VLA SCIENTIFIC MEMO 157

ATMOSPHERIC OPACITY AT THE VLA

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ABSTRACT

Atmospheric measurements made with the VLA at 22.25 GHz gave opacities in the range $\tau = 0.13$ (with a heavy overcast sky) to $\tau = 0.04$ (with clear sky). Measurements at 225 GHz done with a chopper-wheel tipping radiometer are described as well. Some sources of systematic errors are discussed.

I. INTRODUCTION

The tests described in this memo were prompted by Pat Palmer's (internal, unnumbered) memo of 28 September 1985, on "Atmospheric Opacity at K-band" at the VLA. Besides, I wanted to compare the results from the 225 GHz radiometer with those of the array, in order to assess the possibility of using that device to correct data taken at K-band without having to spend valuable observing time doing tipping scans.

The opacity at K-band (22.2 GHz) is due to both oxygen and water vapor. The oxygen is fairly uniform and its contribution is given by [Ulich, Astrophys. Lett. 21, 21 (1980)]:

$$\tau_{O_2} = \alpha(\nu) \exp(-h/h_o): \quad \alpha(22.2) = 0.013 \text{ nepers}$$

$$h_o \sim 5000 \text{ meter}$$

$$h_{VLA} \sim 2175 \text{ meter}$$

whereas the contribution of water vapor is approximately proportional to the amount of precipitable water,

$$\tau_{H_2O} = \beta(\nu) \cdot W \; ; \; \beta(22.2) \sim 0.0060 \text{ neper/mm}H_2O.$$

At ν = 225 GHz $\alpha(\nu) \sim 0$ and the attenuation is almost exclusively produced by water vapor.

$$\beta(225) \sim 0.056 \text{ neper/mm}H_2O$$

[Zammit and Ade, Nature 293, 550 (1981)], but Ulich (op.cit.) gives $\beta(225) \sim 0.067$ and B. Turner (priv. comm.) gives $\beta(225) \sim 0.042$. Therefore, a measurement of τ_{225} can, in principle, be used to provide the amount of precipitable water, which can then be used to deduce the attenuation at 22.5 GHz.

II. MEASUREMENTS WITH THE ARRAY

I did standard tipping scans on 17 October 1985, 5 November (2) and 6 November (3, one of them courtesy of Paul Lillie). The data were analyzed using the standard VLA routines, and also (those of 6 November) independently as follows:

The system temperature at a given elevation E is given by:

$$T_{sys}(E) = T_{REC} + T_{SO}(E) + T_{MA}(1-e^{-\tau/\sin E}) + T_{BG}\, e^{-\tau/\sin E},$$

where E is the elevation;

T_{REC} is the contribution of the receiver;

T_{SO} is due to spillover, which, in principle, depends on E;

T_{MA} is the mean atmospheric temperature, weighted by water and oxygen;

τ is the atmospheric extinction; and

T_{BG} is the 3 K background radiation.

At any elevation, T_{SYS} is measured by firing the noise tube and measuring the total power voltage through the algorithm:

$$T_{sys} = 15 \frac{V_{GTP}}{V_{CAL} - V_{CALOFF}} T_{CAL},$$

where V_{GTP} is the "gated total power;"

V_{CAL} is the voltage when the cal is fired;

V_{CALOFF} is its offset; and

T_{CAL} is the noise tube temperature.

I obtained V_{GTP} and V_{CALOFF} for each antenna from the system startup file (courtesy of Phil Hicks) and used only those antennas for which the ALC values were close to -10 when the system selected the F4 alternate input port to find the total power detector offset. For these, V_{GTP} is nominally 3 volts; I used the difference of the actual gated total power (from the startup file, table headed by "Turn off noise source to find synchronous detector offset," column headed "TP,NT") and the total power offset (from the "select F4 alternate..." table, column headed "TP,NT"). The corrections were minor for all except four antennas, but for those, they were relevant (equivalent to [20-30%] errors in T_{CAL}).

V_{CAL} is printed by the VLA tipping program for the different elevations and V_{CALOFF} came from the startup file (table headed "Turn off noise...," column headed "SD"). The corrections were, in general, again minor (only relevant for four antennas, not the same as above though), and their effect negligible (except for the four antennas just mentioned for which it amounted for up to 50% errors in the derived atmospheric opacities).

I obtained the noise tube values, T_{CAL}, from Paul Lillie, and used only those antennas for which they had been measured after June 1985.

These cuts left 19 antennas (IF-A) and 18 antennas (IF-C) for which the data were analyzed. Table I shows the measured average extinctions (τ).

