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ATS-6 ASCENDING: NEAR HORIZON MEASUREMENTS OVER WATER AT 30 GHz

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Technical Report under Contract NAS5-22576

Prepared for

GODDARD SPACE FLIGHT CENTER

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16. Abstract The return of the ATS-6 satellite to a western longitude during the fall of 1976 presented a unique opportunity to perform low angle of elevation measurements at 30 GHz. For this purpose a receiver using a 1.5 m antenna was set up at Port Aransas, Texas, resulting in a propagation path entirely over water. The 30 GHz beacon was monitored daily for at least one hour from 8 September 1976 to 21 September 1976. During the time the elevation angle changed from 1.5° to 17.3°, the mean attenuation decreased from 20 dB to 2 dB and the standard deviation from over 6 dB to less than .2 dB. The deep fades at angles below 4° show significantly sharper nulls than peaks on a log scale. Spectra of the log amplitude fluctuations vary as the (-8/3) power of the spectral frequency in the limit. A flattening is noticable at the low frequencies. A precipitation event at 8.5° elevation produced a 16 dB fade and significantly increased the variance.

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SUMMARY

The return of the ATS-6 satellite to a western longitude during the fall of 1976 presented a unique opportunity to perform low angle of elevation measurements at 30 GHz. For this purpose a receiver using a 1.5 m antenna was set up at Port Aransas, Texas, resulting in a propagation path entirely over water. The 30 GHz beacon was monitored daily for at least one hour from 8 September 1976 to 21 September 1976. During the time the elevation angle changed from 1.5° to 17.3°, the mean attenuation decreased from 20 dB to 2 dB and the standard deviation from over 6 dB to less than .2 dB. The deep fades at angles below 4° show significantly sharper nulls than peaks on a log scale. Spectra of the log amplitude fluctuations vary as the (-8/3) power of the spectral frequency in the limit. A flattening is noticable at the low frequencies. A precipitation event at 8.5° elevation produced a 16 dB fade and significantly increased the variance.

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1 - INTRODUCTION

Satellite-earth communication systems at millimeter wave frequencies are a growing reality. At angles of elevation above 15° their reliability is limited mainly by rain attenuation. Several experiments have been completed (ATS5, ATS6) or are in progress (CTS, COMSTAR) to quantify this. At lower angles of elevation, however, signal fluctuations caused by atmospheric inhomogeneities, stratifications or ducting or other interactions are a limitation for link reliability. Not many data are available for this case. Most data at low elevation angles have been taken on line-of-sight links. Of these the closest to a satellite-ground link was one having an elevation angle of 2.4° and a 64 km path length. Measurements of amplitude and phase at several frequencies up to 33.33 GHz over this path have been reported by Janes et al. [1970] and by Thompson et al. [1975]. Contributions to the theoretical understanding of some of the observed results were made by Ishimaru [1972]. Their applicability seems to be restricted to weaker interactions of the propagating wave with the atmosphere than were typically observed at the lower elevation angles in the experiment reported here.

Starting 1 August 1976 the ATS-6 satellite was moved from 35°E to 130°W longitude. During transfer the spacecraft drifted in a near geosynchronous orbit at a rate of about 1.4 degrees per day in a westerly direction. In transit the 30 GHz beacon transmitter on board could be activated and its output directed through a parbolic antenna with a 2° beamwidth towards a requesting earth receiving station. This created a unique opportunity to perform low angle of elevation propagation measurements while the satellite ascended above the horizon.

2 - MEASUREMENTS

In order to provide data on the signal amplitude and the spectrum of its fluctuations a 30 GHz receiver was set up at Port Aransas, Texas. This site with 97.04°W longitude and 27.83°N latitude is at the coast of the Gulf of Mexico. A steerable 1.5 m parabolic antenna with prime focus feed in vertical polarization and with a measured 3 dB beamwidth of .47° was placed at an altitude of 13 m above sea level and 450 m from the beach. The signal path, therefore, extended almost entirely over water. The coherent receiver maintained phase lock with the 30 GHz beacon to a signal level of about 35 dB below the maximum recorded signal. The logarithmic amplitude of the received signal was recorded on analog magnetic tape. (Stored for future use.)

The 30 GHz beacon was monitored daily for one hour or more from 8 September to 21 September 1976. During that time the elevation angle, measured relative to the geometric horizon, changed from 1.5° to 17.3°. For a total of 59 representative samples, each 204.8 seconds long and digitized at a 10 Hz rate, some statistical parameters were determined. The 3.36 hours of data analyzed represent about 15% of the recorded data. The daily number of samples was decreased from 7 at the lower elevation angles to 3 at the higher ones, spaced approximately equally through the observation period.

All data were taken during daylight between 1000 and 1700 hours local time. Sky conditions were predominantly partly cloudy. Occasionally rain squalls moved through the signal path. All data reduced, with one noted exception, are for periods when no precipitation was observed falling in the signal path. Air and water temperature stayed close to 30°C. The wind was blowing from the water at an average speed of 16 km/hr with the exception of the 3rd and 4th day of observations, when a weak front changed its direction to northerly.

For each elevation angle an 18 minute sample of the recorded log-amplitude data is reproduced in Figs. 1 and 2. All traces have identical scales.

3 - RESULTS

To find the mean of the attenuation a small correction had to be made. Due to the changing polarization match between satellite and receiver the signal coupled into the feed increased by .65 dB over the 2 weeks of observations. Since the attenuation is at least partly due to water vapor and oxygen absorption it was thought to be useful to present the data dependent on the number of air masses rather than the elevation angle. A simplification was made by modelling the zenith attenuation as evenly distributed over a height up to 9 km. This tends to somewhat underestimate the number of air masses at the very low elevation angles where relatively more of the path is through denser atmosphere.

Table 1 gives the elevation angles at which observations were made, the polarization correction factor and the number of air masses. The adjusted mean attenuations are plotted in Fig. 3 versus air masses. Each point represents one sample. The line in the plot is the result of a linear regression. With the mean attenuation at 90° elevation arbitrarily taken as .8 dB the relation is

Mean attenuation (dB) = .8 x Air masses

The spread of the points is an indication of slow variations present in the mean signal level.

