Sun Tracker Measurements of Attenuation by Rain at 16 and 30 GHz

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This paper describes an instrument for measuring attenuation statistics on an earth-space path simultaneously at 16 and 30 GHz; the high attenuations result from heavy rain. The sun is used as a signal source during the time of day when the sun ordinarily is visible; a measuring range of more than 30 dB is achieved at both frequencies. The brightness temperature of the atmosphere also is measured both day and night. At night the antenna beam is stationary on the local meridian. Daytime brightness temperatures in conjunction with direct attenuation measurements are used to determine the equivalent absorber temperatures which are necessary for the reduction of night brightness temperatures to attenuation values. This paper discusses the measurements made during the first 12 months of operation and gives statistics of these measurements and an analysis of errors in the system.

I. INTRODUCTION

The advent of high performance booster rockets makes it possible to put very high-capacity microwave repeaters in synchronous orbit, possibly resulting in low cost per channel.[1] The large bandwidth required for such a system is in direct conflict with the crowded condition of the microwave spectrum below 10 GHz. We must therefore consider the possibility of operating such a system at frequencies above 10 GHz and must assess the magnitude of large attenuations which may be caused by heavy rain. Estimates based on attenuations for surface rainfall conditions[2] and models of the structure of rain storms indicate that such a system is feasible,[3] but direct measurement of the attenuation statistics is necessary.*

* The overall plan for a system calls for ground-station space diversity, but that is not discussed here.

The apparatus described in this paper has been set up at Crawford Hill, Holmdel, New Jersey, to measure the attenuation statistics of an earth-space path at 16 and 30 GHz using the sun as a signal source. At night the same equipment monitors the temperature of the antenna with the beam in the local meridian. Attenuations up to about 10 dB can be deduced from these temperatures. Attenuations of greater than 30 dB can be measured in the sun-tracking mode; the output time constant is two seconds so that even relatively fast fades can be followed.† Daily cycling of the equipment is automatic and sun coordinates are stored for a week's unattended operation. The sun tracker has been measuring at 30 GHz since October 1967 and at both 16 and 30 GHz in almost continuous operation since December 1967.

II. THEORY OF OPERATION

At 16 and 30 GHz the sun is transparent down to the lower chromosphere so the radiation temperature is fairly constant with time and fairly uniform across the disk of the sun. The value of the disk temperature is about 11,500°K at 16 GHz and 7,500°K at 30 GHz.[4]

If an antenna is pointed at the sun, the increase in antenna temperature because of the sun T_s is given by the product of the disk temperature of the sun and the fraction of the antenna's response which the sun subtends. At 30 GHz somewhat less than half of the response of the sun-tracker antenna falls on the disk of the sun, so $T_s \approx 3000$°K. If the remainder of the antenna's pattern is directed to cold space, the total antenna temperature will equal T_s. If we introduce a uniform lossy medium of transmission coefficient t and physical temperature T_c between the antenna and the sun, the antenna temperature (T_a) will be changed from T_s to

$$T_a = tT_s + (1 - t)T_c \tag{1}$$

where radiation from the attenuating medium takes the place of some of the radiation from the sun. In our case T_c is the temperature of some component of the earth's atmosphere (in particular, rain) and will be about 270°K; but we are not able to measure it directly. For attenuations greater than about 12 dB, the second term of equation (1) will dominate and a simple measurement of antenna temperature therefore would not provide a linear measurement of attenuation; for attenuations greater than about 20 dB the errors resulting from the

† If the signal going into a 2 second time constant is rapidly reduced to zero, the output drops at 2.2 dB per second, whereas if the signal is rapidly increased the output comes within 2 dB of the final value in 2 seconds.

unknown value of T_c would start to be significant. In the sun tracker these problems are solved by having the antenna's main beam scan on and off of the sun at a 1 Hz rate with an angular excursion of 2.6°. When the beam is 2.6° away from the sun, virtually the only radiation is that of the attenuating medium and

$$T_a = (1 - t)T_c . \tag{2}$$

The output of the receiver is sampled during the time the antenna is pointed at the sun and when it is pointed away from the sun; thus a difference voltage is generated. By subtracting equation (2) from (1), one sees that this voltage is proportional to tT_s. As long as T_s is constant any changes in the difference voltage can be interpreted as changes in t; thus, it is not necessary to know T_s in any absolute sense, just as a reference level at the radiometer output. In the sun tracker the difference voltage is passed through a logarithmic converter and presented on a chart recorder so the attenuation can be read directly in dB.