Table I

No.	Day	τ(MEAN), ± (σ of the mean)		Ambient Temperature	Weather
1	17 October, 10:00 A.M.	0.130	0.004	280 K	Heavy Overcast
2	5 November, 3:30 P.M.	0.120	0.006	289 K	Cloudy
3	5 November, 4:00 P.M.	0.114	0.006	288 K	Cloudy
4	6 November, 11:45 A.M.	0.076	0.002	285 K	Clear, windy
5	6 November, 12:15 P.M.	0.080	0.004	285 K	Clear, windy
6	6 November, 8:30 P.M.	0.045	0.001	280 K	Clear, calm

The array was in C/D configuration on 17 October and D configuration on 5 and 6 November. Measurements 1, 2, and 4 were done at azimuth 180°, whereas 3, 5, and 6 were done at 85° azimuth. Antennas for which significant shadowing occurred (2 for 1, 2, 4) have been ignored in the analysis.

The effect of using the T_{CAL} values in the system file instead of the more recent ones was found to be an increase of the scatter of the opacities measured by the different antennas but without significantly affecting the average. I found that the values had not been updated because nobody had entered them in the maintenance sheets and gave Jon Spargo the values that Paul Lillie gave me; so they should be in now. (This "lack of communication" between people on site should be easy to fix.) An error in T_{CAL} produces an error in τ and $(T_{REC} + T_{SO})$ of the same order of magnitude.)

The weather was quite good on 6 November, so I analyzed those data with all the relevant corrections described above, with the results shown on Table II. I used T_{BG} = 2.7 K and T_{MA} = ambient temperature, an approximation; but the correlation between T_{MA} and τ is high and the data were not able to give any better value for the T_{MA} (errors were 50 K to 150 K).

TABLE II

K-band Tipping Curves

Antenna	If A: #5 (Tamb=285K) Tsyso	tau		#6 (Tamb=280K) Tsyso	tau		If C: #5 (Tamb=285K) Tsyso	tau		#6 (Tamb=280K) Tsyso	tau	
2	714	.086	VG	708	.048	G	797	.054	OK	802	.034	OK
3	300	.072	VG	301	.041	VG	320	.070	VG	321	.041	G
6	363	.074	VG	362	.043	VG	240	.059	OK	232	.038	G
7	298	.104	BAD	350	.089	BAD	449	.082	VG	452	.048	VG
9	505	.077	VG	505	.043	G	532	.070	G	533	.040	G
10	593	.090	G	587	.056	OK	388	.069	G	384	.046	G
11	289	.070	VG	289	.042	VG	435	.071	G	435	.041	G
13	284	.056	OK	—	—	—	—	—	—	459	.038	G
14	394	.077	G	390	.059	G	383	.079	G	371	.051	G
16	286	.080	VG	288	.052	VG	453	.083	VG	451	.056	VG
17	272	.074	VG	272	.045	VG	—	—	—	—	—	—
18	452	.085	VG	456	.046	VG	250	.065	VG	249	.041	VG
19	—	—	—	405	.044	G	300	.069	G	296	.045	G
20	346	.078	G	348	.046	G	344	.093	G	342	.054	VG
21	650	.063	BAD	—	—	—	435	.073	G	—	—	—
22	315	.057	VG	314	.037	VG	317	.070	VG	316	.044	VG
23	259	.066	VG	258	.041	VG	109	.076	VG	110	.046	VG
25	840	.072	OK	844	.045	G	415	.070	G	417	.042	VG
26	479	.064	VG	473	.042	G	—	—	—	—	—	—
27	362	.078	OK	360	.056	G	—	—	—	—	—	—

BAD means bad fit, OK, Good and Very Good are the other options. The average values in Table I come from the ones that correspond from good or very good fits in this table.