The theoretical zenith attenuation due to water vapor at 30 GHz is 4×10^{-5} kg^{-1} m^{3} [Crane, 1971]. The measured slope, therefore, corresponds to a liquid water content 18×10^{-3} kg m^{-3} with .08 dB the zenith attenuation attributed to oxygen. During the experiment no measurements of humidity were made, however the calculated value is a reasonable one for the Gulf coast of Texas during the summer.

The standard deviation of the attenuation also changes from sample to sample at each elevation angle. This is demonstrated in Fig. 4 which shows it as a function of air masses. The standard deviation increases with increasing air mass. Some levelling off, however, seems to be indicated above 14 air masses (below ~4°). The averages of the standard deviation for the lowest three elevation angles are within .75 dB. It should be noted that the strong increase between 11 and 14 air masses does not coincide with a significant change in the observed weather parameters. The possibility of

TABLE 1

Correction Factors Applied to Calculated Means

of the Logarithmic Amplitude

Elevation angle Degrees	Polarization dB	Air Masses
1.5	.65	23.4
2.4	.6	18.3
3.5	.55	14.1
4.9	.5	10.8
5.9	.45	9.2
7.1	.4	7.8
8.5	.35	6.6
9.8	.3	5.8
11.2	.25	5.1
12.2	.2	4.7
13.6	.15	4.2
15.0	.1	3.8
17.3	.0	3.3

different fluctuation mechanisms below and above about a 5° angle of elevation might be suggested and should be explored in future work.

The cumulative distributions of the log attenuation relative to the day's mean attenuation are shown in Figs. 5 and 6. Each curve represents one arbitrarily chosen record per elevation. Note that negative values of the ordinate represent signal levels above the mean. The abscissa has a log-normal scale. In all cases the median attenuation is below the mean attenuation, a characteristic of a fading channel.

Included is the cumulative distribution measured by Thompson et al. [1975] in Hawaii at 33.3 GHz over a 64 km path with 2.5° elevation angle. Having eliminated data samples with deep fades from their analysis a flatter distribution than the one shown for 2.4° elevation angle results. No events comparable to their "quiet" fading (with peak-to-peak variations less than 6 dB) were observed on the satellite link with the 2.4° elevation angle.

Power spectra of the log attenuation were calculated for each sample. To facilitate their comparison each spectrum was normalized by dividing by the variance of the sample, thus removing information regarding the total "power" of the variations. Therefore this quantity has been given separately for each of the power spectra in Fig. 7. In this plot typical results for 1.5°, 4.9° and 17.3° angle of elevation are shown. The peak at 2.6 Hz present in the curve for 17.3° is due to noise in the system. Also shown is a curve that varies as the (-8/3) power of the spectral frequency.

For the samples whose cumulative distributions were shown in Figs. 5 and 6 a least squares curve fit was made on the power spectra in the frequency range from about .06 to 1 Hz. The functional relationship chosen was

$$P_{NORMALIZED} = A\, f^{B}$$

because that is the relationship expected to hold on the basis of scattering theory. Assuming the refractive index covariance function to follow a -11/3 power law one would predict the log attenuation spectra to fall off as $f^{-8/3}$ for the frequency range covered. Table 2 gives the results of this curve fitting.

The data presented so far have not included fades caused by precipitation. At an elevation angle of 8.5° a rainstorm moved into the signal path causing a 16 dB increase of the mean attenuations and an increase in the standard deviation from 1.1 to 2.7 dB. The results of a curve fit to the power spectrum of the log-attenuation for four distinct path conditions are given in Table 3. During the prefade period the frequency exponent is -2.6, close to -8/3. As the convective clouds moved into the signal path the variance quadrupled and the exponent increased to -1.8, indicating higher frequency components being emphasized. During and coming out of the fade the exponent is reduced again, but not to the prefade level. It is not obvious whether this was due to the rain, considering the large variations of the frequency exponent as given in Table 2. The chart record for this event is given in Fig. 8.

TABLE 2

Results of Curve Fit $P_{NORMALIZED} = A f^{B}$

for the Normalized Power Spectrum of Log-attenuation

Elevation angle Degrees	A	B
1.5	$2.53\ 10^{-4}$	-1.65
2.4	$3.81\ 10^{-5}$	-2.00
3.5	$8.3\ 10^{-5}$	-2.09
4.9	$4.75\ 10^{-6}$	-2.71
5.9	$7.39\ 10^{-6}$	-2.61
7.1	$1.38\ 10^{-4}$	-1.92
9.8	$8.42\ 10^{-5}$	-2.18
11.2	$3.62\ 10^{-5}$	-2.53
12.2	$3.15\ 10^{-5}$	-2.75
15	$3.3\ 10^{-4}$	-1.68
17.3	$7.22\ 10^{-4}$	-1.25

TABLE 3

Signal Characteristics During a Rain Event

Elevation Angle at 8.5°

Weather	Mean dB	stdv dB	Freq. Exponent (B)
prefade	3.0	1.1	-2.56
going into fade	8.7	2.2	-1.76
maximum fade	19.3	2.7	-2.04
coming out of fade	8.7	2.1	-2.01

4 - DISCUSSION OF RESULTS

Probably the most significant aspect of the experimental data presented in this paper is the range of the elevation angles covered. Observations by the National Bureau of Standards group in Hawaii [Thompson et al., 1975] showed that the severity and character of the signal amplitude fluctuations vary greatly from day to day. Since data for each elevation angle in The University of Texas investigation were obtained on a different day, the variations due to differing atmospheric conditions tend to mask the dependence of some parameters on elevation angle. Nevertheless, some features are worthy of note even if the statistical samples are limited.