At night the sun is not available and only equation (2) can be used as a measure of attenuation. In this case a Dicke switch is used and the temperature of the antenna is subtracted from the temperature of a reference termination at about 290°K. The quantity plotted on the chart recorder is

$$\Delta T = 290°\text{K} - (1 - t)T_c .$$

Uncertainties in the value of T_c limit the range for which t can be recovered to about 10 dB in this mode of operation.

An additional output is obtained during the daytime by using the Dicke switch to connect the input of the receiver to the reference termination during the transition portion of the scanning cycle, that is, when the main beam is neither fully on nor off of the sun. A radiometer output similar to that in the nighttime operation is obtained by comparing the off-sun antenna temperature with the reference termination temperature. From the simultaneous measurements of T_a and t, T_c can be calculated.

III. EQUIPMENT

Figure 1 shows the physical layout of the equipment. A five-by-nine-foot plane reflector is mounted as a polar heliostat to reflect the sun's rays in the direction of the earth's north polar axis. A four-foot aperture conical horn-reflector antenna looks south along the same

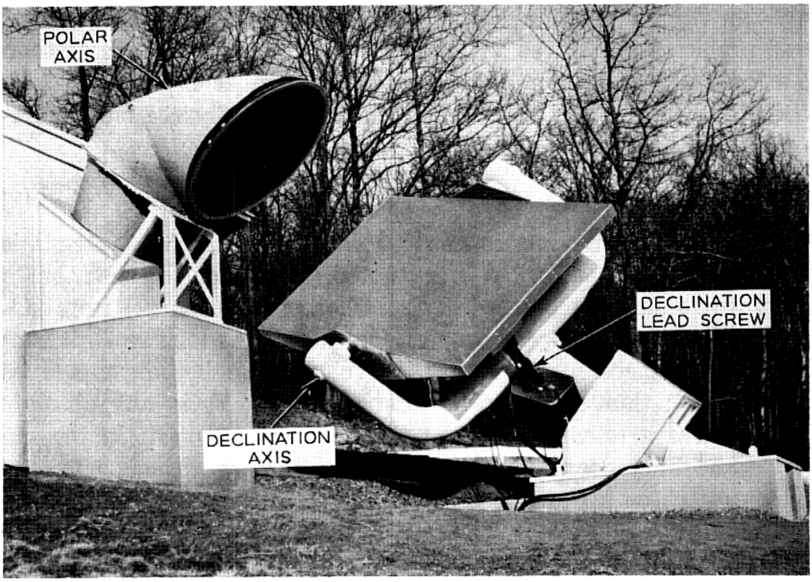

Fig. 1 — View of sun tracker from southwest showing equipment cab, horn reflector, and polar heliostat flat.

axis and collects most of these rays. The hour-angle motion for tracking the sun during any one day is provided by driving the reflector about its polar axis at a 24-hour per revolution rate. This tracking motion is automatically started each morning from an approximate starting position when the read-outs indicate a coincidence between the antenna beam and the ephermeris positions of the sun for that day. The seasonal motion of the sun (in declination) is corrected daily by motion of the reflector about its declination axis at half the angular rate. A motor-driven lead screw is automatically energized for a timed interval each morning to provide the required motion. The declination axis of the reflector is also used for the 1 Hz scanning motion mentioned in Section II. The upper end of the declination lead-screw connects to a crank shaft which is turned at about 1 Hz in the sun tracking mode of operation. A resolver, turned by the same shaft, generates timing signals for the radiometers.

The output of the horn-reflector antenna is in a circular waveguide. One linear polarization is split off by a polarization coupler for the 16 GHz receiver and the orthogonal polarization passes through a waveguide taper to the 30 GHz receiver. Figure 2 is a block diagram of the radiometer system.