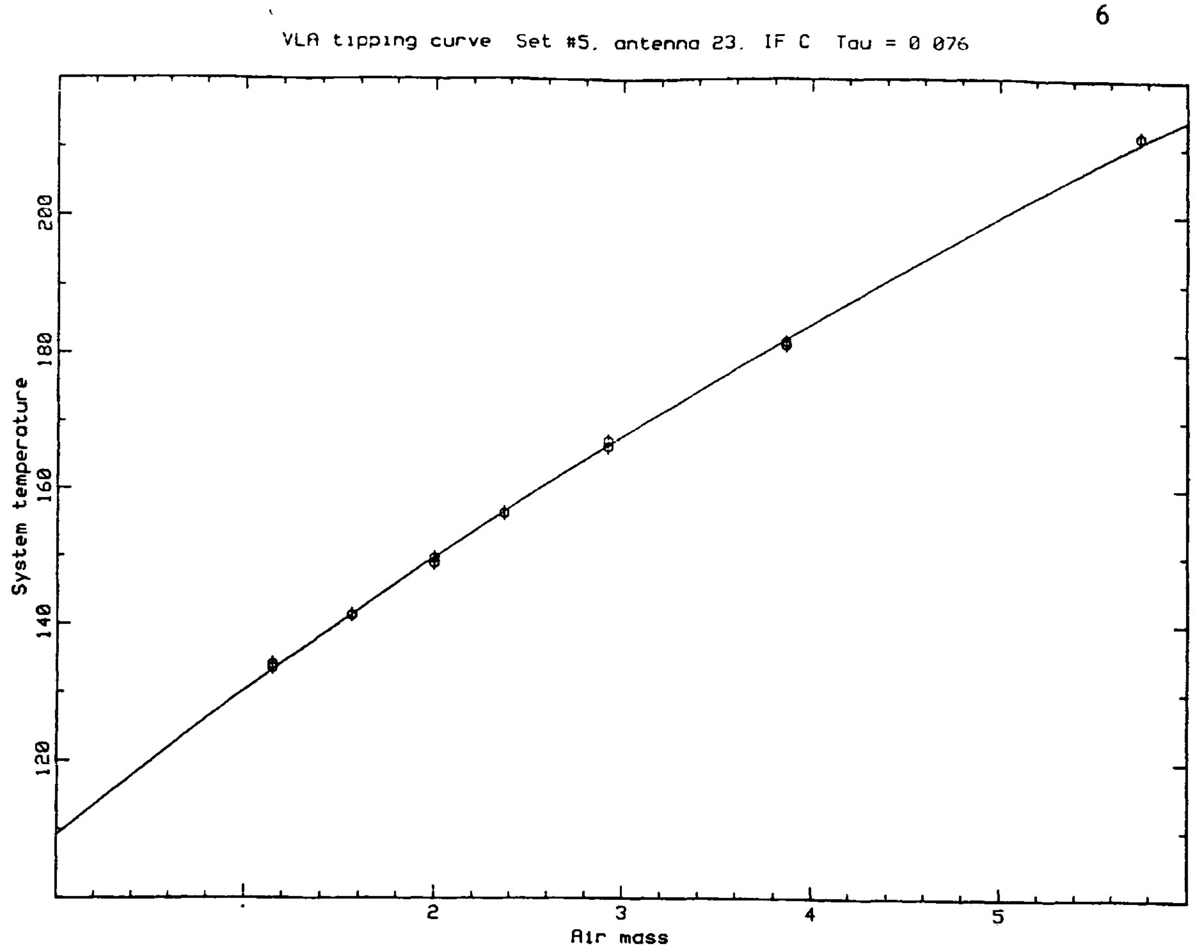

Figure 1

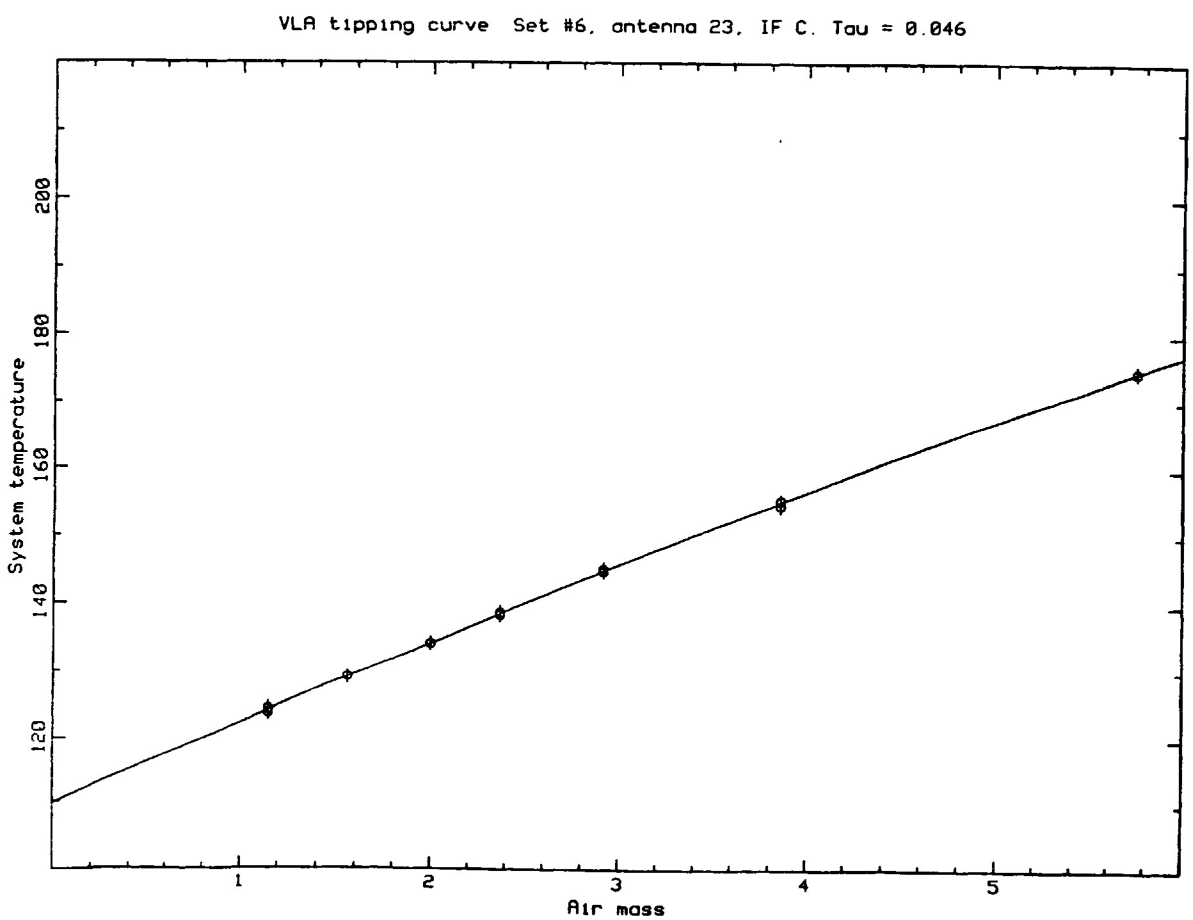

Figure 2

To conform with the convention used by Spangler (VLA Scientific Memo No. 143) and with the output of the VLA tipping program I have added

$$T_{systo} = T_{REC} + T_{SO} + T_{BG}$$

which appears in Table II. Notice that the agreement of the values measured in No's 5 and 6 is quite good, in spite of a factor of 2 difference in the opacities. Figures 1 and 2 show the data for antenna 23, IF C which has a low noise HEMT amplifier.

The fitted curves in Figures 1 and 2 do not suggest any significant dependence of T_{SO} with angle in spite of the low elevation of three of the data points (two at 15°, air mass = 3.86; and one at 10°, air mass = 5.76) in each graph. These points were frequently off the curves (especially for measurement No. 1) but that was surely due to clouds.

Measurements 2 and 3 showed no azimuth dependence (after excluding those antennas affected by shadowing; for those, the low elevation points were off as well--not surprising).

III. MEASUREMENTS WITH THE 225 GHz RADIOMETER

The optical depth measurer uses a 225 GHz room-temperature radiometer which receives radiation from the sky:

$$T_A = T_{REC} + (1-\varepsilon)\ T_{SBR} + \varepsilon\ T_{MA}\ (1-e^{-\tau \sec z}) + \varepsilon T_{BG}\ e^{-\tau \sec z},$$

where

$T_A \equiv$ Antenna temperature seen by the radiometer;

$\varepsilon \equiv$ Coupling efficiency;

$T_{SBR} \equiv$ Temperature at which the losses are terminated;

$T_{MA} \equiv$ Mean ("weighted" by its H_2O and O_2 distribution) atmospheric temperature;