Some readily noticeable features of the records reproduced in Figs. 1 and 2 are:

a) The variance of the signal is much greater for the lowest elevation angles, decreasing rather uniformly with increasing elevation angle. This is illustrated graphically in Fig. 4 which gives a plot of standard deviation of log amplitude versus number of air masses. In this plot the severity of the fluctuations levels off somewhat for quite low elevation angles. This may well be due to changing weather conditions but might be due in part to the height of the most pronounced atmospheric anomalies. Assuming the atmosphere is spherically stratified, the angle a straight ray makes with the horizontal increases with altitude. For very small elevation angles, the ray is in a layer of given thickness a much greater distance if the layer is near ground than if it is at a considerable height. The computed number of air masses as a function of elevation angle is a weighted average of the path length in the different layers; this average is considerably less than the proportionate path length in the lowest layers and more than the proportionate path length in the higher layers. That is, if the disturbing layer is relatively high in the atmosphere, using the number of air masses traversed by the ray as the abscissa causes a plotted quantity that is proportional to the distance the ray travels in the elevated layer to level off at the lowest elevation angles. Fig. 9 illustrates this point by showing a plot of the cosecant of the angle the ray makes with the horizontal at heights of 0 and 9.0 km versus the number of air masses.

b) The depth of the fades is roughly the same for the first three records but the rapidity of the fluctuations is conspicuously less on the middle day. One would expect the fluctuation rate to be nearly proportional to the mean wind speed perpendicular to the signal path. For low look angles, if the mean wind velocity is horizontal but at the same azimuth as the satellite, the wind is mostly along the path with only a small component perpendicular to the ray. It appears that this was the case on the day the second record was made. The azimuth angle to the satellite was about 98° on this day. On the previous day the surface wind was from the SE but began to swing around as a weak front approached from the north. The wind direction was recorded as from ESE on the day in question and had rotated around to NNE by the following day. There was no significant change in the ground-level wind speed during these three days but the direction changed. By the fourth day the wind had swung back to the ENE. It seems reasonable to deduce that the rate of fluctuations on the second day was slow because the wind at that time was along the signal path.

c) When the signal fades are deep, which occurred mostly on the first three days, the log-amplitude minima are much sharper than the peak signal swings. This is quite noticeable on the signal records and is also in evidence in the cumulative distribution curves in Fig. 5 in that the high-signal ends level off but on the low-signal side the distribution curves become steeper at their ends. This feature is not discernible in the cumulative distribution curves in Fig. 6 for the days on which the signal swings were considerably less.

This sharp-minima effect is present, or at least is emphasized, because the data is recorded on a scale that is close to linear for log amplitude. This means that the mechanism in the atmosphere causing the signal fluctuations is not one in which many, many weak and uncorrelated regions along the path each modify the signal strength a little bit. If this were the case the effect of a given small region would be to modify the signal strength by a percentage or dB amount, the absolute change in signal strength thus being proportional to the signal strength at that point. This model, the one frequently assumed, leads to the prediction that a log-amplitude record would have similar increases and decreases.

The generally assumed statistical model of the refractive-index variations is one of random fluctuations from a mean profile which are locally homogeneous and isotropic. The "strength" of the fluctuations can be taken to be a function of height but the general features of the predicted effect on the traversing signal is rather insensitive to the distribution with height.

The frozen-in hypothesis is taken. That is, the refractive-index structure is assumed to be carried along at the mean wind velocity, the effect of velocity variations being considered negligible.

The three-dimensional (power) spectral density of refractive index is assumed to be of the form

$$\Phi(\vec{k}) = Au^{-n} \tag{1}$$

in which u is the magnitude of the vector wave number $\vec{k}$ and A and n are positive constants. For the Kolmogorov spectrum in the inertial sub-range $n = 11/3$ so it is expected n should be assumed to be in the neighborhood of this value.

Ishimaru [1972] and others have shown that for this refractive-index model the predicted power spectral density of the received signal is constant up to near the frequency, f_1, and then falls off as the (1 - n)-th power of the frequency for frequencies above f_1. This quantity is related to the physical parameters of the path by $\omega_1 = 2\pi f_1 = V\sqrt{2k/L}$ in which $k = 2\pi/\lambda$, L is the effective distance of the turbulent medium from the receiver, and V is the mean cross-wind speed.

Letting α denote the elevation angle of the path, for the horizontally stratified atmosphere assumed L is proportional to csc α except for quite small α when the curvature of the stratifications is significant. For the range of α encountered in the measurements reported herein, $\csc \alpha \approx \alpha^{-1}$. Thus ω_1, the angular frequency at which the break in the predicted spectral density curve occurs, is approximately proportional to $V\sqrt{\alpha}$.

Figure 10 contains averaged normalized power spectra for four different days, selected pretty much at random with those for the highest elevation angles being omitted because the fluctuations were quite small. Successive curves have been shifted one abscissa division to the right. A decided break is present in the spectra for days 9 and 10 when the elevation angle is considerably larger than for the other two days. It is supposed that a break would occur on the spectra for days 1 and 5 if they were extended to lower frequencies. The cross-wind velocity, as well as the elevation angle, would be expected to influence the frequency at which the break occurs but using ground-level wind velocity to obtain values for $V\sqrt{\alpha}$ for each day did not give a parameter that appeared to correlate with the actual break frequencies. Elevation angle seemed to be the dominant factor.

The lesser mean slope for the spectra of day 1 is no doubt due to the sharp minima which contribute excessively to the higher frequencies.

