VLA SCIENTIFIC MEMORANDUM NO. 143

CORRECTION OF VLA K-BAND AMPLITUDES FOR ATMOSPHERIC ATTENUATION

Steven R. Spangler

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ABSTRACT

A method for correcting VLA K-band (22.5 GHz) amplitudes for the effect of atmospheric attenuation (extinction) is discussed. Use is made of the well-known "tipping scan" or atmospheric emission method. Procedures and software for acquisition and reduction of the data are discussed.

I. INTRODUCTION

As the VLA observes a source at progressively lower elevation angles, two effects produce an apparent drop in fringe amplitude: (1) an increased system temperature, and (2) increased absorption by the atmosphere. Both effects are due to the fact that the line of sight to the source traverses a greater distance through the atmosphere, and both will be especially acute at the VLA K-band (22.5 GHz), which is at the center of the atmospheric water vapor line. A potential additional effect is the elevation-dependence of the forward gain of the antennas, which may become significant at K-band. We will not, however, further discuss this last effect.

Until recently, neither of the two aforementioned effects were corrected for in standard VLA data reduction. The effect of elevated system temperature is now (as of July 21, 1982) compensated for by applying system temperature corrections online. Correcting for attenuation is not as straightforward and comprises the subject of this memo.

At the outset, it should be stressed that the method described in this memo represents a first order attempt to monitor and correct for the effects of atmospheric attenuation. The approach used is not particularly elegant from an experimental standpoint, and a number of simplifying assumptions are made which are probably not valid. These assumptions are discussed below. It is hoped that the procedures discussed in this report will remove most of the effects of atmospheric attenuation and furnish a significant improvement over what would be obtained if no corrections at all were made.

The main reason for encouraging a VLA observer to make extinction measurements at the time of K-band observations is the fact that atmospheric attenuation at this frequency is highly variable. The dominant source of opacity at wavelengths of about 1 cm is atmospheric water vapor. The water vapor content at a given site can obviously change drastically from one observing session to another, or even within a session. This variability is confirmed by the observations presented below and nullifies the practice of making "secant z" corrections with a global coefficient. Atmospheric attenuation will be of particular importance to programs which: (a) are intended to monitor source variability; (b) will involve comparison of K-band maps with those made at other frequencies; and (c) have calibrator and program source separated by a substantial angular distance, as will typically be the case at K-band.

II. THE ATMOSPHERIC EMISSION METHOD OF DETERMINING EXTINCTION

The atmospheric-emission method of determining attenuation is described by Kuz'min and Salomonovich in the book "Radioastronomical Methods of Antenna Meassurement." We assume the system temperature is comprised of contributions from the receiver and the sky,

$$T_{sys} = T_0 + T_{ma} \left\{1-\exp(-t)\right\} \tag{1}$$

In equation (1), T_{sys} is the measured system temperature, T_0 is the receiver temperature (or equivalently the in vacuo system temperature), T_{ma} is the temperature of the layer responsible for the emission and absorption, and t is the optical depth. The optical depth is given by:

$$t = \int_0^\infty k dl \tag{2}$$

where k is the absorption coefficient. If we assume that the absorbing layer is a plane-parallel slab, then

$$t = \langle k\rangle H \text{ secant}(z), \tag{3}$$

where $\langle k\rangle$ is the mean absorption coefficient, H is the thickness of the layer, and z is the zenith angle of the observation. In general, the term $\langle k\rangle$ H should be written as,

$$\langle k\rangle H = \sum_i \langle k\rangle_i H_i, \tag{4}$$

the sum being over all species contributing to the absorption and emission. Kuz'min and Salmonovich indicate that the two principal contributors to (4) are oxygen and water vapor, with the latter being dominant. We can define $\Gamma_0 = \langle k \rangle H$, and with x = secant(z), equation (1) becomes,

$$T_{sys} = T_0 + T_{ma} [\Gamma x - \frac{1}{2} \Gamma^2 x^2] \quad (5)$$

correct to second order in the optical depth. Given measurements of the system temperature at a number of zenith angles and an estimate of the temperature T_{ma}, equation (5) can be used to determine two free parameters; T_0, the receiver temperature or system temperature in vacuo, and the extinction coefficient. Given a determination of the extinction coefficient, K-band amplitudes can be corrected for the effect of atmospheric extinction. The ratio of the observed amplitude A, to that which would be observed above the Earth's atmosphere, A_0, is given by:

$$A/A_0 = \exp [- \Gamma x] \ . \quad (6)$$

III. CAVEATS REGARDING THE TECHNIQUE

Before proceeding to a discussion of the acquisition and reduction of tipping scan data, it is worthwhile to mention some warnings regarding the method used. Two topics deserve attention.