$\tau \equiv$ Optical depth at zenith; and

$T_{BG} \equiv$ 2.75 K background radiation.

The radiometer actually measures the difference between T_A and the radiation temperature of an ambient temperature (T_{AMB}) absorber (piece of Eccosorb). Furthermore, assuming $\varepsilon \sim 1$ gives:

$$\text{Voltage output} = \Delta V \propto T_{AMB} - T_{MA}\,(1-e^{-\tau \sec z}) - T_{BG}\, e^{-\tau \sec z}.$$

Now

$$T_{BG} << T_{AMB} \rightarrow \text{ignore};\ T_{AMB} \sim T_{MA}$$

$$\rightarrow \Delta V = D\,(T_{AMB} \cdot e^{-\tau \sec z})$$

It is not necessary to know D to determine τ as:

$$\log_e \Delta V = \log_e D - \tau \sec z + \log T_{AMB},$$

and $-\tau$ is the slope of a straight line, independently of the value of D.

(A) Measurements of November 1985

At the time of these tests, the actual instrument had a non-negligible offset, and was apparently not linear over the full range of operation. Besides, the tiltable mirror is controlled by a motor and servo circuit with a feedback loop to keep its position stable; this was not achieved and some serious rocking occurred. Furthermore, minor shaking of the box (like if one drops the cover in a cold windy day after having reset the elevation pot) causes significant drifts that might last about 30 sec and seriously affect the measurement. This could have been connected with the rocking instability described above.

Table III gives the fitted values from two series of measurements, the first done on 6 November 1985, at ~1:15 P.M.; the second series was done on 6 November 1985, at 8:30 P.M., simultaneously with measurement No. 6 described above.