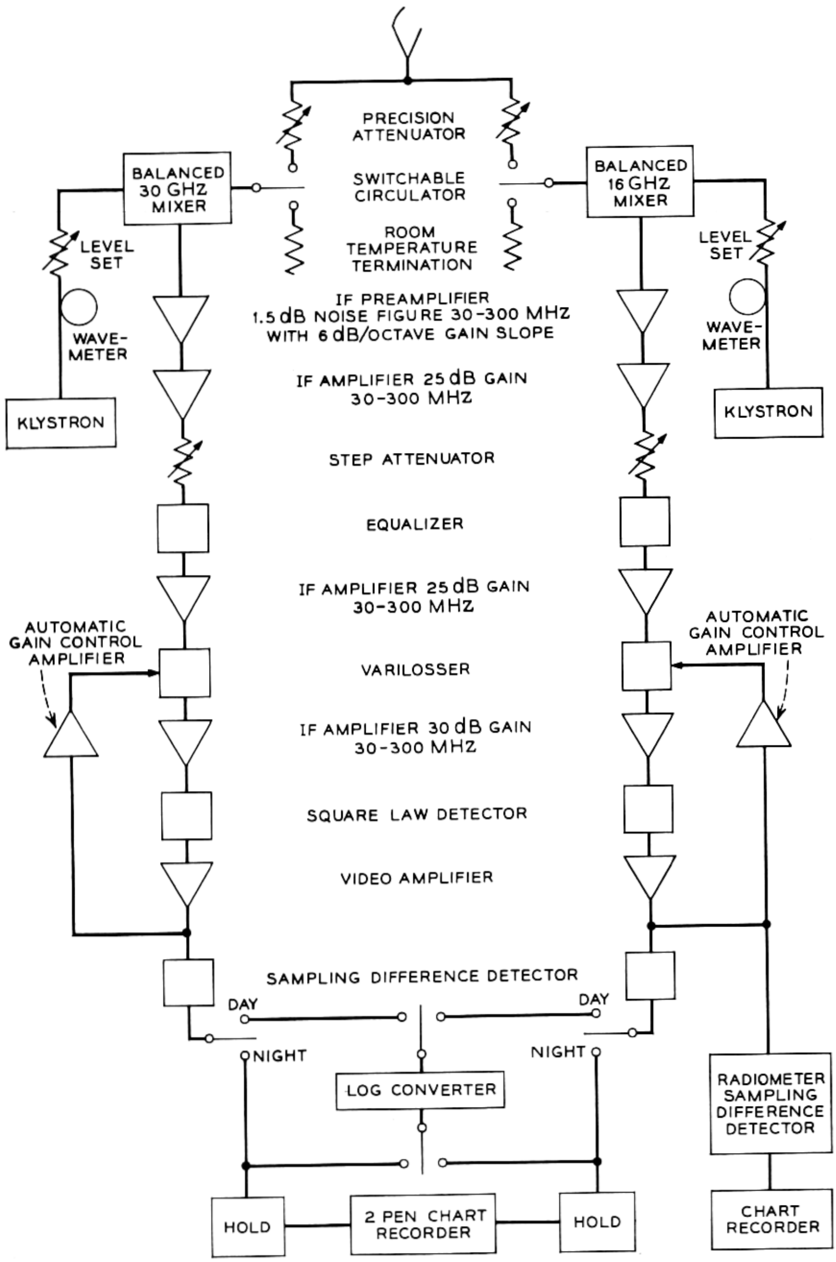

Fig. 2 — Block diagram of sun tracker receivers.

The balanced Schottky-barrier-diode mixers have broadband input circuits allowing double sideband response and are directly connected to transistor IF preamplifiers. The resulting down converter has a low noise temperature (T_r) which varies somewhat over the IF band-pass of the system with a broad minimum around 70 MHz. The gain has a 6 dB per octave slope characteristic of high frequency transistors operated in the β cutoff region. The equalizer following the second IF amplifier changes the sloping frequency response of the system to a weighting function [gain $\alpha(T_o/T_r)^2$] which minimizes the fluctuation level at the output of the square law detector when referred back to the input temperature. The weighted average double sideband noise temperature of the receivers is 840°K at 30 GHz and 1300°K at 16 GHz. The noise bandwidth exceeds 200 MHz in both cases. The noise temperatures of the receivers are degraded in the radiometer system by the combined loss of about 1 dB in the calibrating attenuator and switchable circulator.

The operating cycle of the radiometer, when tracking the sun, is shown in Fig. 3. The top curve shows the declination of the antenna beam as a function of time; the second curve shows the resulting output of the square law detector of the 30 GHz receiver. The third curve shows the drive to the circulator switches which connect the receiver inputs to the room temperature reference terminations during the quarters of the cycle while the declination is changing rapidly. This switch causes the shoulder in the second detector output. The fourth curve shows the drive to the main sampling difference detectors. Positive sampling occurs during the quarter of the cycle when the beam is closest to the sun and negative sampling during the quarter cycle when the beam is farthest from the sun. The positive and negative samples are stored on separate capacitors with a charging time constant of 0.5 second.

