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MEASUREMENTS OF TRANSATMOSPHERIC ATTENUATION STATISTICS AT THE MICROWAVE FREQUENCIES: 15, 19, AND 34 GHz

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16. Abstract

Attenuation statistics resulting from a twelve month observation program are presented. The sun is used as a source of microwave radiation. The dynamic range of atmospheric attenuation measurement capability is in excess of 30 dB. Solar radiation characteristics with amplitude variations of a few percent are easily measured, while at the same time provision is made to accommodate a 10 dB range above the quiet sun level if major solar flare activity occurs. The solar phenomenon was extracted from the data since it is not an objective of the measurement program. A discussion and analysis of the measurement technique is presented in support of the experimental data.

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PREFACE

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The authors would also like to acknowledge the late Mr. Gene Feldman of the Microwave Department, Semiconductor Division Sylvania, whose death on November 9, 1970 has been a great loss to the scientific community. This loss is not only because of his technical contributions but more importantly because he set such high standards of moral integrity and personal dignity. On numerous occasions during the difficult task of designing and constructing the specialized instrumentation Mr. Feldman befriended the authors and provided critical microwave devices. The industry and scientific community will miss him for his unselfish technical contributions and for what he represented. The authors will miss him because he was our friend.

1.0 INTRODUCTION

When radio waves propagate through the troposphere and ionosphere they undergo various types of signal degradation and perturbation due to non-isotropic and turbulent characteristics of the media. Some of the propagation anomalies which prevail are angular bending, group time delay, phase instability, doppler frequency shift, attenuation, rotation of the plane of polarization, dispersion effects and scintillations. In addition, the presence of celestial bodies such as the sun and radio stars introduces noise interference.

Stringent requirements on the performance of electronic systems have arisen with the advent of the space age and high performance aircraft. These electronic systems are essential for the guidance, tracking and control of both space vehicles and airborne vehicles and in addition are essential for communication within the earth space vehicle complex.

In analyzing and evaluating the capabilities and performance of various electronic system concepts, it is necessary to consider the degradation in the signal information brought about by the propagating medium. In general, the troposphere and the ionosphere are the regions surrounding the earth which affect the propagation of electromagnetic waves. Thompson, (ref. 1) has recently completed a survey of atmospheric transmission properties which summarizes much of this information.

Signal deterioration results from the fact that there exist in the earth's atmosphere spatial inhomogeneities which are continuously varying as a function of time. The spatial variations, for the most part, yield statistical-bias errors, while the time-varying component results in fluctuating inaccuracies.

Those atmospheric effects which may seriously limit the performance of future telecommunication services above 10 GHz are absorption, emission and refraction. The earth's atmosphere affects the amplitude, phase, polarization and direction of microwaves with a strong frequency dependence. The spectrum between 10 GHz and 40 GHz has the potential of being considered the most likely candidate for future Earth-space communication links as well as guidance and landing systems for aircraft. At these higher frequencies, relatively high gain antennas are achieved with modest aperture diameter; broad channel capability allows high information capacity and the total available bandwidth, even in the restricted atmospheric windows, exceeds the entire spectrum below 10 GHz.

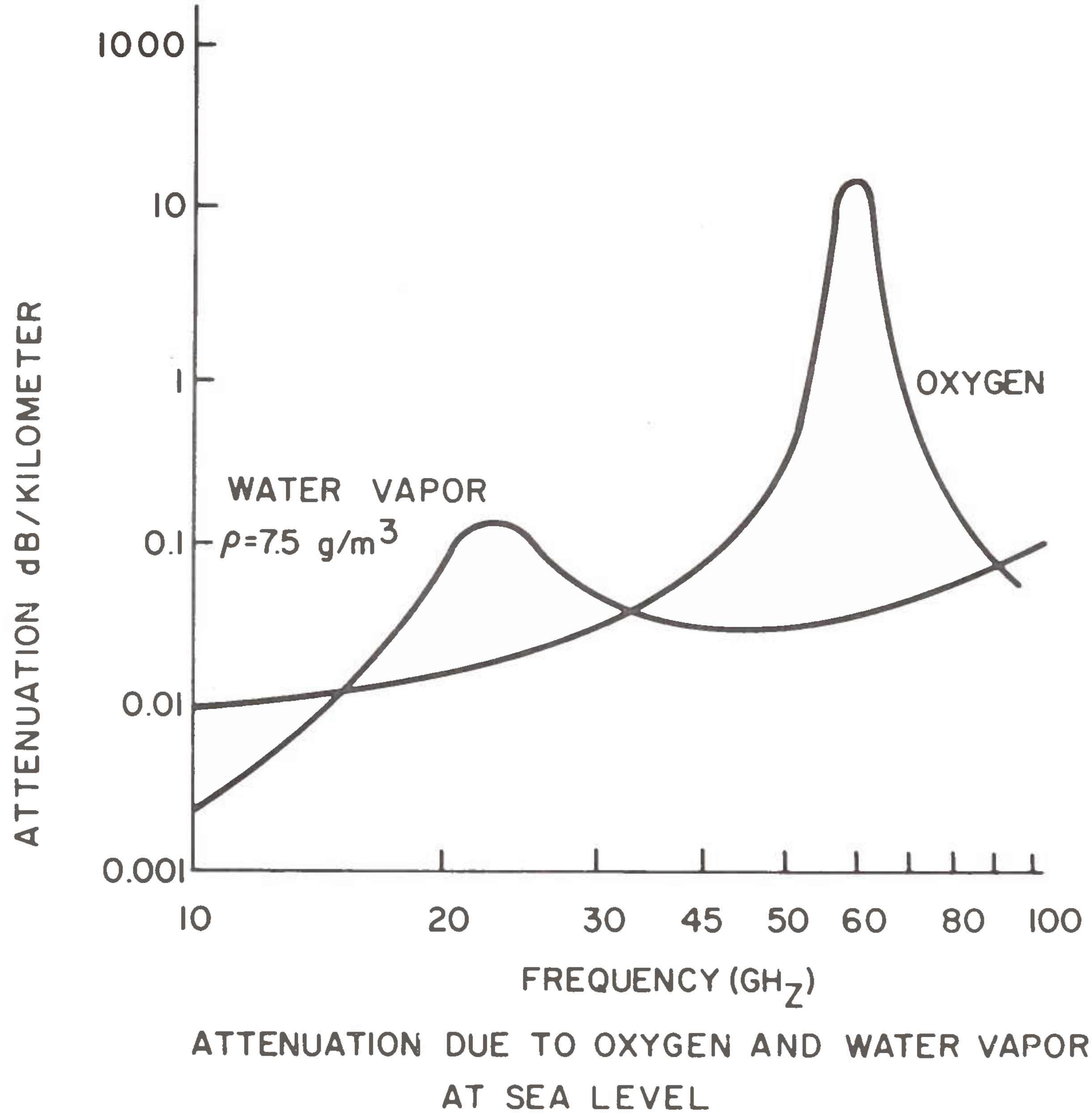

Figure 2.1.- Amplitude plot of attenuation coefficients of oxygen and water vapor at sea level.