In order to check the linearity of the device and also for consistency, I measured ΔV with a liquid nitrogen load (instead of the sky) and obtained $-\Delta V = 1.25$ volts, implying $D_{LN2} = 6.3 \times 10^{-3}$.

The dispersion in the values of D is disturbing, but in view of the systematic problems described above maybe not completely unexpected. (Bringing D_{LN2} in agreement with the average of the values in Table III implies T_{LN2} = 101 K which is too high.)

TABLE III

Function Fitted: $-V = C \cdot \exp\{-\tau \cdot \sec z\}$

		C(volts)	τ(neper)	
Set No. 1				
	run 1	1.96±0.07	0.36±0.02	
	run 2	2.00 0.07	0.39 0.02	
	run 3	2.15 0.12	0.39 0.03	
	run 4	2.13 0.07	0.37 0.02	
	run 5	2.18 0.11	0.38 0.03	(Fig. 3)
	run 6	2.10 0.08	0.36 0.02	
	run 7	1.96 0.06	0.33 0.02	
	run 8	1.96 0.08	0.34 0.02	
Average		2.05 0.03	0.37 0.01	

T_{AMB} = 285 K → D = 7.2 x 10^{-3} V/K (from eqn. *)

Set No. 2				
	run 1	1.92 0.06	0.37 0.02	
	run 2	1.94 0.06	0.36 0.02	(Fig. 4)
Average		1.93 0.04	0.36 0.02 → D = 6.9 x 10^{-3} V/K	

The measured opacities give τ(22.2 GHz) = 0.052 for both sets. (Ulich's β(225) yields τ(22.2) = 0.041 while Turner's gives τ(22.2) = 0.064.) In any case, the uncertainties are such that the value of τ(22.2) is not unreasonable. Nevertheless, what is not reasonable is that both sets produced the <u>same</u> result,