The sampling duty cycle of ¼ gives a speed of response equivalent to a 2-second time constant. The fifth trace shows that the logarithmic converter (Fig. 2) operates on the output of the 30 and 16 GHz sampling difference detectors alternately during the remaining two quarters of the cycle. The sixth curve shows the drive to the radiometer sampling difference detector; it samples positively when the receiver is connected to the room temperature termination and negatively while the main beam is pointed away from the sun producing an output proportional to ΔT of equation (3).

The last trace shows the drive to the automatic gain control sampling circuit. The action of the automatic gain control is to adjust the

IF variolosser as necessary to keep the output level of the receiver at a fixed value during the portion of the cycle that its input is connected to the room temperature termination. An integrator in the automatic gain control amplifier prevents the gain from changing rapidly. Dead times in the cycle have been exaggerated for clarity in the figure.

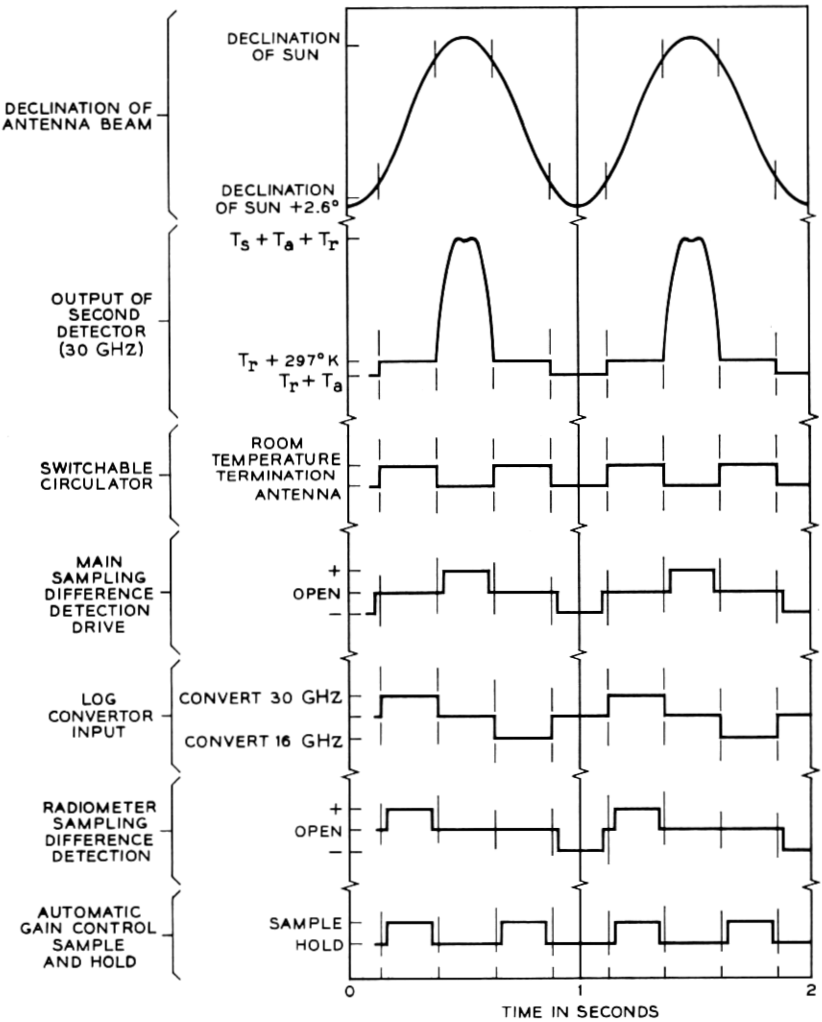

Fig. 3 — Switching cycle of sun-tracker radiometers.

During nighttime operation the antenna beam is pointed to the meridian at the declination the sun had the previous day. The switchable circulators are operated as Dicke switches at about 2 Hz and the sampling difference detectors operate as phase sensitive detectors with blanking at the switching time. Their outputs go directly to the hold circuits which drive the recorder.