(a) Antenna Spillover. In equation (1) it is explicitly assumed that the system temperature is due to (i) the constant receiver temperature and (ii) emission in the telescope beam along the line of sight. In reality there will be a third contribution, that of antenna spillover due to the feed illuminating the ground beyond the reflector edge and also power scattered from the feed support legs, etc. If this spillover contribution to the system temperature does not depend on zenith angle, then it is of no concern; it will be absorbed into T_0. This, however, is not expected to be the case. The contribution due to the feed illuminating ground beyond the edge of the dish will be a maximum when the antenna is pointed at the zenith, and a minimum when the telescope is pointed at the horizon. The magnitude of this contribution will clearly depend on how the antenna is illuminated; rough estimates indicate a temperature difference of 7 - 10 K will occur between zenith and horizon. As will be seen below, this is far less than the observed system temperature changes, fostering hope that the resultant errors will be small. Furthermore, the system temperature increment due to spillover decreases with decreasing elevation angle, i.e., in the opposite sense to that of atmospheric emission. The result should be an underestimate of the extinction coefficient.

(b) Errors in Noise Tube Values. To obtain T_0 and Γ_0 from the measurements, one must specify the temperature of the absorbing layer, T_{ma}. This is obtained from VLA weather station data. The system temperatures are computed using the "known" values of the noise tubes. If there are errors in these values, then there will be different temperature scales for the atmosphere and the receiver. The radiometry will subsequently be in error, as will be the determination of the extinction coefficient. It is to be hoped that recognition of this point will motivate improved determination of noise tube values.

IV. ACQUISITION AND REDUCTION OF TIPPING SCAN DATA

A computer program has been developed to perform a least-squares fit of eq. (5) to data consisting of system temperature measurements at a number of zenith angles.

(a) Acquisition of Data. Instructions for making a tipping scan, and a form for recording the data may be found in the file EXTINC.INS in the author's area on the VLA DEC-10 computer. To obtain your own copy, type the following while in the DEC-10 monitor state:

```
COPY EXTINC.INS[13,#]←EXTINC.INS[13,56]
PRINT EXTINC.INS
```

where # is your programmer number. This set of commands will copy the file over and print it out for you.

The instructions are reasonably self-explanatory and should require little comment. However, a couple of points are worth mentioning. First of all, the reduction program (to be described below) expects the input data to be raw voltages corresponding to the noise tube and total power signals, not the system temperatures themselves. The program will convert these raw numbers to system temperatures. The data requested by the program are the following "DCS monitor point values"; 1:000 (cal value, A IF), 1:001 (total power, A IF), 1:020 (cal value, C IF), 1:021 (total power, C IF). These data may either be read from a DCS data tap, or recorded by the operator. In addition to these data, you will need to know the noise tube values for the A and C IF's. These may be found in the "Front End Status Book" maintained in the Control Room. Ask the operator for assistance. The system temperature is related to the aforementioned data by the following formula:

$$T_{sys} = 15\ (V_{tp}/V_{cal})\ T_{cal}. \qquad (7)$$

Here V_{tp} is the voltage corresponding to total power (monitor points 1:001 or 1:021), V_{cal} is the voltage corresponding to the noise tube (monitor points 1:000 or 1:020), and T_{cal} is the noise tube value.

The second point regards the number of elevation angles at which measurements should be made. The practice of the author has been to make measurements at 13 positions from 60 degrees to 10 degrees elevation, including a descending as well as ascending scan. This practice allows one to compare the consistency of the ascending and descending measurements. However, fewer measurements would almost certainly be adequate, provided that a range of "airmasses" were sampled.

(b) Reduction of Data. A program has been developed to take the raw data, convert the DCS readings to system temperatures, and produce a least-squares fit of equation (5) to the data. The program will return the following information; (i) for each IF, the extinction coefficient and in vacuo system temperature, (ii) a comparison of the observed system temperatures with those given by the model (5), and (iii) the atmospheric transmission coefficient (reciprocal of factor by which amplitudes are to be corrected) at each of the zenith angles at which measurements were made.