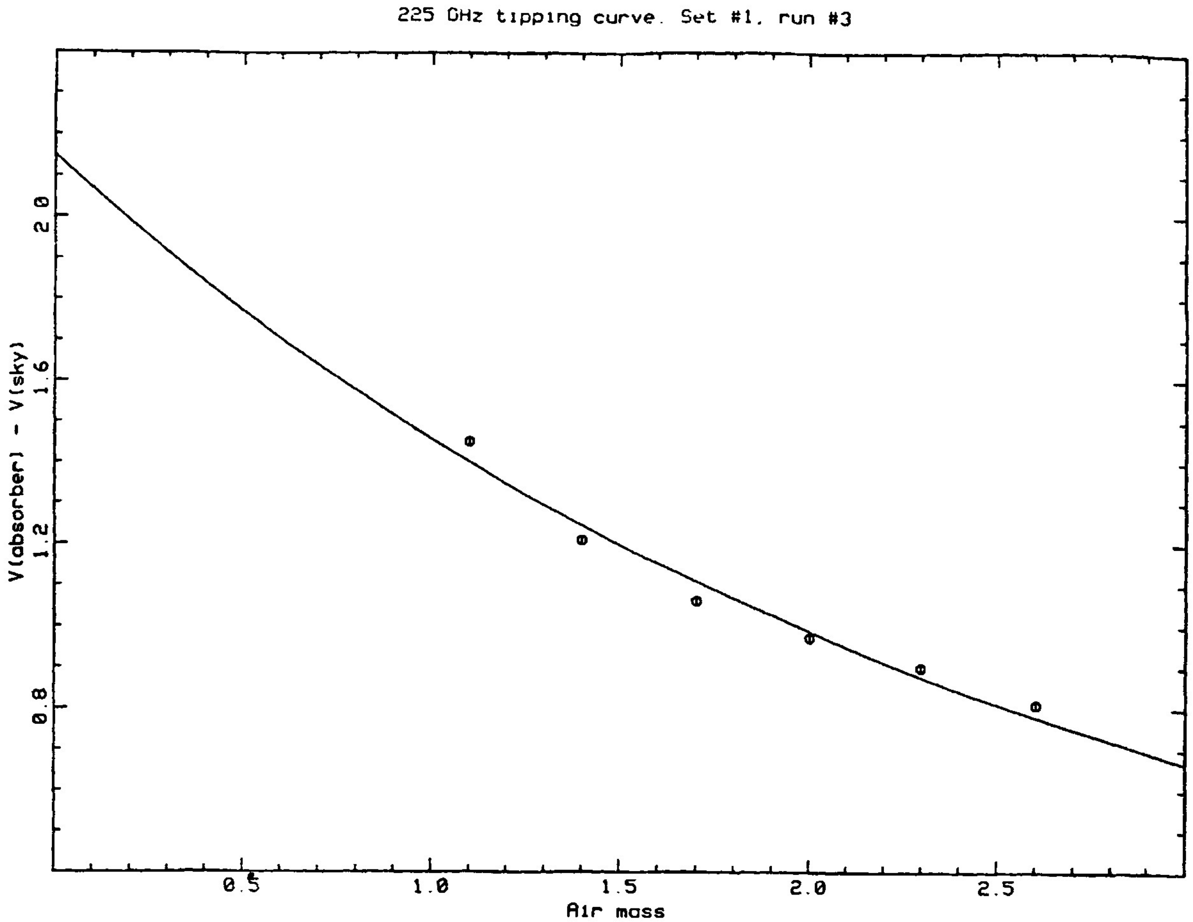

Figure 3

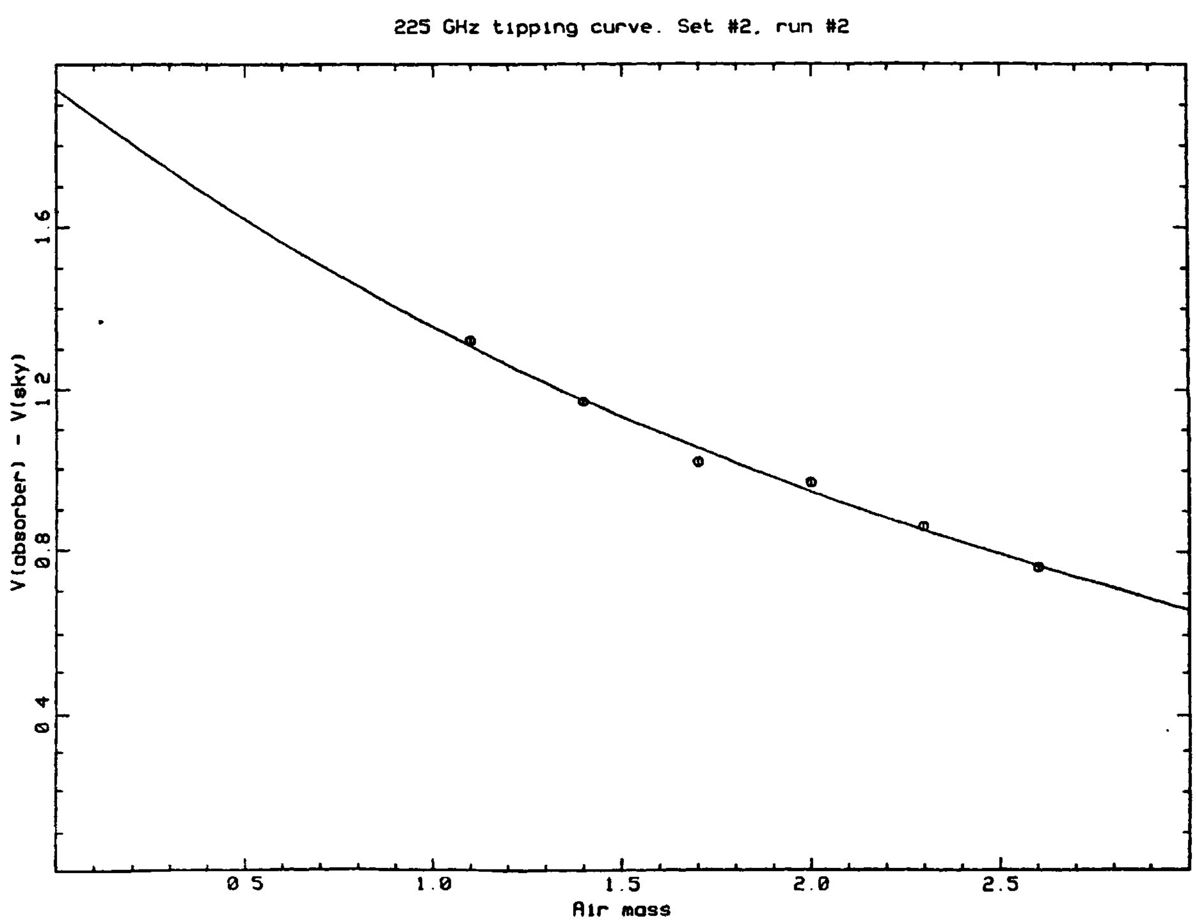

Figure 4

whereas the array gave 0.080 and 0.045 at the corresponding times. The spread in the data for set No. 1 in Table III is likely due to the systematic problems discussed above. (It was very windy and the measurement was a bit hurried; I spent more time per point for set No. 2, with a cold, calm sky, and got better consistency and agreement with the VLA measurement (No. 6) although this could have been fortuitous.

(B) Measurements of February 1986

Several modifications done by Paul Lillie and collaborators have improved the performance of the tipping radiometer. The offset has decreased and at the same time the gain has been increased so that the uncertainty due to drifts in the said offset was negligible at this time (i.e., it had no significant effect on the derived opacities).