Various parameters of the system are summarized in Table I. The temperatures quoted refer to the antenna terminals. Room temperature and liquid nitrogen cooled absorbers are used as temperature standards at 30 GHz and a noise lamp and a room temperature absorber are used at 16 GHz.

IV. CLEAR WEATHER ATTENUATION

The antenna temperature (pointed away from the sun) has been measured as a function of elevation on a typical clear winter day (+3°C, 60 per cent relative humidity) and again on a hot summer day (37°C, 52 per cent relative humidity). Values of 8.3° and 17.1° K per atmosphere at 30 GHz and 4.1° and 7.8°K per atmosphere at 16 GHz respectively, were found. These correspond to 0.15 and 0.25 dB per atmosphere at 30 GHz and 0.06 and 0.12 dB per atmosphere at 16 GHz, assuming the absorption took place at 250°K (winter) and 284°K (summer). Attempts to measure these rather small atmospheric absorptions directly using the sun, under atmospheric conditions similar to the above, have been frustrated by variations in atmospheric absorption, solar brightness, or antenna gain during the course of the measurement. Consistent results have obtained only at low elevation angles where the thickness of the atmosphere changes rapidly with hour angle.

The normalization procedure which is normally used on sun tracker records cancels out clear weather attenuation. Thus attenuations quoted in other parts of this paper are increases above the clear weather value.

Table I — Parameters of the Sun Tracker

	16 GHz	30 GHz
Antenna beam width	0.92	0.54°
Antenna temperature of sun (T_s) (30° elevation)	1900°K	3000°K
Receiver double side band noise temperature	1700°K	1100°K
Measuring range on sun (1.5 dB peak error)	30 dB	35 dB

V. TYPICAL RECORDS

Figure 4 shows tracings of the output of the sun tracker during two 24-hour periods. The left two-thirds of both charts is night operation with antenna temperature presented on linear scales for both frequencies. The right portion is in the sun-tracking mode with a scale factor of 10 dB per major division. The sun is behind some trees during part of the sunrise.

The upper record was taken on a clear day. During the lower record, several showers with rainfall up to 75 mm per hour occurred near the site. The high temperature peaks on the night portion of the 30 GHz record show rounding, indicating that the peak antenna temperature of about 275°K is close to the temperature of the attenuating rain. The three peaks of attenuation in the daytime portion of the record occurred at solar elevation of 8°, 15°, and 18°.

Figure 5 contains tracings of the sun-tracker output on three other days. Figure 5a is from a 24-hour period when the sky was heavily overcast and occasional drizzle occurred. The attenuation did not exceed 2 dB during this period even for low elevations and was less than 1 dB most of the time.

The lower records were obtained before the 16 GHz receiver was installed so that only 30 GHz levels are plotted. During the night that the lower level record was taken (b) passage of a cold front produced snow and ground level temperatures fell below 0°C. The next morning about ¼ inch of rough ice was frozen on the reflector of the sun tracker. When the ice was removed from the reflector (at the right end of b), the signal level from the sun returned to normal.

The following sequence of events is postulated to explain the record. As snow fell on the warm reflector it melted to slush. The liquid water content of the slush has a very high absorption coefficient when its thickness amounts to an appreciable fraction of a wavelength above the aluminum reflector; as the slush collected, the antenna temperature approached ambient temperature. After the snowfall stopped, the antenna temperature remained constant until the air temperature lowered sufficiently to slowly freeze the slush into ice which is a dielectric with a low absorption coefficient; thus the antenna temperature dropped to a value typical of the overcast night (Fig. 5b). When the sun rose and the sun tracker started tracking it, however, the signal level was about 7 dB below normal because of phase perturbations (and a consequent reduction in gain) caused by the rough dielectric on the reflector. Removal of the ice returned operation to normal (final short segment in b).