The program may be run from any DEC-10 terminal, and prompts the user for the necessary input data. To begin with, copy the program into your area with the command

COPY TIP.F4[13,#] ← TIP.F4[13,56].

To run the program, type 'EXECUTE TIP.F4'. The program will begin to run and will prompt the user for the input data it needs. Figure 1 shows an example of the input format typed on the screen by the program and (framed by lines) the user response. It should be noted that the program does not accept free format; numbers must be in the columns indicated by the 'X' characters. The first line of input parameters are for the wavelength of observation, date, and time of measurement. These numbers are used only for bookkeeping purposes and are not used in any computation. The second line is for the noise tube values in the A and C channels, the air temperature (or whatever temperature one wishes to use for the absorbing layer), and the number of elevation angles at which measurements were made. The third set of input contains the actual data, with one line for each data point on the tipping scan. The first number in each line is the elevation angle at which the measurement was made. The next two numbers are the A channel cal and A channel total power signals (DCS monitor points 1:000 and 1:001), respectively. The fourth and fifth numbers are the same quantities, but for the C channel (DCS monitor points 1:020 and 1:021). After each line, strike the return key and proceed to enter the next line. When you have entered the number of measurements previously specified, the program will print the message "DATA INPUT COMPLETE" and proceed with execution.

Figure 2 displays the output produced by the program. This page will be produced on both the user's terminal screen and the DEC-10 line printer. The first two lines merely echo the information regarding date, cal strengths, etc. The section titled "Summary of Fit" presents the information of greatest interest, which is the two parameters determined from the least-squares fit. For each IF, we have the receiver temperature (in vacuo system temperature) and the extinction coefficient Γ_o ("GAMMA(1)"). While the system temperatures in the two channels may, of course, be quite different, one should expect the extinction coefficients to be in good agreement.

Further information of interest is contained in the section "Data and Model Fits". The first two columns give, respectively, the elevation angles and airmasses (secant(z)) at which measurements were made. Column 3 lists the observed system temperatures for the A channel, and column 4 gives the model system temperature from equation (5), given the least-squares fit parameters. Column 5 gives the atmospheric transmission coefficient. Columns 6-9 give the same information as 3-5, but refer to results from the C channel data.

V. RESULTS

Seventeen observations of the type described above were made at the VLA site in the period Oct. 03, 1981 to May 21, 1982. More data are in the process of being gathered, but will not be discussed in this memo. Figure 3 shows some sample observations. The Nov. 17, 1981 and Jan. 25, 1982 measurements were made during clear-sky conditions. These observations are characterized by good agreement between the ascending and descending measurements, and relatively low values for the extinction coefficient. The Oct. 03, 1981 and May 21, 1982 observations were made during the period following a thunderstorm, and partly cloudy conditions, respectively. These observations are characterized by high extinction coefficients, discernable differences between ascending and descending measurements, and "structure" in the T_{sys}-secant(z) relationship.

Most measurements were made using antenna 9, which possesses a K-band maser receiver. The receiver temperature for this antenna is perhaps a factor of 3-4 less than that of the other antennas in the array. However, as noted in Section III-b above, errors in noise tube values can lead to systematic errors in the parameters resulting from the data analysis. It appears possible that such a situation exists in the case of antenna 9. Measurements of the noise tube values in September 1981 yielded values of 9.60 and 9.90 K for the A and C channels, respectively. At the author's request, the noise tubes were remeasured in Dec. 1981 and found to be 12.4 and 11.9 K, respectively. It seems curious that such a change would have occurred in so short a time, and may indicate that the differences in these values are of the order of the measurement uncertainty. Accordingly, all antenna 9 data have been reduced with both sets of cal values.

Possibly as a result of errors in the adopted cal strengths, the receiver temperature T_0 occasionally appears to vary with changing Γ_0. This has been noticed when more than one measurement has been made in a given session. This, of course, is unphysical, and points to phenomena not considered in Section II. Observations on Oct. 03, 1981, when the extinction coefficient changed markedly during the observing session, suggested that this effect was less pronounced when Sept. 1981 cal strengths were adopted. This indicates that temperature scale errors may be responsible, but other effects, such as spillover contributions, cannot be dismissed.

