59	1.10	1.22

Table 1: Predicted opacities in the 650 and 850 GHz windows, based on NRAO's *uncorrected* version of Liebe's 1989 model, ATM's Liebe 1989, and ATM's Liebe 1993, using the 10%, 25%, and 50% 225 GHz opacities. This table indicates that the submillimeter opacities could be as much as a factor of two worse than NRAO's old uncorrected Liebe model had predicted.

	South Pole		Mauna Kea		Chajnantor	
Quartile	1992	1992	Average	Average	1995	1995 Oct
%	Apr-Sep	Other	Jan-Jun	Jul-Dec	Apr-Sep	- 1996 Mar
.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

Table 2: 225 GHz Zenith Opacity in three possible submillimeter sites from NRAO tipper data (published by Chamberlin *et al* 1997).

- Hill's data agrees with NRAO's buggy version of the Liebe model

We cannot completely discredit the old NRAO Liebe model, but we can suggest that the submillimeter opacities could easily be much worse than we were expecting. This all calls for more measurements. The submillimeter opacity predictions of the three models, based on the 225 GHz site testing data on the Chajnantor site are given in Table 1. This table indicates that the submillimeter opacities could be as much as a factor of two worse than NRAO's old uncorrected Liebe model had predicted. Even so, Chajnantor should be a much better submillimeter site than Mauna Kea, due to the lower precipitable water vapor, as inferred from the 225 GHz opacities (Scott Foster's private communication published by Chamberlin *et al* 1997, see Table 2).

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