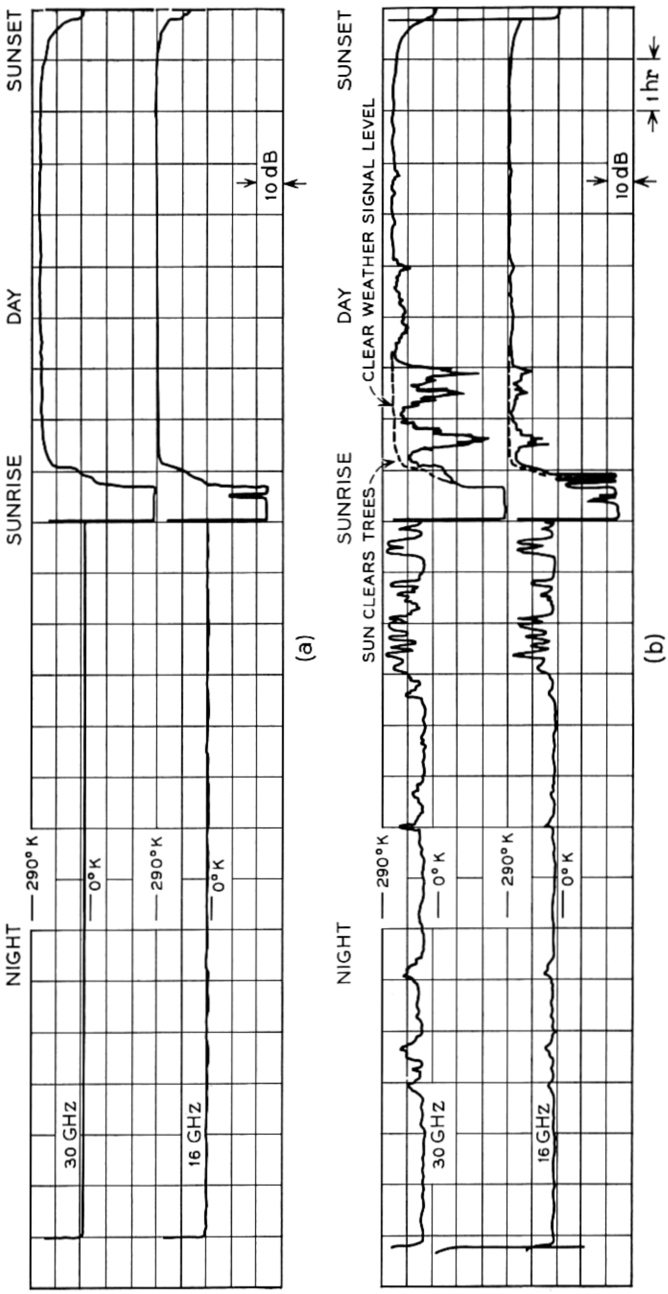

Fig. 4 — (a) Output of sun racker during a clear 24 hour period; the left portion of the record is nighttime operation with antenna temperature scales as indicated. The right portion shows sun tracking operation in which the scale factor is 10 dB per major division. (b) Output of sun tracker during occasional moderate showers (December 12, 1967).