A histogram of observed extinction coefficients determined for the VLA site are shown in Figures 4 and 5 for the two different sets of antenna 9 cal values. Measurements are differentiated on the basis of prevailing meteorological conditions. One may draw a number of conclusions from the results of Figures 4 and 5. (1) There is a great range of K-band extinction conditions encountered at the VLA site. (2) There appears to be a qualitative relationship between the value of the extinction coefficient and meteorological conditions. As expected the extinction coefficient is higher during cloudy periods or when there is precipitation. (3) Under clear conditions, the extinction coefficient is typically in the range 0.05 -0.12.

Figure 6 indicates the implications of these results for astronomical observations. The K-band atmospheric transmission coefficient is plotted as a function of airmass (or, equivalently, elevation angle) for a number of values of the extinction coefficient.

J. Moran (private communication) has suggested that the observed extinction coefficients at the VLA site are higher than one would expect given the low humidity. Moran and Rosen (1981, Radio Science, 16, 235) and S.G. Mango (unpublished NRL report) have found that for the East Coast, a linear relationship exists between the K-band extinction coefficient and the absolute humidity. Moran contends that his measurements fall well above the empirical curve established for the East Coast.

Given this report, one should naturally be concerned about the integrity of the measurements made, as described in this memo, with a VLA antenna as opposed to, for example, a horn antenna. Could spill-over effects, etc., be conspiring to make the observations yield a spuriously high extinction coefficient? To investigate this possibility, data from the VLA 20.7-GHz water vapor radiometers were examined. These instruments have the advantage of possessing well-calibrated receivers. Although these measurements were not simultaneous with tipping scan observations, they are consistent (given consideration of the frequency difference) with atmospheric extinction of the magnitude reported in this memo.

While the question of the dependence of the extinction coefficient on absolute humidity merits further investigation, a more directly relevant concern is the magnitude of the extinction coefficient. Mango's results show that for clear-sky conditions at the Maryland Point Observatory, the 19.4 GHz extinction coefficient is typically in the range 0.04 -0.12, i.e., close to that of the VLA site at 22.5 GHz. If, as is expected, the opacity is primarily due to water vapor, the extinction coefficient at 22.5 GHz should exceed that at 19.4 GHz by a factor of 2 - 2.5, indicating that the VLA site is superior as regards atmospheric transparency by the same factor.

```
execute tip.f4
LINK:    Loading
[LNKXCT TIP execution]
```

INPUT PARAMETERS

BAND	DATE	IAT
XX.X	XXXXXX	XXXX
1.3	051282	1034

A CAL	C CAL	TEMP	NPTS
XX.XX	XX.XX	XXX.X	XX
9.60	9.90	279.4	13

***** INPUT DATA FROM DCS ******

	****A	IF***	***C	IF****
ANGLE	CAL	TP	CAL	TP
XX.X	X.XXX	X.XXX	X.XXX	X.XXX
60.0	2.800	2.965	3.335	2.990
40.0	2.690	2.965	3.390	3.020
30.0	2.570	2.970	3.020	2.985
25.0	2.510	2.965	2.935	2.985
20.0	2.450	2.970	2.800	2.985
15.0	2.275	2.970	2.595	2.990
10.0	2.015	2.990	2.280	2.990
15.0	2.200	2.965	2.545	2.985
20.0	2.400	2.960	2.800	2.985
25.0	2.495	2.960	2.940	2.985
30.0	2.595	2.960	3.060	2.985
40.0	2.695	2.960	3.195	2.985
60.0	2.790	2.960	3.330	2.985

***** DATA INPUT COMPLETE ******

FIGURE 1

ANALYSIS OF EXTINCTION DATA

BAND	DATE	IAT
1.3	51282	1034

A CAL	C CAL	TEMP	NPTS
9.60	9.90	279.4	13

SUMMARY OF FIT

	A IF	***C IF***
TSYS(0am)	133.8	111.9
GAMMA(1)	.059	.063

DATA AND MODEL FITS

		*****A IF********			*****C IF********		
ANGLE	AMASS	TSYS	MODEL	ATTEN	TSYS	MODEL	ATTEN
60.0	1.15	152.5	152.3	.934	133.1	131.6	.930
40.0	1.56	158.7	158.4	.912	132.3	138.1	.906
30.0	2.00	166.4	165.0	.888	146.8	145.0	.881
25.0	2.37	170.1	170.2	.869	151.0	150.6	.861
20.0	2.92	174.6	178.0	.841	158.3	158.8	.831
15.0	3.86	188.0	190.5	.795	171.1	171.9	.783
10.0	5.76	213.7	212.9	.711	194.7	195.2	.694
15.0	3.86	194.1	190.5	.795	174.2	171.9	.783
20.0	2.92	177.6	178.0	.841	158.3	158.8	.831
25.0	2.37	170.8	170.2	.869	150.8	150.6	.861
30.0	2.00	164.3	165.0	.888	144.9	145.0	.881
40.0	1.56	158.2	158.4	.912	138.7	138.1	.906
60.0	1.15	152.8	152.3	.934	133.1	131.6	.930