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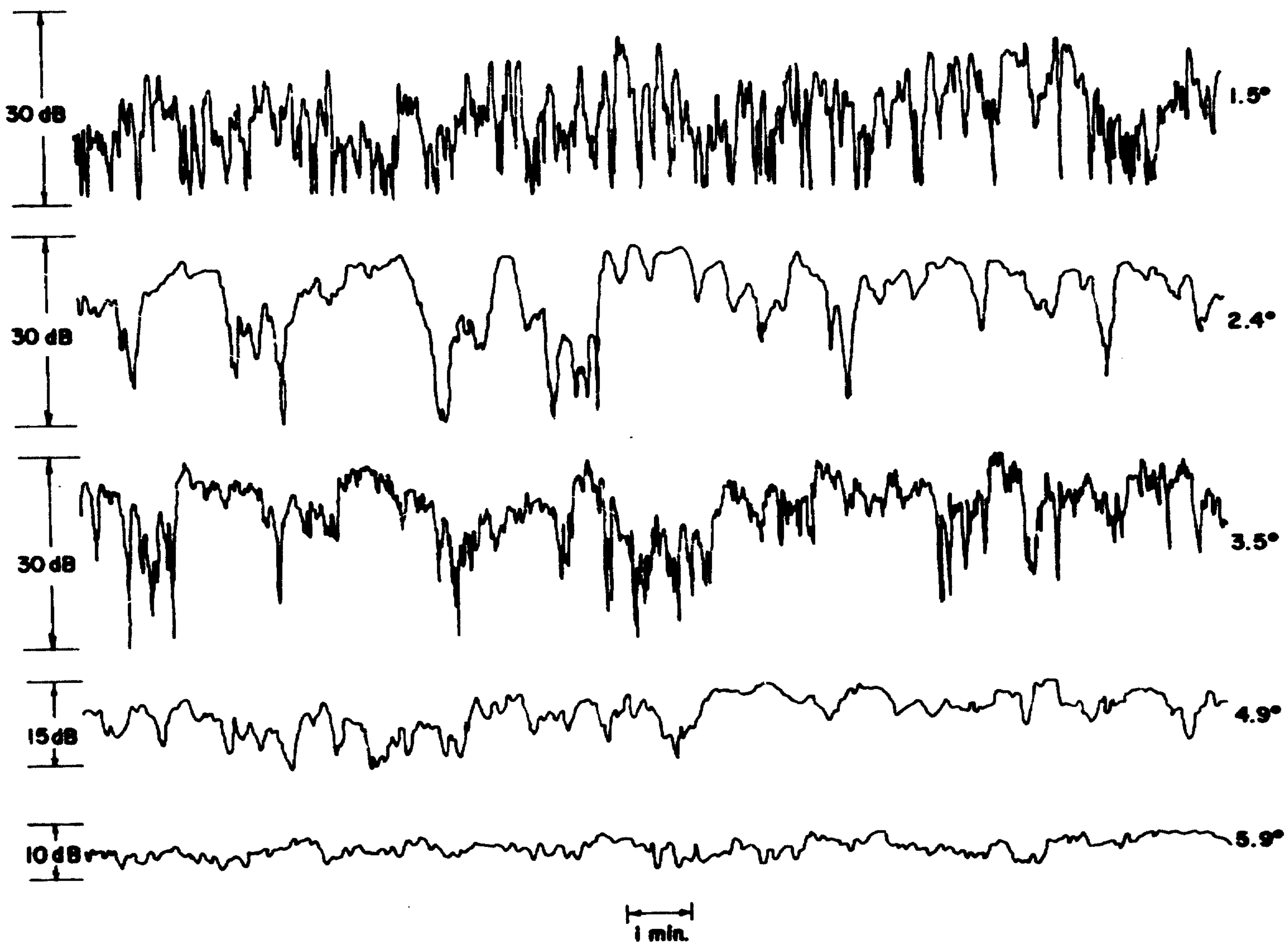