It should be noted that the pressure and temperature dependence of the H_2O absorption is sensitive to frequency. Near resonance the dependence is P^{-1} and T^{-2}; off resonance the dependence is P and T^{-3} and well removed from resonance is P and $T^{-3/2}$. Also, in the atmosphere the water vapor density is proportional to vapor pressure and the attenuation depends on the fraction of water vapor present. This means that attenuation can occur at high altitudes with the same effectiveness as in the lower, denser layers if the mixing ratio is the same. Near resonance the high altitude water vapor may produce quite remarkable results as pointed out by Barrett and Chung.

The pressure and temperature dependence of O_2 for the frequency of interest is P^2 and $T^{-5/2}$. However, the altitude distribution of water vapor and oxygen may be quite different and variable. Consequently, measured absorption and absorption calculated from models or ground observations may be quite different.

2.2 EMISSION

At millimeter and submillimeter wavelengths, oxygen and water vapor are the primary sources of emission and absorption in the atmosphere. The effects of other gases such as CO_2, SO_2, N_2O and NO_2, because of their low molecular density, are normally negligible. The general laws of thermodynamics relate the absorption characteristics of a medium to those of emission. In the microwave region the intensity of radiation $I_{(\nu)}$ emitted at a frequency, ν, received from a particular direction, may be related to an equivalent temperature T by the following relation:

$$I(\nu)d\nu = \frac{2kT\nu^2 d\nu}{c^2} \qquad \text{(Rayleigh-Jeans Formula)} \qquad (2.8)$$

where the antenna temperature along a vertical path in the atmosphere is given by:

$$T_A = \int_0^{\infty} T \exp(-\tau)\, d\tau = \int_0^{\infty} \alpha(x)T(x) \exp\left(-\int_0^x \alpha dx'\right) dx \qquad (2.9)$$

passing from a lower to upper layer is bent downward. Under these conditions, the apparent position of a source outside the lower atmosphere appears at an elevation angle slightly greater than that corresponding to the true position. The refraction correction for a standard atmosphere is shown in Fig. 2.2 (ref. 1, p. 173) as a function of elevation angle for both microwave and optical wavelengths. For a dry atmosphere, the index of refraction is almost constant for the entire electromagnetic spectrum. When water vapor is added it can be shown that the dipole moment of the molecule tends to follow electric-field changes at microwave frequencies but not at optical frequencies; as a result, the microwave index of refraction is greater. Refractive effects vary widely with meteorological conditions, and for some abnormal cases the wave bends sharply downward (superrefraction), upward (subrefraction), or becomes trapped (ducting). A loss in signal due to refraction should be distinguished from attenuation by absorption or multiple scattering. In the latter case the energy is for all practical purposes lost, whereas in the former case the wave is only bent, thereby resulting in a change in angle of arrival at the antenna. This angle change can be compensated for, if known (ref. 7).

3.0 MEASUREMENT TECHNIQUES

3.1 METHODS OF MEASURING ATMOSPHERIC ATTENUATION

There are two methods of determining atmospheric attenuation without having to use a space vehicle. In the first, attenuation may be measured by observing the extinction of an exo-atmospheric source as a function of the zenith angle. The second method depends upon the measurement of atmospheric emission from which the corresponding attenuation is calculated using an assumed atmospheric mean temperature. The magnitude of atmospheric attenuation and the relative time interval of its occurrence at millimeter wavelengths must include consideration of the elevation angle of observation. Knowledge of the percentage of time during which relatively high values of attenuation are observed is irrelevant without consideration of the elevation angle of observation at the time of occurrence.

Conventional radiometric techniques used to measure attenuation are involved with either mechanically moving a single antenna beam between the sun and reference position in a time period short compared with the anticipated time of significant signal events, or electronically switching between two antenna feeds equally displaced about the boresight axis of a parabolic antenna.

Either method, however, suffers from limitations imposed by the time required to mechanically cycle the antenna system between two directions and obtain a measure of sun temperature, followed by sky noise temperature. Though this is not a serious consideration in the measurement of atmospheric attenuation, it may, however, negate the possibility of observing very critical radiation characteristics at the onset of a solar flare. For this reason, mechanical motion of a single antenna beam is not favored.

The optimum approach involves selection of either electronic beam switching between paired feeds in the focal plane of a parabolic antenna or electronic switching between the antenna feed outputs of completely separate antenna elements mounted on a common elevation-over-azimuth pedestal at a fixed-look angle separation. The latter approach is definitely favored since it affords greater flexibility in selecting and adjusting the angle between the two observing directions (sun and sky); in addition, it offers the opportunity to use a variety of low-noise antenna systems without introducing the contaminating effects of aperture blockage associated with multiple feed systems. An important consideration in the selection of the antenna system is the sidelobe level, in particular, the backlobe structure which intercepts the Earth's terrain. This may act as a variable component

The observations of T_S and T_A are made simultaneously at the same elevation angle (though slightly different azimuth angles). Assuming that τ will be constant for observations at the same elevation angle

$$T_S - T_A = \frac{1}{L} e^{-\tau} \oint \frac{G(\theta,\phi)}{4\pi} T_{SB} \, d\Omega_s \qquad (3.3)$$

where $d\Omega_s$ is the solid angle of the sun.

For a plane earth approximation (zenith angles of observation θ_z less than 80^o) the atmospheric opacity τ can be expressed in terms of the zenith absorption coefficient τ_o in the form

$$\tau = \tau_o \sec \theta_z \qquad (3.4)$$

It is important to note that (3.4) is valid only under the atmospheric condition of uniform horizontal stratification at the time of observation. For this condition τ_o can be obtained from the slope of the plot of log $(T_S - T_A)$ versus sec θ_z. The value of the exoatmospheric antenna temperature of the sun can be obtained from the same plot by extrapolation of the intercept corresponding to sec $\theta_z = 0$.