At this time, I decided to check the actual elevation angles at the various positions of the parabolic reflector and found:

(1) The instrument is used on non-level ground which, coupled with whatever error the instrument itself contributes, gave a forward tilt of 2 ± 0.5 degrees which would have biased the opacities high (see below).

(2) As pointed out by Paul Lillie, the elevation of the parabola is controlled by a carbon pot whose resistance is very much dependent on the temperature. We found that when the settings commanded an elevation of 14.3 degrees (the lowest used), the actual elevation was about -5° at an ambient temperature of about -3 C. The effect was somewhat erratic, sometimes small, but seemed to bias the elevations consistently and progressively towards lower values; this would have again biased the measured opacities high.

The carbon pot will be changed sometime soon; although it could not hurt to regulate the temperature inside the radiometer box to avoid any other temperature-dependent problems.

After some experimenting, I found a better position for the reflector (it can be adjusted mechanically to include an offset-elevation); which resulted in no significant rocking (<0.5°) at the time of my measurements.

I then found new settings for the different wanted elevations (using a bubble-level and an adjustable protractor) and made the measurements displayed in Table IV. The weather deteriorated significantly through the run and I gave up after thick clouds started rolling in. A series of snow storms in the next few days prevented further testing before I left the site.

Table IV

Function fitted: $-\Delta V = C \exp(-\tau \cdot \sec z)$

C(volts)	τ(neper)	
3.89 ± 0.03	0.165 ± 0.004	(Figure 5)
4.16 ± 0.05	0.186 ± 0.005	
4.18 ± 0.06	0.194 ± 0.008	
4.45 ± 0.07	0.233 ± 0.008	(Figure 6)

Average 4.17 ± 0.14

therefore D = 0.015 volts/Kelvin

assuming $T_{at} = T_{amb} = 277.5$ K

Again, a test with a liquid nitrogen load gave D = (0.0145 ± 0.0005) volts/Kelvin in reasonable agreement with the average value derived in Table IV. Notice that the dispersion of the values of C (first column) is