Figure 1 30 GHz log amplitude for elevation angles from 1.5 to 5.9°

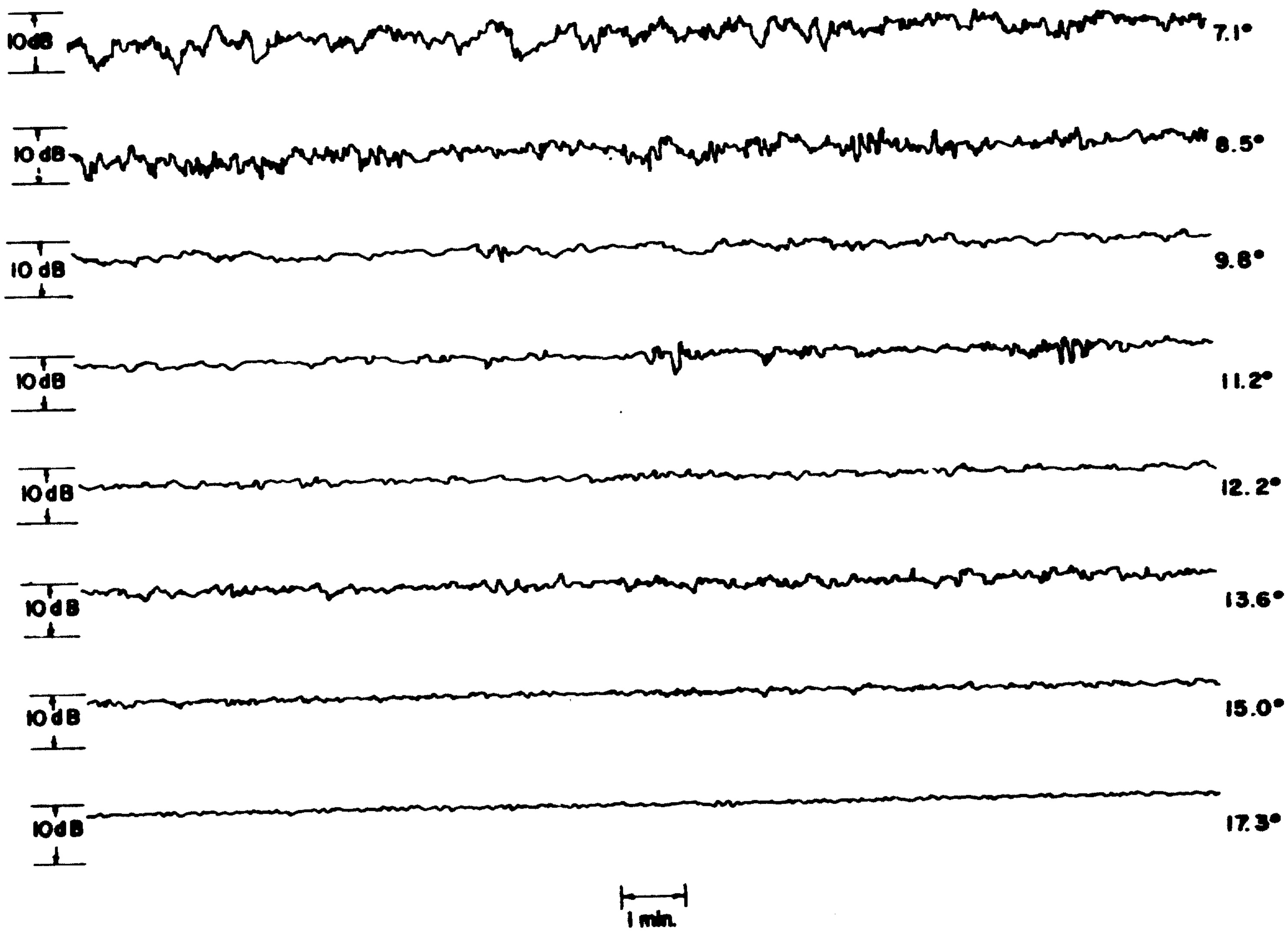

Figure 2   30 GHz log amplitude for elevation angles from 7.1° to 17.3°

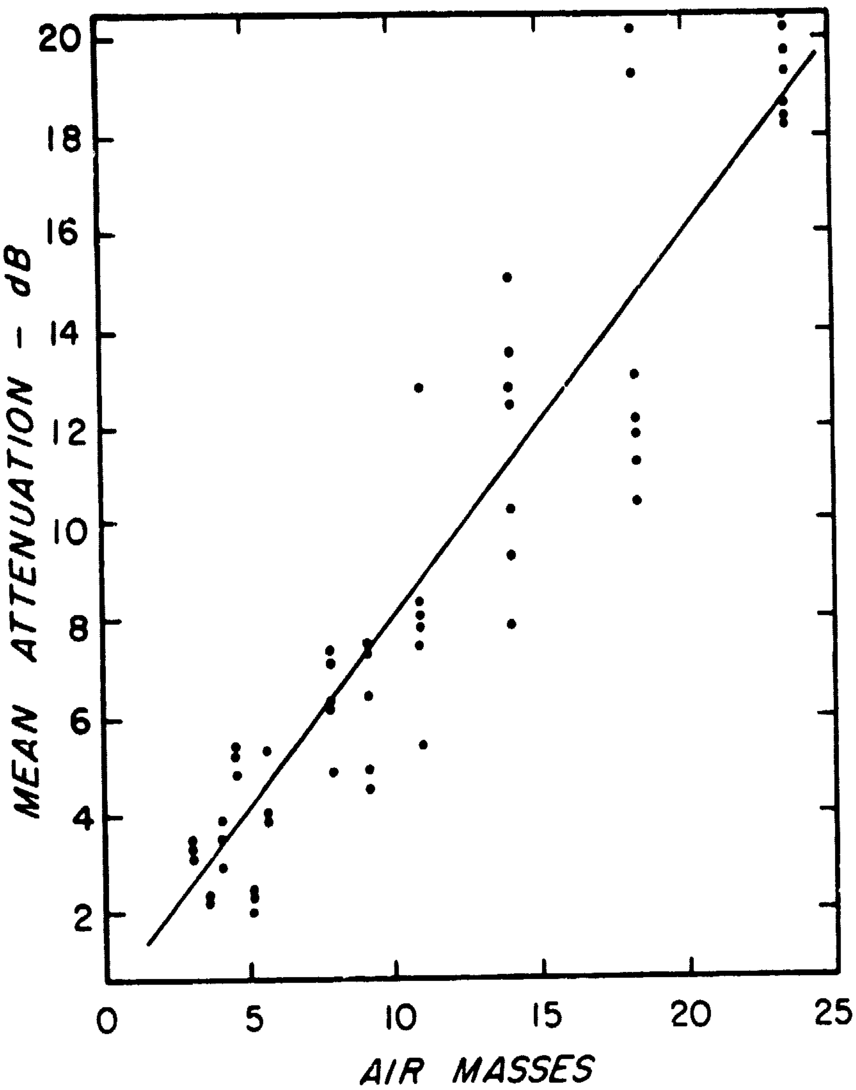