The atmospheric attenuation can also be calculated from the measured sky temperature as a function of elevation angle. For a narrow-beam antenna with low sidelobes, particularly low backlobe contributions, the antenna temperature is determined by the response of the main beam and the first few forward sidelobes. With the assumption that the atmospheric absorption coefficient is essentially constant over this small angle, the observed sky temperature (3.2) takes the form

$$T_A = \frac{1}{L}\left(1 - e^{-\tau_o \sec \theta_z}\right) T_{sky} + (1 - 1/L)\, T_L \qquad (3.5)$$

The transmission line between the antenna feed and receiver input introduces an additive but fixed noise bias term, and also reduces the amplitude of the sky radiation temperature through direct attenuation. These effects, in combination with antenna backlobe contributions, frequently negate the efficacy of obtaining a *secant law* for sky radiation even under uniformly clear sky conditions.

4.0 DISCUSSION OF THE MEASUREMENT PROGRAM

4.1 RATIONALE FOR CHOICE OF OBSERVING FREQUENCIES

The frequencies of observation selected for this investigation are: 15, 19, and 34 GHz. The 15 and 19 GHz frequencies fall on the lower side of the atmospheric water vapor resonance at 22 GHz. The 34 GHz frequency falls in the line well between the water vapor resonance at 22 GHz, and the molecular atmospheric oxygen resonance at 60 GHz. This frequency selection affords the opportunity to investigate those portions of the spectrum between 10 and 34 GHz considered the most likely candidates for future Earth-space communication links by nature of their location, either on the skirts or in the wells between water vapor and atmospheric oxygen resonant lines which are predominant in this portion of the microwave and millimeter spectrum.

4.2 INSTRUMENTATION

Three radio telescopes operating at 15, 19 and 34 GHz, as shown in Fig. 4.1, have been assembled and installed on an east-west baseline. The antenna system at each frequency consists of a pair of identical antennas which are mounted above the declination axis of an equatorial mount driven by a synchronous clock. The equatorial mount consists of a polar-mounted five-foot searchlight as shown in Fig. 4.2. The dual antennas are illuminated by a scalar feed and have a cylindrical tunnel structure to minimize primary pattern spill-over at the lip of the secondary reflector to insure that the observed antenna temperature is determined by the response of the main beam and the first forward lobes. The boresight directions of the two identical antennas are displaced in the hour-angle coordinate by an amount adequate to assure that the sidelobe contribution of the sun in the sky temperature reference antenna is at least 5 dB below the dynamic range of atmospheric attenuation measurement capability. It is desirable to make this angular displacement small to minimize the effect of sky temperature gradients which will be sensed by the dual-antenna beam system near sunrise and sunset. Other directions than the hour-angle direction might be considered for use at angular displacement of the reference antenna beam relative to the sun antenna beam. However, this tends to complicate data analysis. For observation sites within the United States, with the possible exception of the southern tip of Florida, angular separation of the two beams in the hour-angle coordinate is most convenient. For observing sites closer to the equator, angular displacement of the two beams in the declination coordinate would be more appropriate. For low latitudes, the declination angle separation provides a near-equivalent elevation angle for the two antennas at sunrise and sunset. In addition, the

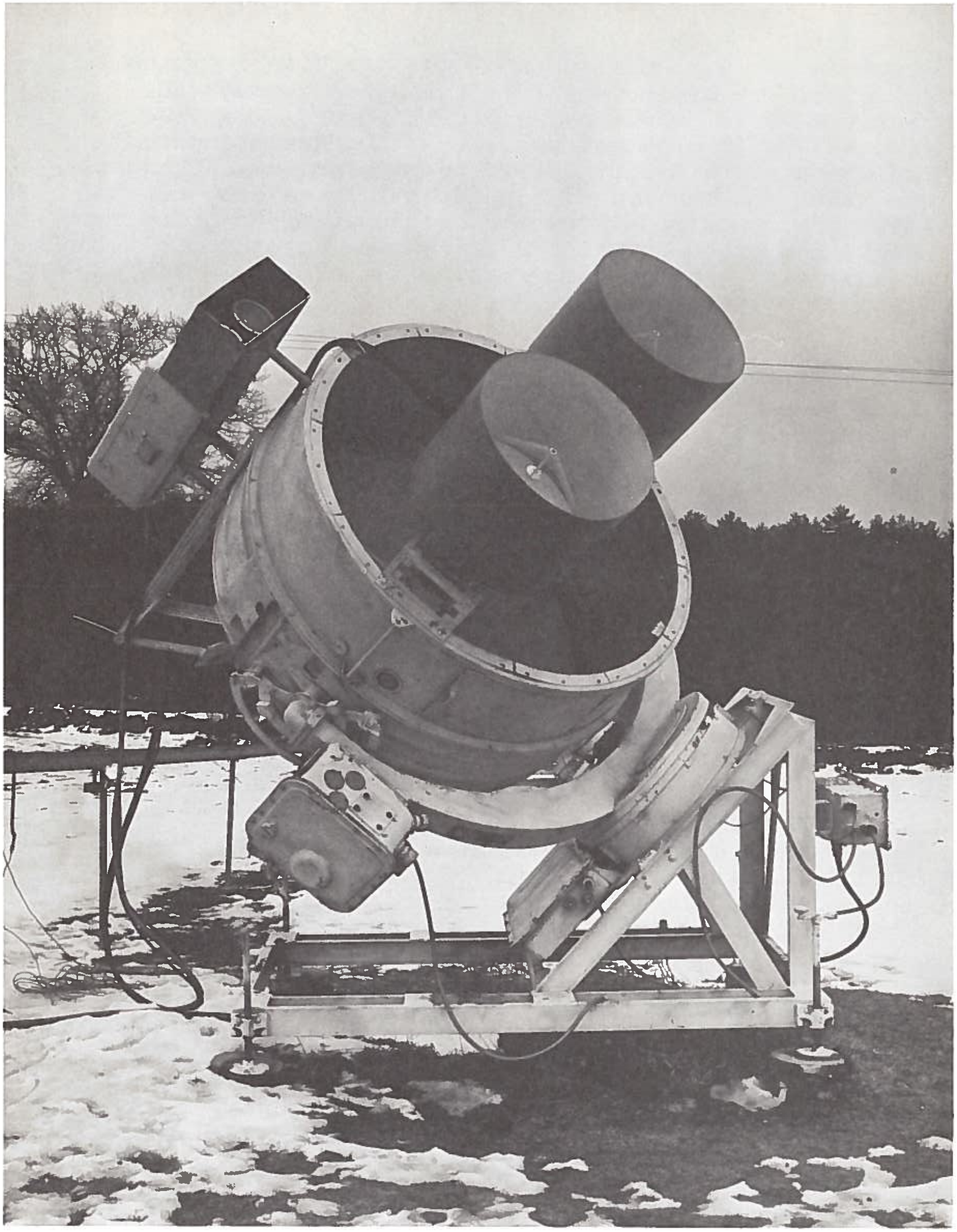

Figure 4.2.- Dual frequency radiometric sensors at 34 GHz and 60 GHz polar mounted.