END OF EXECUTION
CPU TIME: 0.37 ELAPSED TIME: 4:49.67
EXIT

FIGURE 2

VLA K BAND TIPPING SCANS

DATA AND MODEL FITS

FIGURE 3

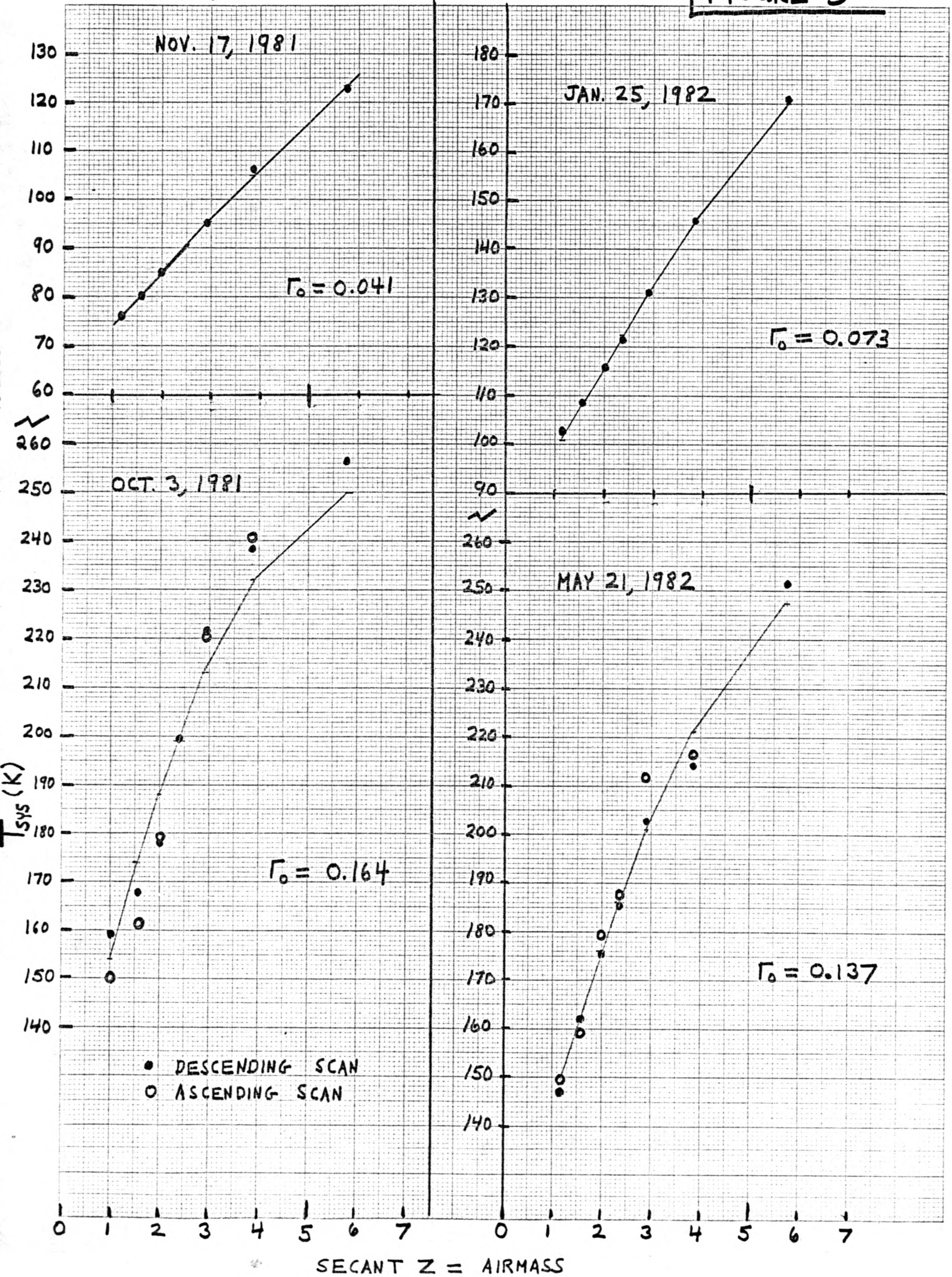


FIGURE 4

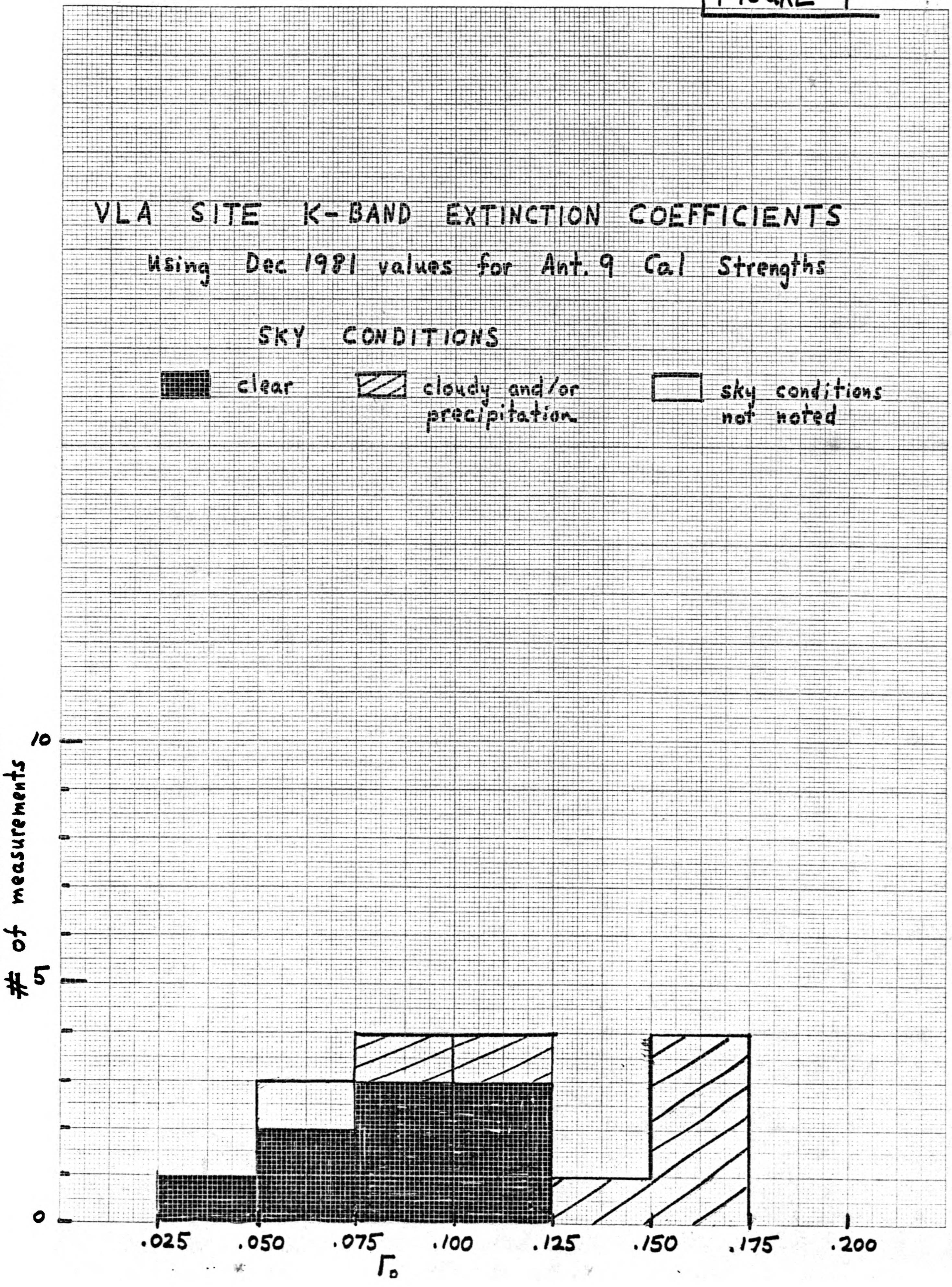