Figure 3 Mean attenuation of each sample

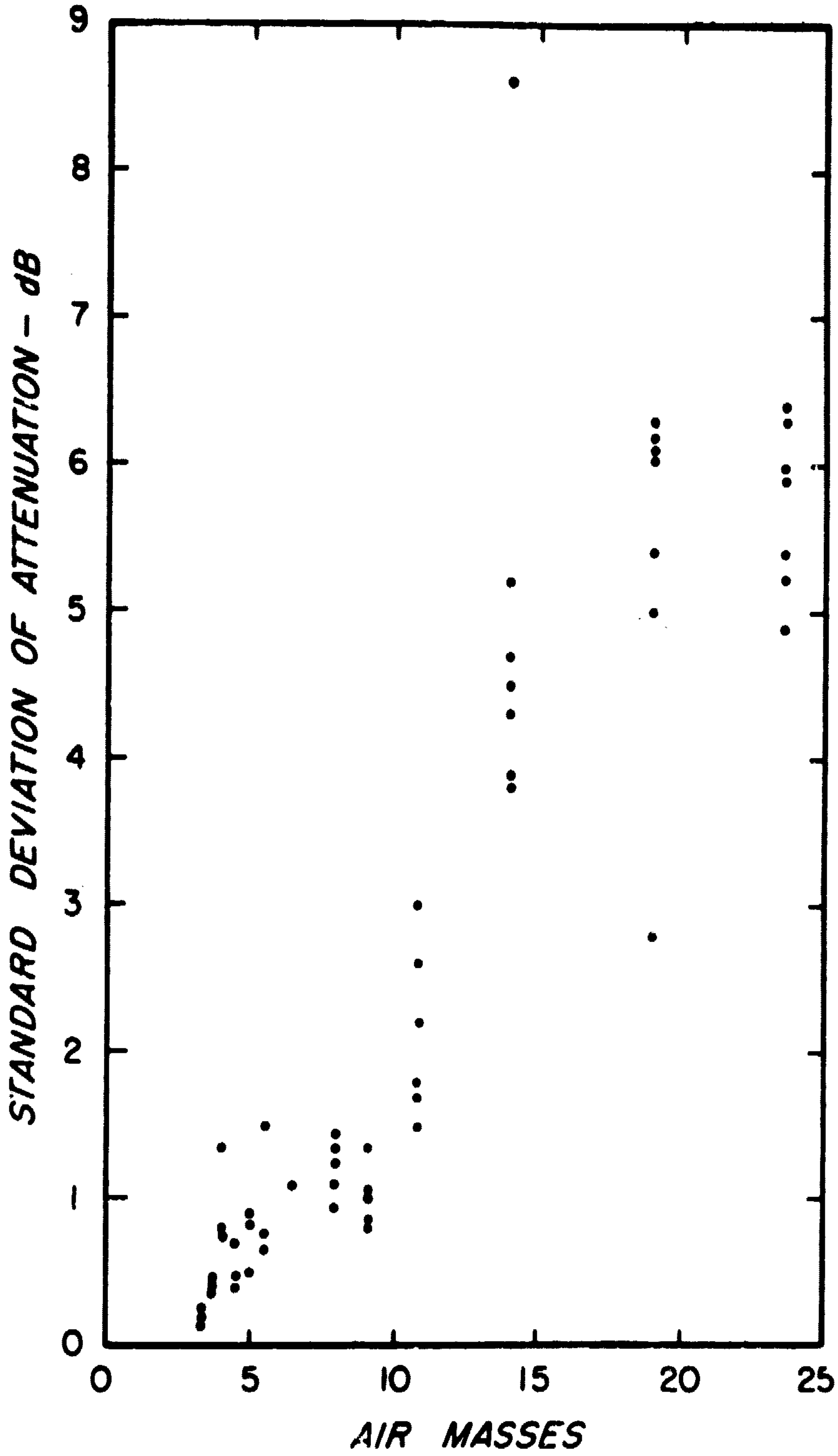

Figure 4 Standard deviation of each sample

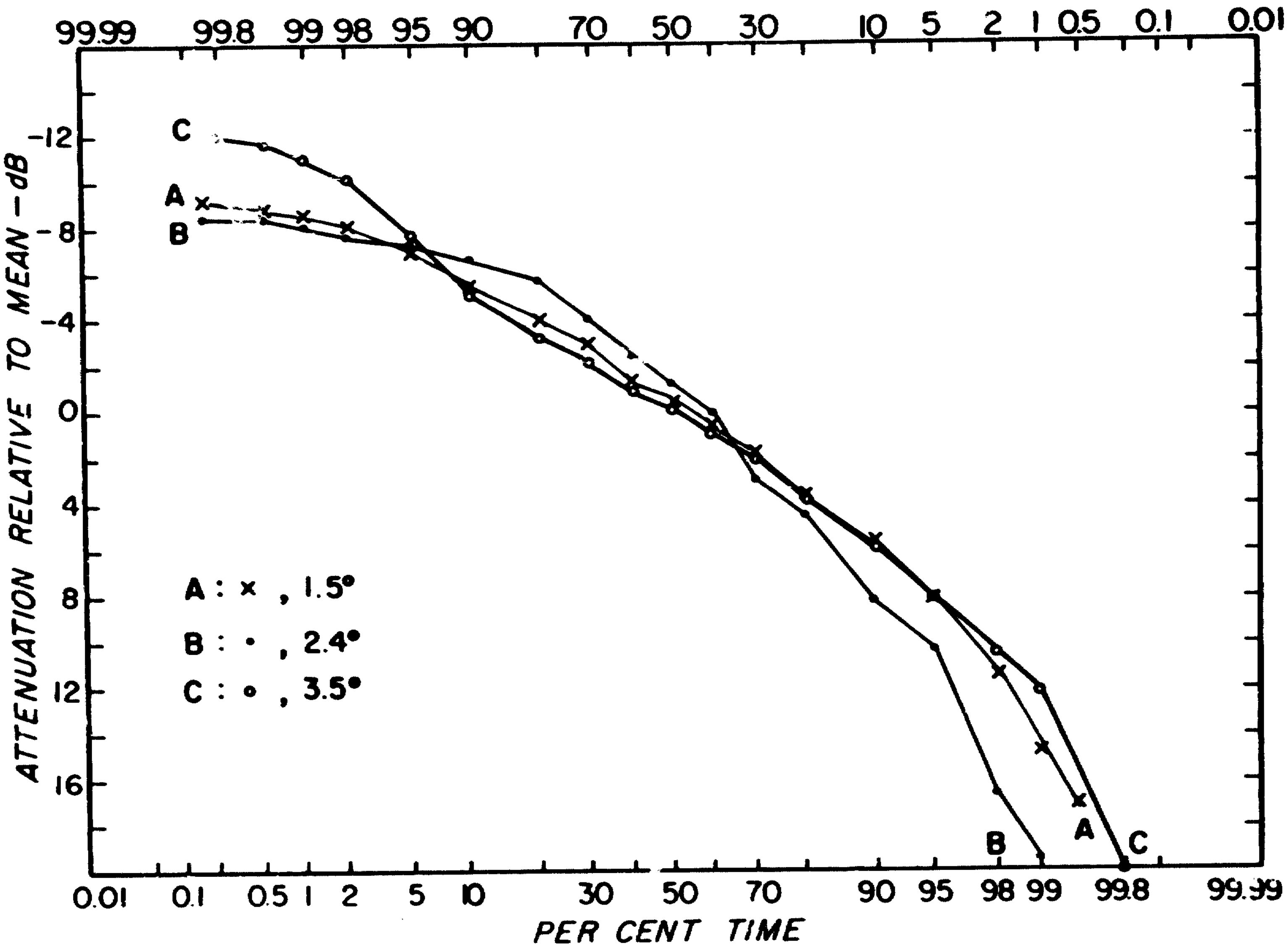

Figure 5 Cumulative distribution of signal attenuation

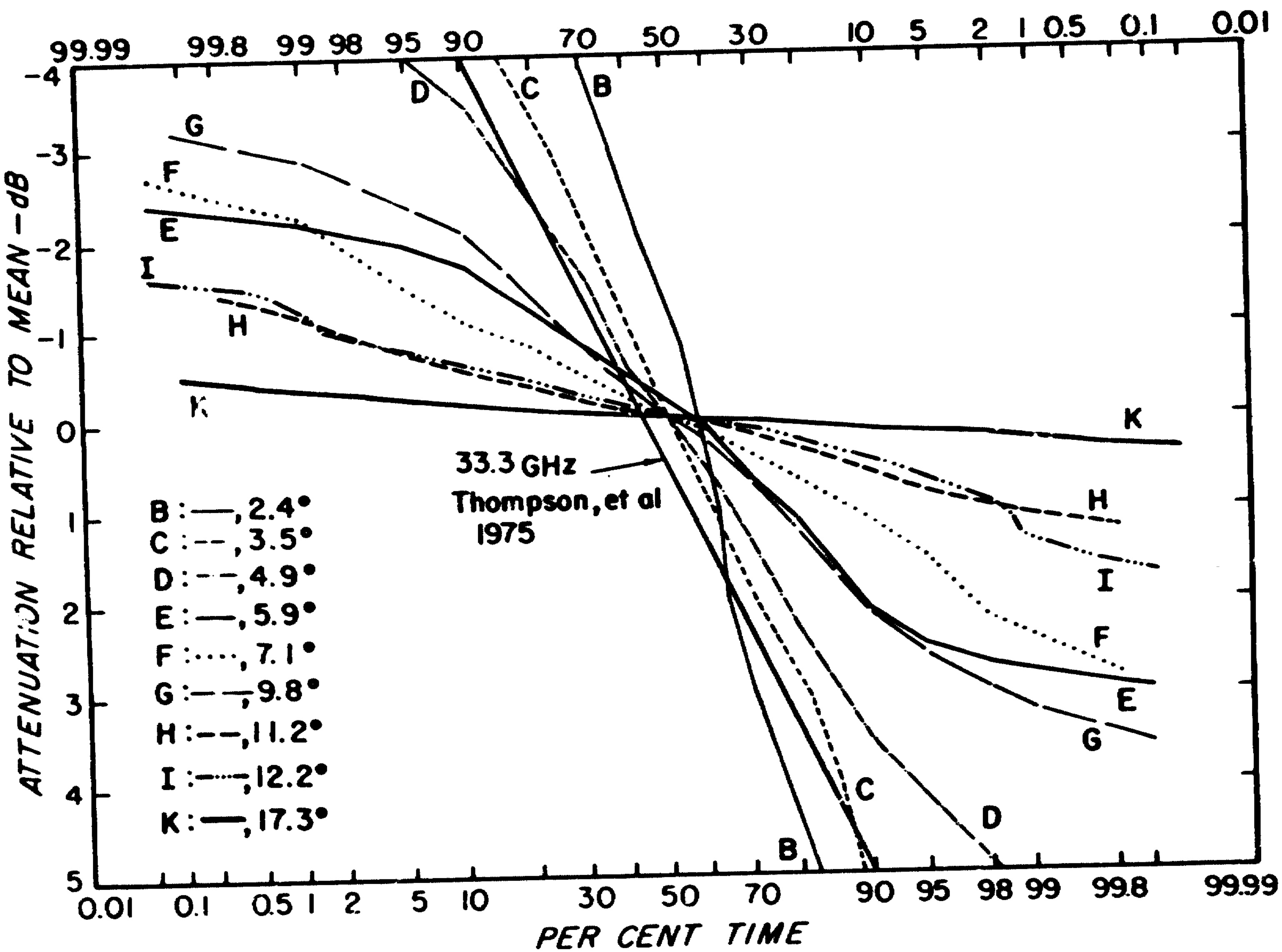