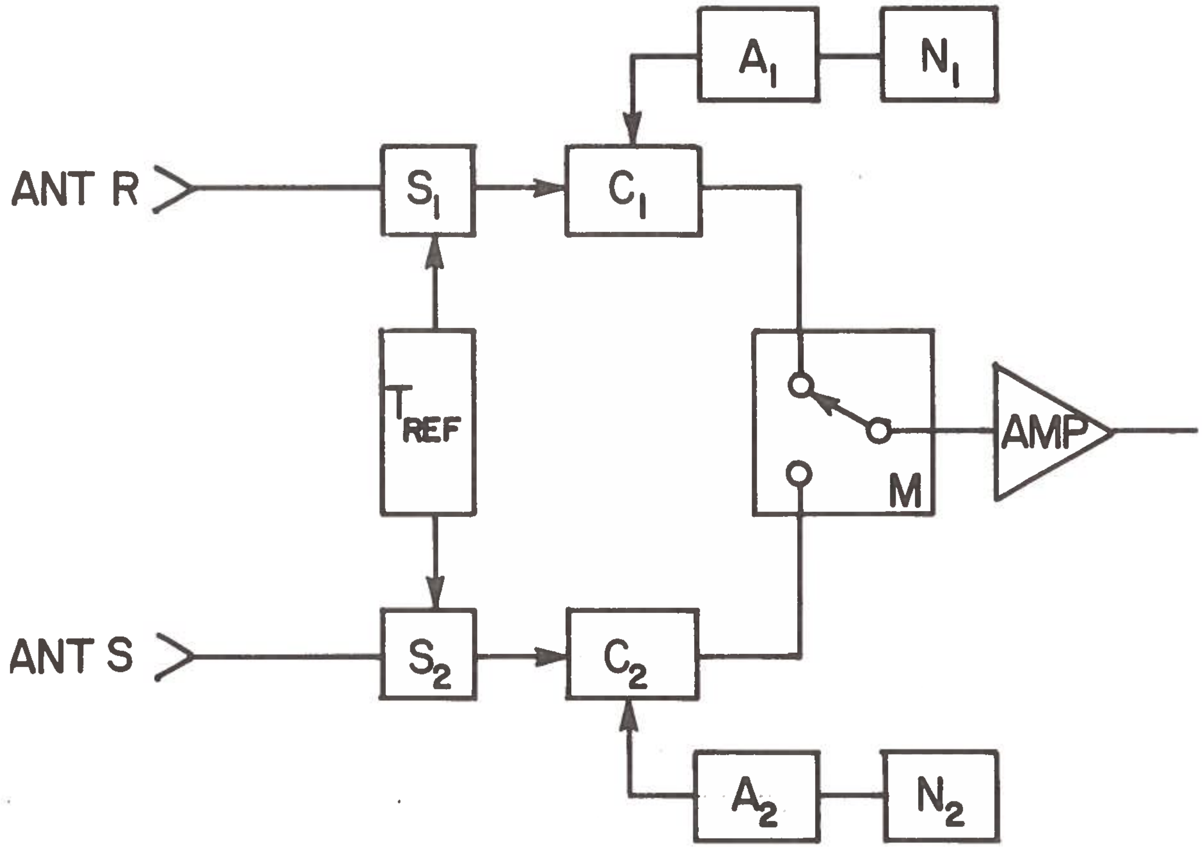

Figure 4.3.- Simplified block diagram of a radiometric sensor for measuring solar radiation and atmospheric attenuation.

4.3 SIGNAL PROCESSING AND CALIBRATION

The required radiometric sensitivity is determined by the sky noise fluctuation level when making atmospheric attenuation measurements. With present-day mixer preamplifiers, a sensitivity of 0.25°K rms can easily be achieved with a post-detection integration time constant of 1 second. The statistical noise fluctuation at the output indicator associated with the inherent receiver noise will not be significant in determining the dynamic range of atmospheric attenuation measurement capability. Hence, the use of exotic low-noise amplifiers would be redundant.

The atmospheric attenuation signal and that of major solar flare activity are processed by the "log video" channel. The 0-dB level would be preset at the antenna temperature corresponding to the quiet sun in the absence of atmospheric attenuation.

Figure 4.4.- Data receiving, recording and antenna pointing consoles.