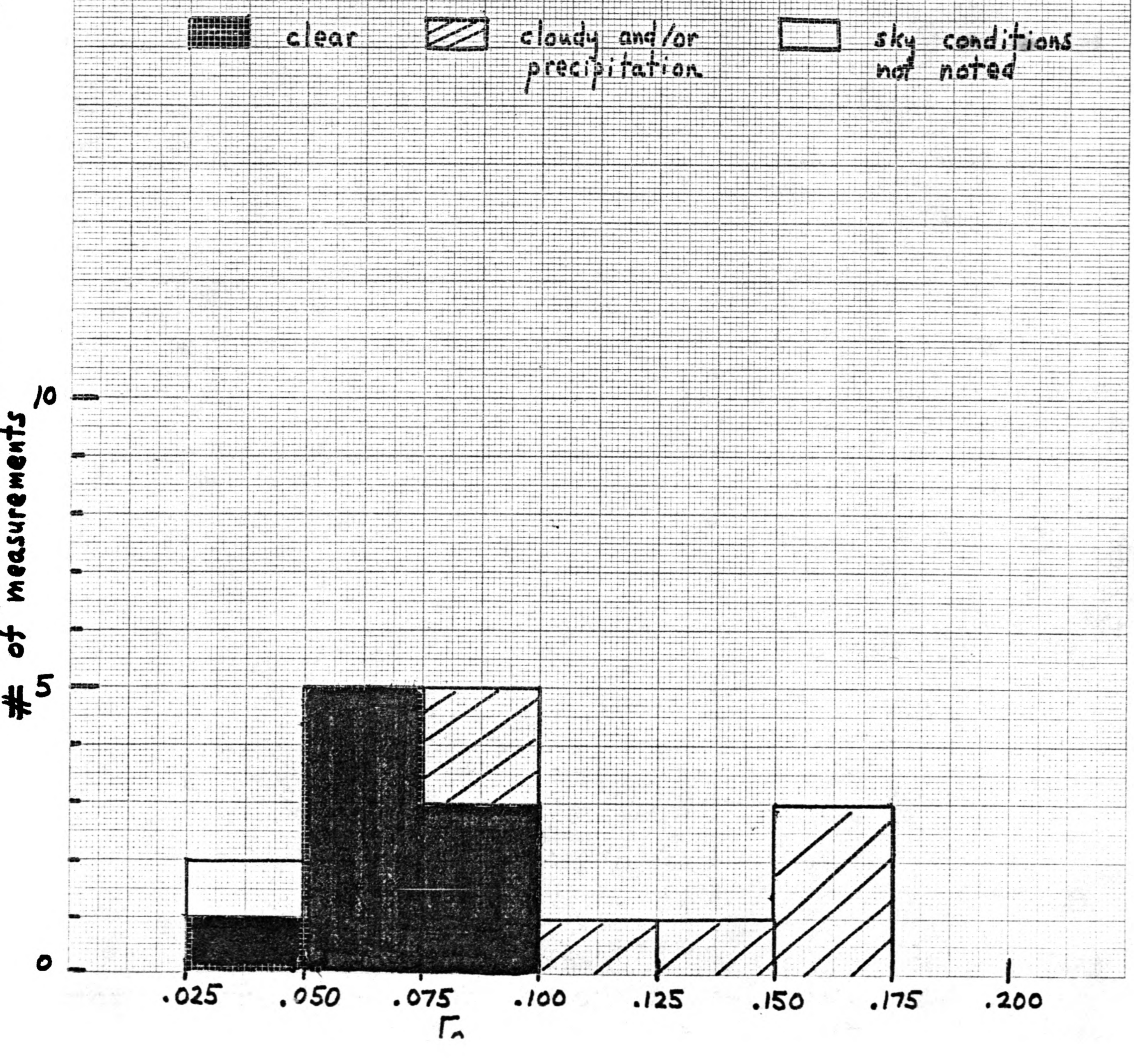

VLA SITE K-BAND EXTINCTION COEFFICIENTS
Using Dec 1981 values for Ant. 9 Cal Strengths
SKY CONDITIONS
clear
cloudy and/or precipitation
sky conditions not noted
# of measurements
10
5
0
.025
.050
.075
.100
.125
.150
.175
.200
Γ_0

FIGURE 5

VLA SITE K-BAND EXTINCTION COEFFICIENTS

Using Sept. 1981 values for Ant 9 Cal Strengths

SKY CONDITIONS



ATMOSPHERIC EXTINCTION FOR VARIOUS Γ_0

FIGURE 6.