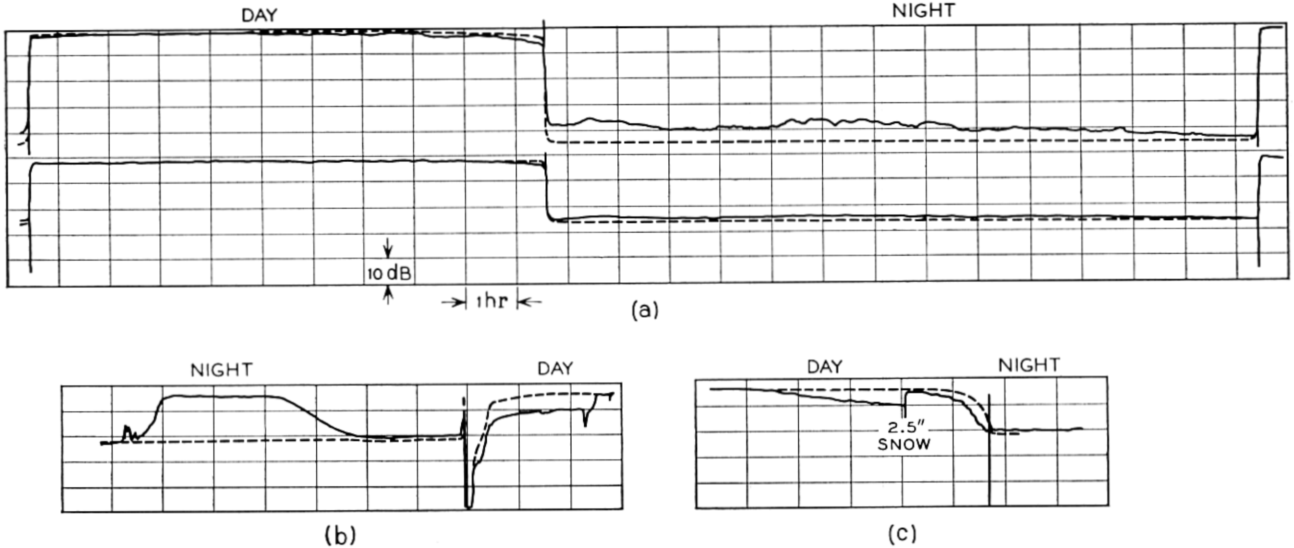

Fig. 5 — (a) Output of sun tracker during a 24 hour period of overcast skys and occasional drizzle. The dotted line indicates clear weather output. Notice that the gain has been increased in this record compared with Fig. 4, but things are otherwise the same (March 10, 1968). (b and c) Records at 30 GHz for times of wet and dry snowfall; see text for explanation (November 15, 1967 and November 30, 1967).

The lower right record (c) was taken on a cold afternoon when snow fell uniformly for several hours. In 2½ hours about 2½ inches of snow collected on the reflector. When the snow was removed from the reflector to measure the effect of the falling snow, the signal level returned to about 1 dB below the normal level. More snow collected on the reflector, but the antenna temperature was hardly affected in the night-time mode.

VI. ATTENUATION STATISTICS

At this writing, the sun tracker has been in full operation for more than a year. On two occasions the attenuation at 30 GHz continuously exceeded the measuring range of the system (35 dB) for more than 30 minutes. During one of these periods the attenuation at 16 GHz exceeded 30 dB four separate times for a total of 15 minutes. It is clear from these results that if a reliable communication satellite system is to be constructed using these frequencies it will be necessary to have some form of ground-station space diversity for operation during such periods.

A summary of the percentage of time that the attenuation exceeded various levels is shown in Tables II and III for 30 and 16 GHz. In both cases day and night statistics are shown separately since the measurement technique is different. Figures 6 and 7 are histograms showing the number of fades exceeding 9 dB at 30 and 16 GHz as a function of duration of the fade. No attempt has yet been made to divide this statistical data according to the elevation of the sun. It is expected that some differences will occur as a function of elevation; however, one of the two long-term high-attenuation periods, mentioned before, occurred when the elevation angle was about 60° and the other immediately before sunset.

VII. RATIO OF ATTENUATION AT 30 GHZ TO ATTENUATION AT 16 GHZ

If one knew the drop size distribution in an attenuating rain, the ratio of attenuation at 30 GHz to that at 16 GHz could be calculated. Using surface drop size distributions, Hogg has calculated that the ratio will lie between about 3.8 for small drops characteristic of 0.1 mm per hour rain and 2.2 for large drops characteristic of a 100 mm per hour rain.[5] Values over this range have been observed at various times.

Figure 8 is a scatter plot of attenuation at 16 GHz against attenuation at 30 GHz for various sample times during the first two hours of

Table II — Cumulative Distribution of Attenuation at 30 GHz for Day and Night Observations

Attenuation at 30 GHz (in dB)	Percent of total observing time* (3851 daylight hours)
> 3	1.97
> 6	1.00
> 9	0.55
> 15	0.309
> 21	0.174
> 27	0.105
> 33	0.069
	(4826 nighttime hours)
> 3	1.148
> 6	0.300
> 9	0.113
> 12	0.052

* December 8, 1967 through December 8, 1968. The daytime observations include all elevations from a maximum of 74° down to as low as 2° or 3°. Nighttime observations are made at a constant elevation varying from 73° on June 21 to 26° on December 21. Elevation effects may contribute to the differences between day and night distributions as well as rainfall differences.

the daytime portion of the record shown in Fig. 4(b). Except for two of the points, the dashed line which represents a constant ratio of 3.4 to 1 is a good fit to the data. Figure 9 shows points from a thunder storm in which the ratio taken from the second order-fitted curve varies from 3 at high attenuations to more than 4 at low attenuations. Figure 10 shows points from another thunderstorm during which two separate observers remarked on the unusually large size of the raindrops. The ratio in this case was about 2.2 to 1. The ratio for other rains has fallen within the range indicated above.