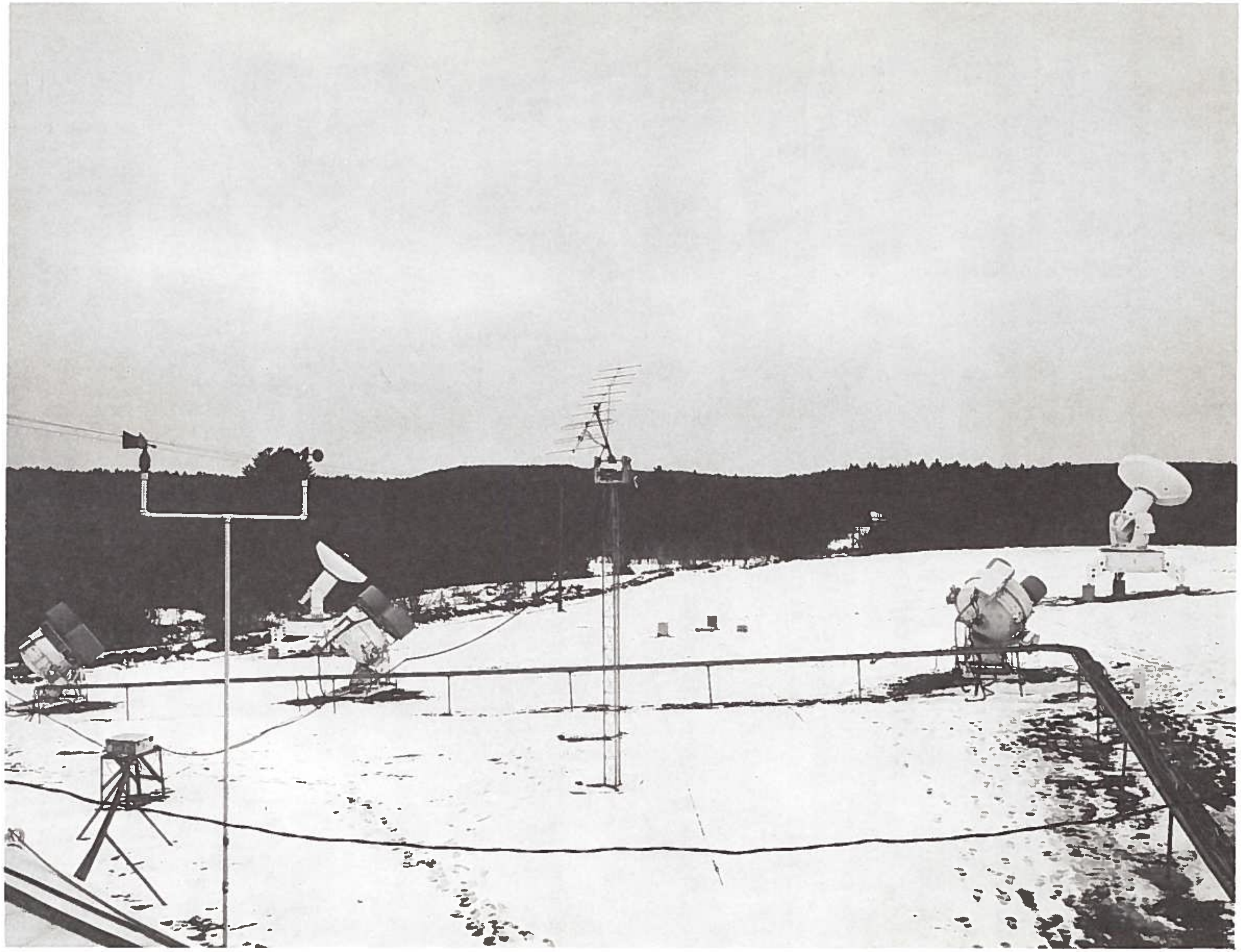

Figure 4.5.- Meteorological sensors including rain gauges, anemometer and wind speed indicator.

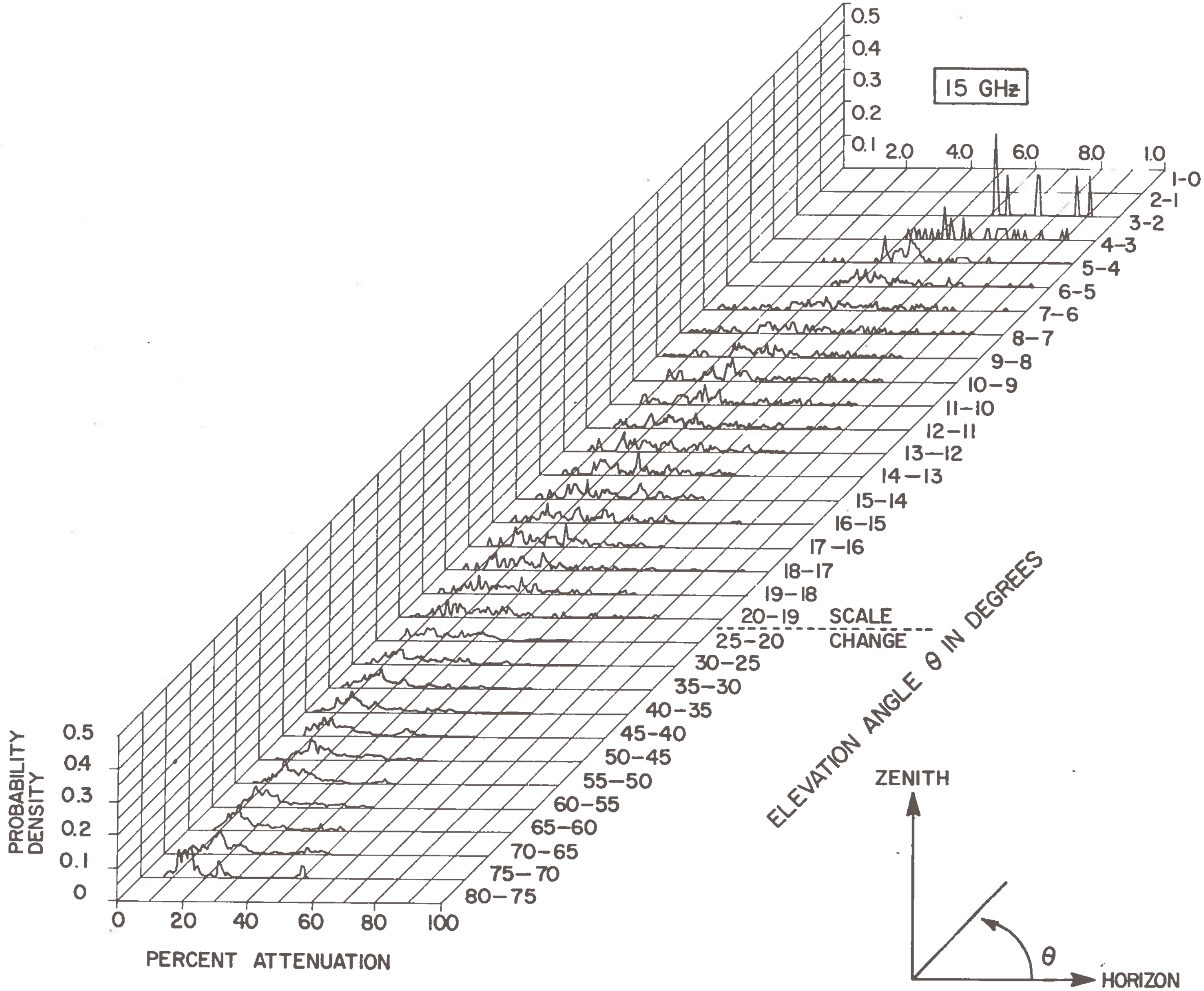

Figure 4.6.- Probability density functions of attenuation at 15 GHz at multiple observing angles.