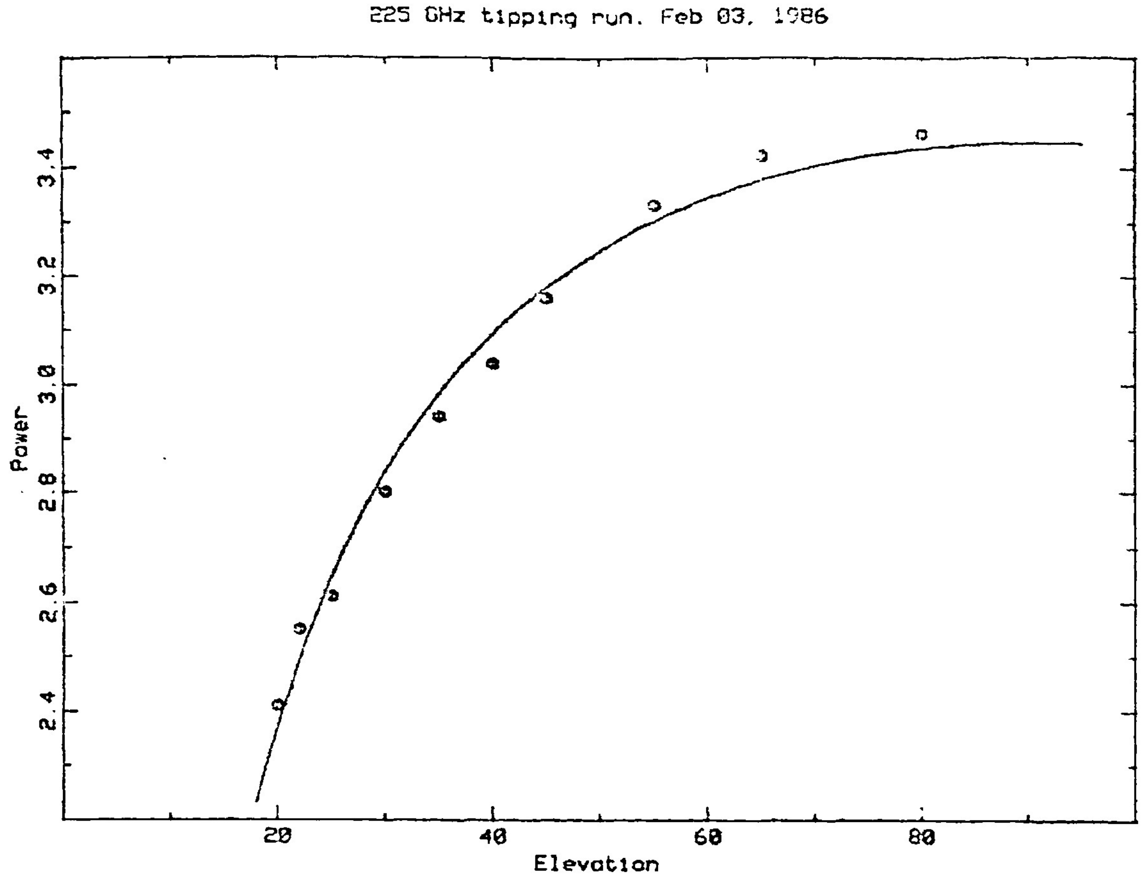

Figure 5

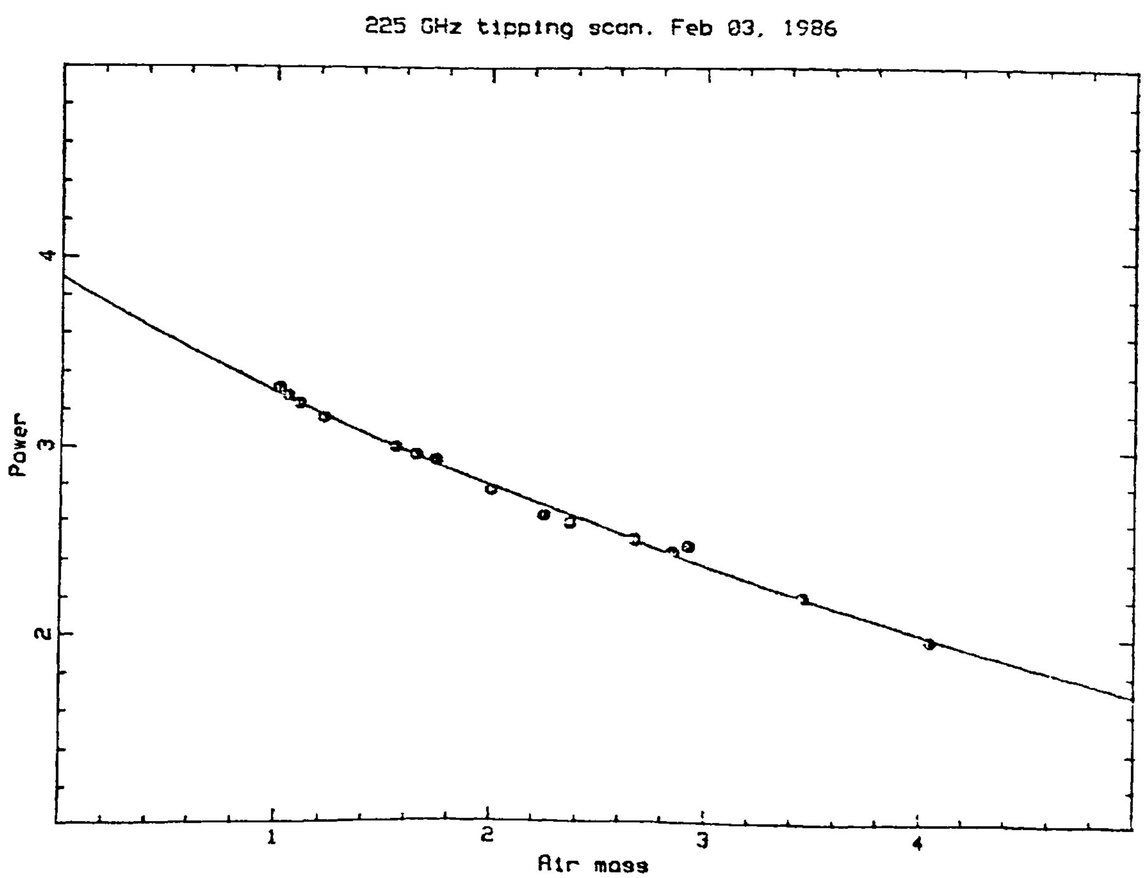

Figure 6

about four or five times what it should be, judging from the derived uncertainties of each point. More work needs to be done here.

The increase of τ with time was certainly due to a front moving in. The ambient temperature was 4.5 C and the sky was clear and (subjectively seemed) dry at the start.

IV. Conclusion (?)

The array provides consistent results at 22.25 GHz. I found that the corrections discussed in §II lowered the dispersion of the opacities derived from the various antennas but did not modify the average values significantly.

The tipping radiometer needs further testing. Thermal regulation of the electronics would surely help and is highly desirable if it is going to be used to monitor (remote) sites unattended. If used at the VLA, it should be periodically checked.

The uncertainty in the extrapolation of K-band opacities from those at 225 GHz needs to be investigated by simultaneous measurements the way I attempted with the November observations. This would be very useful to observers if a clear correlation emerges.