Figure 6 Cumulative distribution of signal attenuation

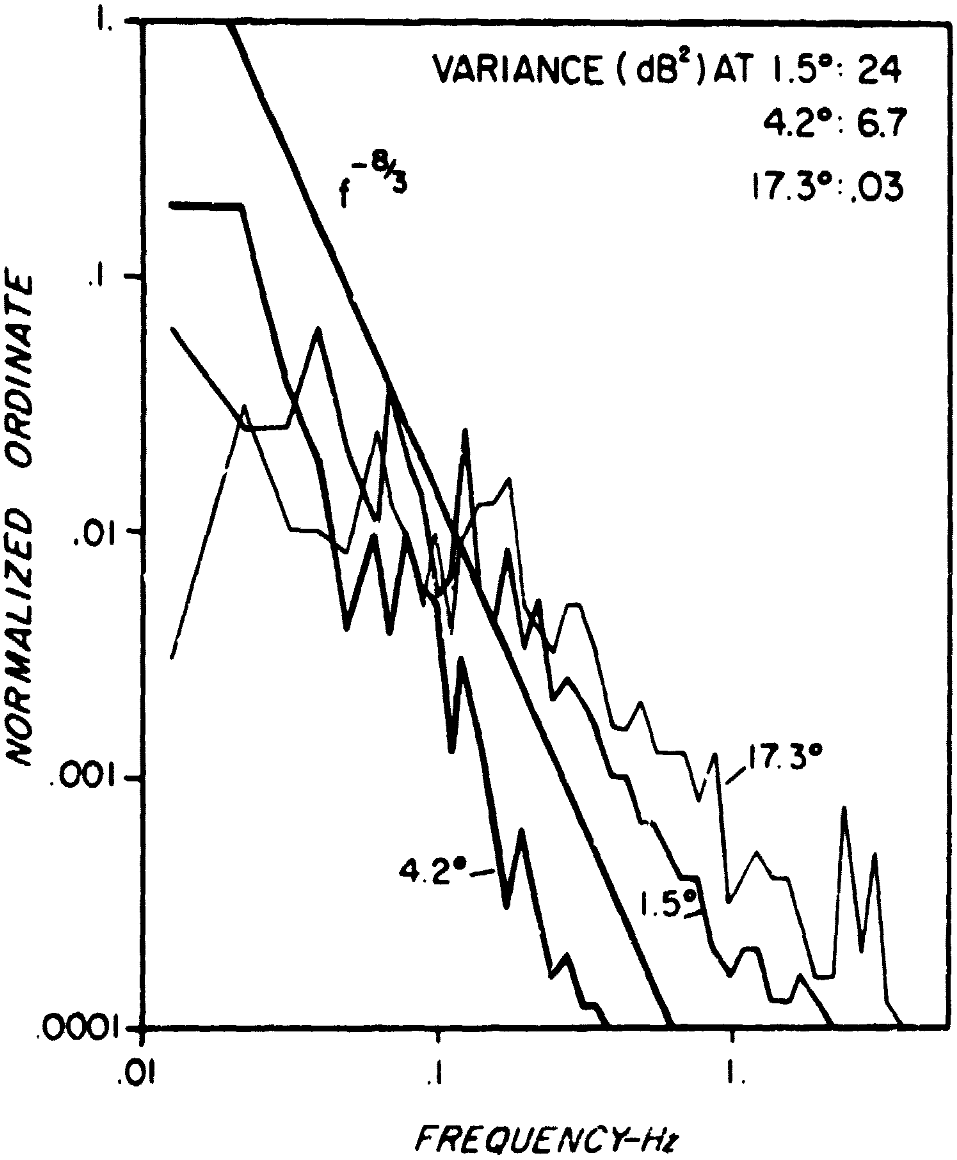

Figure 7 Typical single record power spectra of the attenuation fluctuations

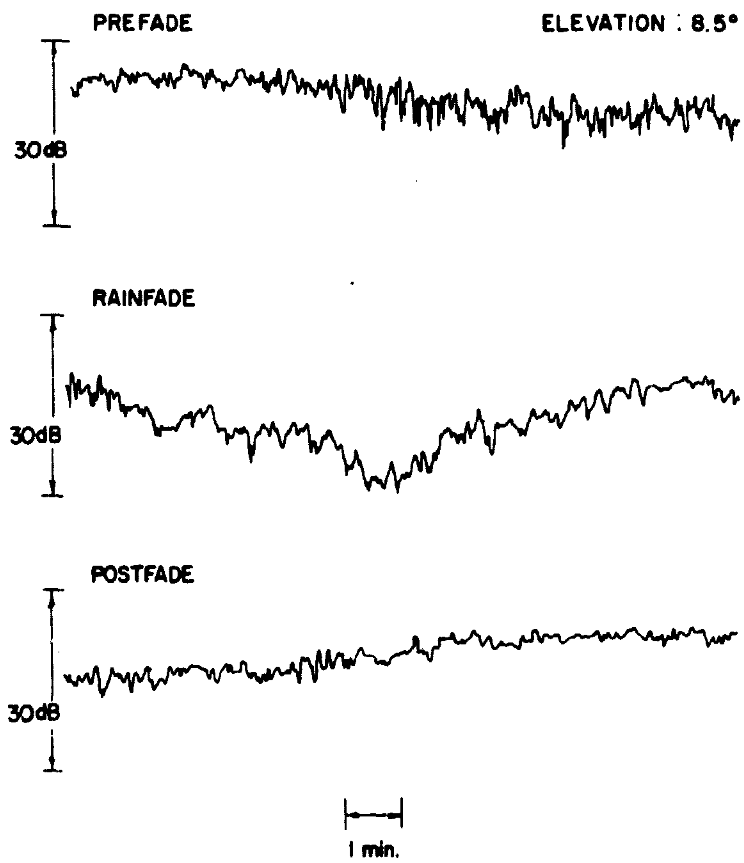