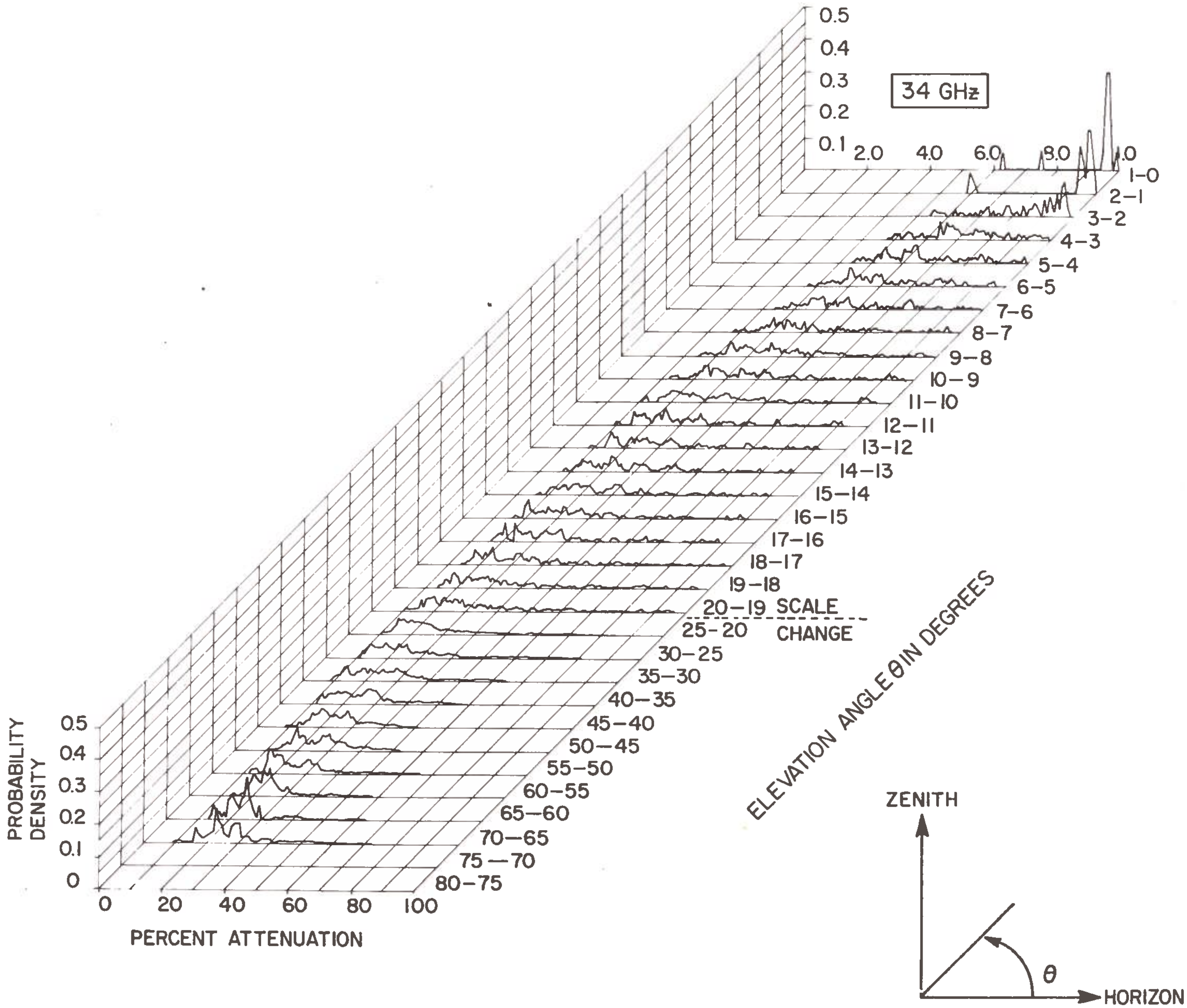

Figure 4.8.- Probability density functions of attenuation at 34 GHz at multiple observing angles.

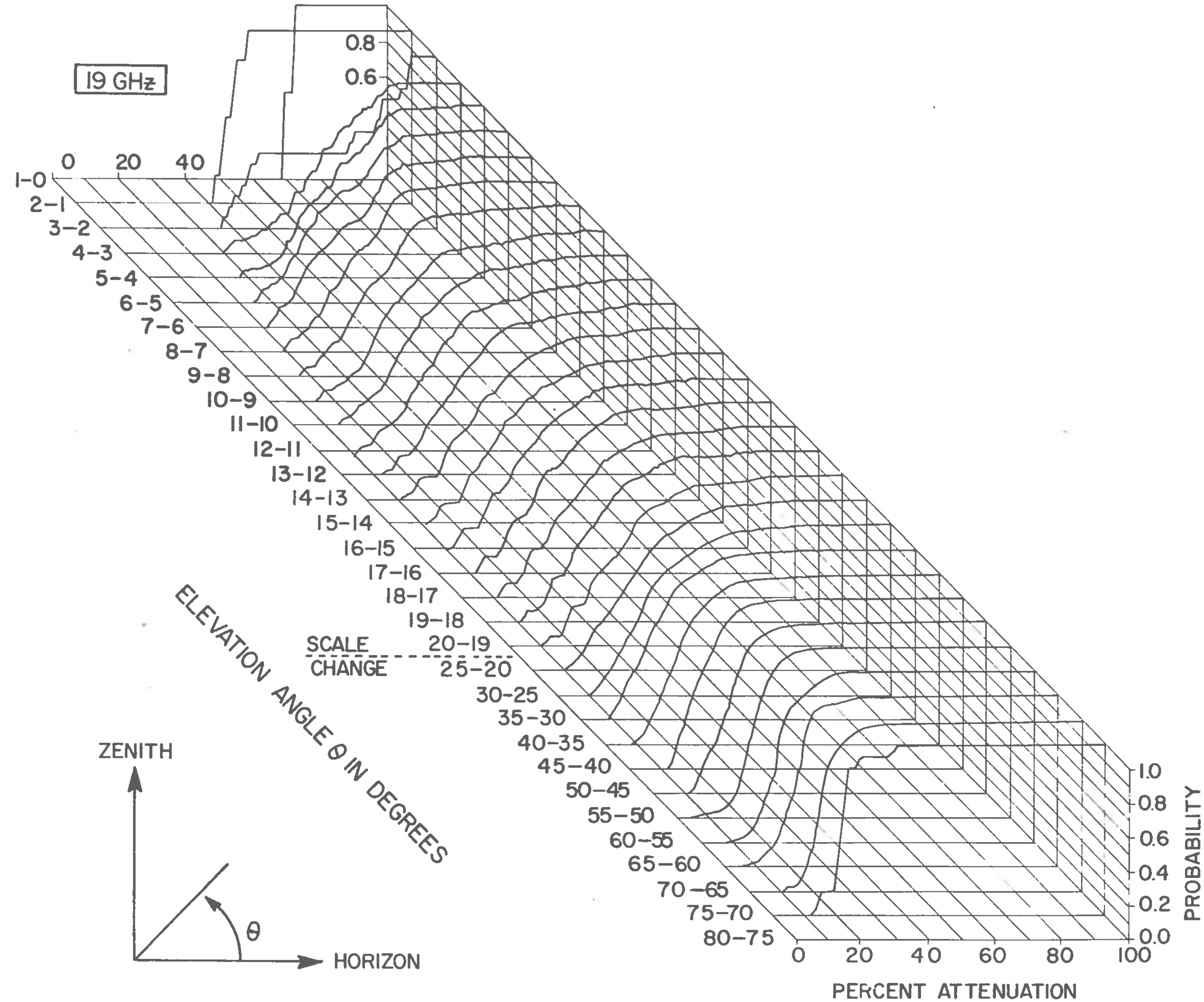

Figure 4.10.- Probability functions of attenuation at 19 GHz at multiple observing angles.