Figure 8   Behavior of the 30 GHz signal at 8.5° angle of elevation during a precipitation fade event

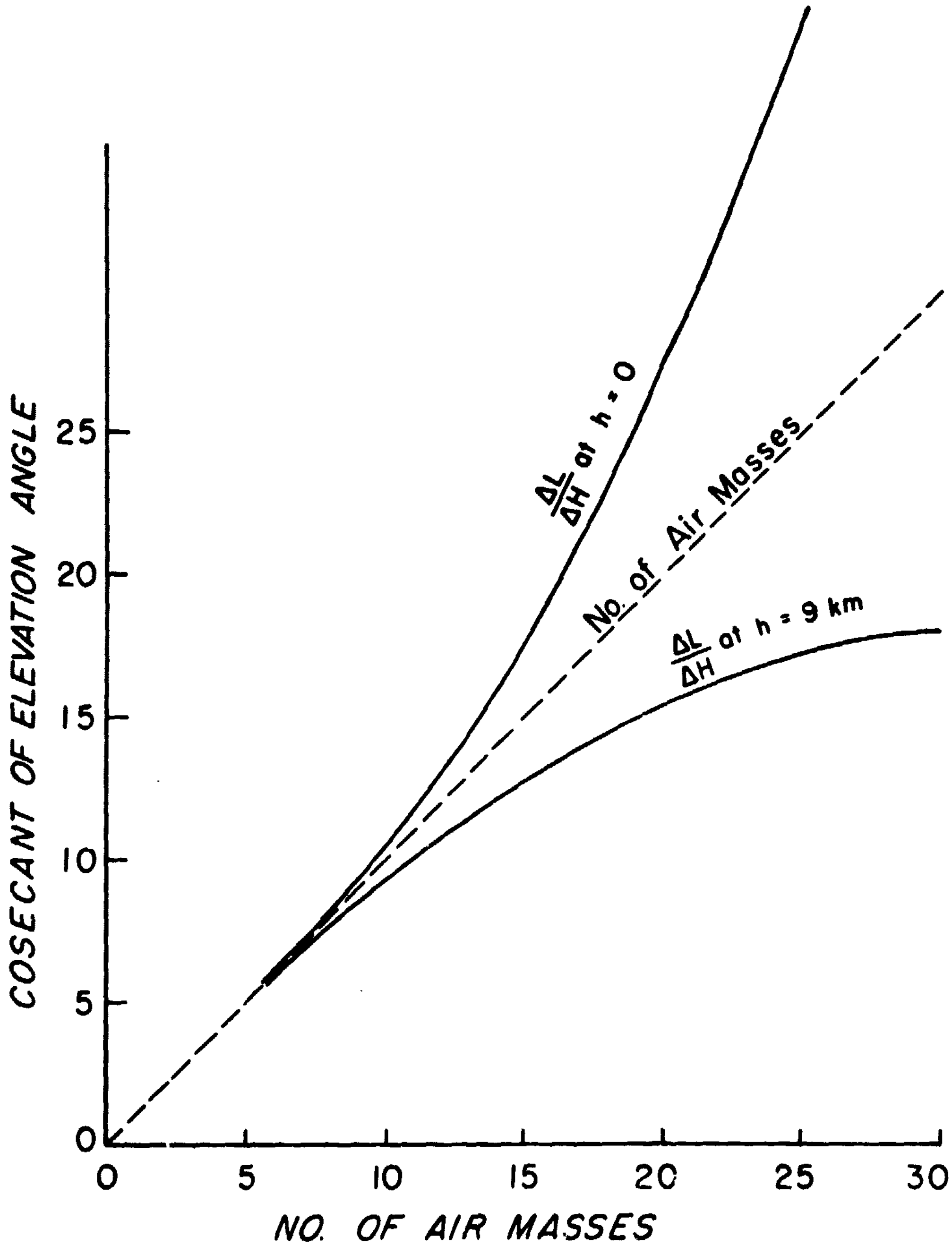

Figure 9 The incremental path length ΔL, at two altitudes, through an altitude increment ΔH, normalized