TABLE 4.1.- LIST OF MEAN AND STANDARD DEVIATIONS FOR FIGS. 4.6 AND 4.9.

15 GHz ELEVATION ANGLE (DEGREES)	PERCENT ATTENUATION		TOTAL OBSERVING TIME (SECONDS)
	MEAN	DEVIATION	
80-75	0.0	0.0	0
75-70	19.0	10.8	16770
70-65	22.3	11.5	123320
65-60	20.7	9.7	104091
60-55	21.1	9.0	133460
55-50	20.6	8.3	109290
50-45	23.0	9.4	105960
45-40	20.6	10.4	147436
40-35	21.4	13.4	140198
35-30	20.4	11.9	152157
30-25	23.4	13.3	144410
25-20	25.9	13.1	125347
20-19	27.2	14.5	19117
19-18	26.5	12.3	18693
18-17	27.1	12.9	18055
17-16	26.6	11.1	15083
16-15	28.2	12.7	13726
15-14	29.6	12.7	13804
14-13	29.7	12.7	13307
13-12	31.5	13.4	12727
12-11	32.6	14.9	12038
11-10	33.8	15.1	11444
10-9	34.7	14.8	10468
9-8	36.3	16.0	9490
8-7	39.8	18.5	7720
7-6	42.3	17.6	6550
6-5	48.2	14.6	5830
5-4	51.5	12.6	3588
4-3	62.2	13.6	1510
3-2	72.5	11.0	400
2-1	0.0	0.0	0
1-0	0.0	0.0	0

TABLE 4.3.- LIST OF MEAN AND STANDARD DEVIATIONS FOR FIGS. 4.8 AND 4.11.

34 GHz ELEVATION ANGLE (DEGREES)	PERCENT ATTENUATION		TOTAL OBSERVING TIME (SECONDS)
	MEAN	DEVIATION	
80-75	0.0	0.0	0
75-70	0.0	0.0	0
70-65	28.8	10.9	45850
65-60	25.7	8.7	51760
60-55	27.6	9.4	73963
55-50	26.8	9.2	99190
50-45	27.8	8.4	121290
45-40	26.4	8.2	176495
40-35	27.6	12.1	170629
35-30	26.5	11.9	185291
30-25	28.8	14.7	191026
25-20	29.5	15.5	265362
20-19	33.6	17.2	36257
19-18	35.6	17.9	33552
18-17	36.4	17.6	31540
17-16	37.3	16.6	26217
16-15	38.8	17.2	26402
15-14	40.4	17.3	23635
14-13	41.6	16.9	22268
13-12	43.3	17.0	21223
12-11	44.7	17.8	19448
11-10	46.7	18.0	19449
10-9	49.2	17.6	17987
9-8	50.7	16.8	17243
8-7	54.1	16.0	15351
7-6	58.1	14.8	14625
6-5	61.4	13.6	12881
5-4	66.4	13.3	12317
4-3	72.3	12.4	10920
3-2	85.1	12.5	4864
2-1	92.0	12.3	2300
1-0	93.1	9.0	850

APPENDIX

ANALYSIS OF MEASUREMENT INSTRUMENTATION

A.1 INTRODUCTION

A common method for measuring atmospheric attenuation, particularly at millimeter wavelengths, is to use the sun as an exo-atmospheric source of *constant intensity* and relate variations in measured intensity with weather conditions at the time of observation. Hence, solar radio telescopes which provide an integrated view of the entire solar disk are very similar, and in several cases, identical to the instrumentation frequently used to measure atmospheric attenuation. The similarity in instrument requirements suggests an efficient means for accomplishing both measurement objectives using one instrument.

A.2 REVIEW OF MEASUREMENT INSTRUMENT REQUIREMENTS

The measurement of the solar characteristics of solar activity at millimeter wavelengths requires:

(1) Ability to sense small changes (±2 percent) in the quiet sun level (undisturbed sun) and to detect bursts of very short duration, i.e., of the order of a few seconds, characterized by a relatively small increase to the total solar flux;

(2) Measurement of the amplitude and duration of major solar flares which may, on occasion, provide a 5- or possibly 10-fold increase in solar flux intensity relative to the quiet sun level;

(3) Measurement of sky noise temperature to an accuracy sufficient to subtract this contaminating source of noise from the desired observational data.

Since the phenomenon of solar activity is random with time and its occurrence is frequently unanticipated, particularly at millimeter wavelengths, a further requirement is continuous observation of the sun while it is above the horizon.

Unfortunately, when the antenna beam is pointed toward the sun, the received radiation includes the contaminating effects of atmospheric attenuation and radiation. The observed antenna temperature in this case can be expressed in the simplified form:

$$T_s = \frac{T_{sb}}{L_m} + \left(1 - \frac{1}{L_m}\right) T_m \qquad \text{(A.1)}$$

mild weather conditions. The ability to obtain useful and accurate data concerning solar characteristics at millimeter wavelengths is, therefore, primarily limited by the atmospheric conditions at the time of observation. In particular, it is limited by the degree to which the atmosphere exhibits a near-uniform horizontal stratification. Under these conditions, one may be able to apply a secant law correction (ref. 6) to the observed data, thus determining the value of L_m, and hence, the antenna temperature of the sun T_{sb} in the absence of the atmosphere. These natural restraints can be accommodated to some degree through appropriate selection of the observing site and care in observing procedures.

A.3 INSTRUMENT DESIGN ANALYSIS

Important considerations in instrument design are selection of the antenna aperture size, the method of mounting, and the antenna drive mechanism. A simple mounting arrangement and drive mechanism consists of an equatorial, or polar, mount driven in the hour-angle coordinate by a synchronous clock. On the assumption that this approach is taken, the size of the antenna aperture and, in particular, the angular size of the main beam relative to the angular size of the sun as viewed from Earth, becomes the most significant design consideration.

To provide an integrated view of the solar disk the main beam angle should be at least 0.5 degree. An antenna beam angle of this size, however, will accentuate degradation in observed data caused by (1) the non-synchronous apparent diurnal motion of the sun; (2) small errors in the mount polar axis alignment; and (3) mount gear backlash.

These effects can be made negligible by increasing the antenna beam angle (decreasing antenna aperture size), however, not without decreasing the available signal-to-noise ratio. If, for example, one assumes that the noise level is determined by the statistical nature of system noise and exhibits a root mean square value of $\overline{T_N}$, then the signal-to-noise ratio at the receiver output, when the antenna is pointed toward the sun, is given by:

$$\frac{S}{N} = \frac{T_s}{\overline{\Delta T}_N} \qquad \text{(A.2)}$$

The relationship between the observed antenna temperature of the sun in the absence of an atmosphere and the angular size of the antenna main beam angle is (to a good approximation) given by short time intervals (typical of heavy rain), atmospheric attenuation measurements imply the need for the highest practical signal-to-noise ratio that can be obtained under clear weather conditions. Where a 20-dB signal-to-noise ratio would be perfectly acceptable for solar measurements, a 30- or 40-dB instrument capability is frequently desired for atmospheric attenuation measurement capability, therefore, that determines the antenna aperture size if one instrument is to perform both solar and atmospheric attenuation measurements.

Since the maximum signal is obtained when the antenna beam angle is equivalent to the observed angle of the solar disk, one might conclude that further improvement beyond this point would require a sophisticated low noise receiving system, i.e., a maser amplifier or equivalent. Though this would improve the signal-to-noise ratio under clear weather conditions, the introduction of a maser-type amplifier provides no improvement in measuring large values of attenuation under adverse weather conditions. This is a consequence of the fact that the fluctuation level at the output indicator system under adverse weather conditions is determined by rapid non-statistical spatial variations in atmospheric attenuation, even in the case where a conventional superheterodyne mixer is used as the receiver input circuit. The simple fact is that the maximum value of atmospheric attenuation that can be measured as millimeter wavelengths is not determined by the performance of present day equipments, but rather by the ratio of the brightness temperature of the sun on a clear day to the sky noise fluctuation level under adverse weather conditions at the frequency of observation.

These natural restraints determine measurement capability, even in the case where the antenna aperture is made sufficiently large to obtain the maximum possible signal when the entire antenna main beam is contained within the projection of the solar disk. For example, if one assumes a *perfect* antenna system which provides an antenna temperature equivalent to the brightness temperature of the sun (approximately 8000° K) (ref. 10) at 35 GHz, a 39 dB atmospheric attenuation measurement capability implies that the fluctuation level at the output indicator, either when the antenna beam is pointed toward or away from the sun, must be less than 1 °K, since the magnitude of the component of the signal received with the antenna pointing in the direction of the sun, in this case, would be only 1°K. The interplay of non-statistical atmospheric noise fluctuations is quite apparent in this example when one notes that the sun component would be 10 °K for 29-dB attenuation and only 0.1°K for 49-dB attenuation. In each case, non-statistical fluctuations at the output indicator must be correspondingly smaller to provide a valid measurement of the average atmospheric attenuation value.

There are several possible approaches, viz.:

(1) Mechanically move a single antenna beam between the sun and reference position in a time period short compared with anticipated time or significant signal events;

(2) Electronically switch between two antenna feeds equally displaced about the boresight axis of a parabolic antenna;

(3) Electronically switch the input to the receiver between two identical antennas; one pointing in the sun direction, and the other in the reference direction.

One can move a single antenna beam on and off the sun by either moving the entire feed and reflector structure or by moving one of these elements relative to the other. Nearly equivalent performance would be obtained by either approach insofar as mechanizing the motion for a small angular displacement between the sun position and the sky reference position. One need only be concerned in the case in which the reflecting element is mechanically moved with respect to the prime feed to accomplish the full angular daily coverage from horizon-to-horizon. This would, undoubtedly, require the introduction of a correction factor in the measured data to accommodate antenna beam distortion as a function of elevation angle of observation.

Either method, however, suffers from limitations imposed by the time required to mechanically cycle the antenna system between two directions and obtain a measure of sun temperature, followed by sky noise temperature. Though this is not a serious consideration in the measurement of atmospheric attenuation, it may however, negate the possibility of observing very critical radiation characteristics at the onset of a solar flare, i.e., the antenna motion on and off the sun, though cycled over a period of a few seconds, does not meet the performance requirements for continuous patrol of solar activity. For this reason, mechanical motion of a single antenna beam is not favored.

The optimum approach involves selection of either electronic beam switching between paired feeds in the focal plane of a parabolic antenna or electronic switching between the antenna feed outputs of completely separate antenna elements mounted on a common elevation-over-azimuth pedestal at a fixed-look angle separation. The latter approach is definitely favored since it affords greater flexibility in selecting and adjusting the angle between the two observing directions (sun and sky); in addition, it offers the opportunity to use a variety of low-noise antenna systems without introducing the contaminating effects of aperture blockage associated with multiple feed systems. An important consideration

TABLE A.1.- SUMMARY OF DESIGN CONSIDERATIONS

Parameter	Determined by	Approach
Antenna mount	Apparent sun motion	Equatorial mount
Antenna mount drive	Apparent sun motion (to first order)	Synchronous
Antenna Aperture Diam.		
Maximum	Non-synchronous sun motion	Effect < 4%
Minimum	S/N = 30 db for measurement of L_m	Base on ΔT_{atmos} natural restraint
Receiver	a) S/N,Q.S.* = 20 dB for sun measurement, standard atmosphere. b) S/N,Q.S. = 30 dB for atmosphere measurement. c) Measured ΔT_{atmos} for $L_m \geq 15$ dB.	Base design on receiver output peak-to-peak fluctuation level = ΔT_{atmos}
Outputs	1) Sun measurements	a) Linear from 1/2 to 2 x Q.S. Accuracy ±1% Linearity < 1% b) Log from Q.S. to 10 x Q.S.
	2) Atmospheric measurements	c) Log from 0 to -30 dB where Q.S. = 0 dB.

*Q.S. = antenna temperature of quiet sun

data analysis. For observing sites within the United States, other than possibly the southern tip of Florida, angular separation of the two beams in the hour angle coordinate is most convenient. For observing sites closer to the equator, angular displacement of the two beams in the declination coordinate would be more appropriate. For low altitudes, the declination angle separation provides a near-equivalent elevation angle for the two antennas at sunrise and sunset. In addition, the high elevation angle of the sun at local meridian crossing is less susceptible to differential path length through the atmosphere. Reverse conditions, of course, apply at northern latitudes. In any event, these effects are of greatest concern in the measurement of solar radiation characteristics; in particular, small changes about the quiet sun level. Even under mildly adverse weather conditions, the observation shows little correlation with the elevation angle of observation for elevation angles above 10 to 15 degrees.