VIII. SUN VERSUS SKY BRIGHTNESS MEASUREMENTS

As explained in Section II a sky brightness measurement is made at one frequency simultaneously with the measurements of attenuation using the sun. With both attenuation and brightness the equations of Section II can be solved in either of two ways. In Fig. 11 a scatter plot has been made of attenuation derived from the sky-brightness measurement using equation (2) against simultaneous attenuation measured in the direction of the sun. It can be seen from this and other data that if the correct value for T_c is used (272°K in this

TABLE III— CUMULATIVE DISTRIBUTION OF ATTENUATION AT T6 GHZ FOR DAY AND NIGHT OBSERVATIONS

Attenuation at 16 GHz (in dB)	Percent of total observing time* (3839 daylight hours)
> 1	1.59
> 2	0.84
> 3	0.45
> 5	0.259
> 7	0.158
> 9	0.112
> 11	0.085
> 13	0.065
> 15	0.049
> 20	0.034
> 25	0.023
> 30	0.013
> 33	0.009
	(4812 nighttime hours)
> 1	0.46
> 2	0.13
> 3	0.05
> 6	0.022
> 9	0.016
> 12	0.012

* Same dates as Table II. The daytime observations include all elevations from a maximum of 74° down to as low as 2° or 3°. Nighttime observations are made at a constant elevation varying from 73° on June 21 to 26° on December 21. Elevation effects may contribute to the differences between day and night distributions as well as rainfall differences.

case), measured sky brightness values can be interpreted as attenuations with reasonably small scatter up to and perhaps beyond 10 dB. (Some of the scatter in Fig. 11 is undoubtedly caused by real differences in attenuation in the two directions.)

A more interesting way of looking at this same data is to invert the equations and compute the apparent medium temperature T_c. In Fig. 12 the derived value of T_c has been plotted (dots) against measured attenuation for the same data as used in Fig. 11. At low values of attenuation the average value of T_c seems to be below the ice point even though the air temperature near the earth's surface was about 295°K during this rain. Super cooling might play some role in causing this low apparent temperature, but it is more likely that scattering as discussed in Section IX causes the main effect.

At high values of attenuation the measured value of T_c goes up to as high as 290°K; this is a very definite effect since the measured

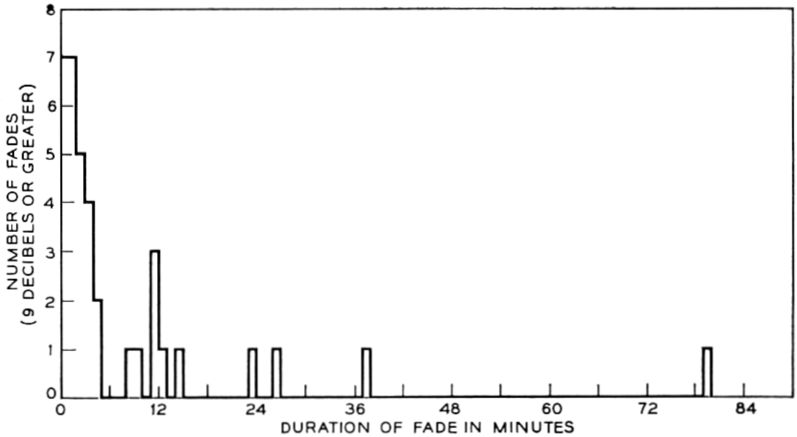

Fig. 6 — Number versus duration for fades of 9 dB or greater at 30 GHz for the period December 1967 to August 1968.

brightness temperature rises to 290°K. However, if a plot like Fig. 11 is made using such a high value of T_c, there is a definite curve at attenuations above 5 dB and the fit is unacceptable by 10 dB. There are two contributions to the higher values of T_c at higher attenuations. First, scattering ceases to be very effective in lowering T_c; instead of scattering radiation from the cold sky into the antenna beam, the lower drops scatter radiation from upper drops into the beam. Second, at high values of attenuation only the lower and hotter portion of the rain contributes effectively to the brightness since the lower drops absorb the radiation from the upper drops and replace it with their own.

IX. DEVIATIONS FROM SIMPLE THEORY

The output of the sun tracker could depart from the true attenuation in the path to the sun for several reasons:

(*i*) Nonlinearities and instabilities in the radiometers, are small enough to be negligible.

(*ii*) Mispointing the antenna beam as a result of atmospheric refraction, use of noon solar positions during an entire day, and mechanical misalignment cause the signal from the sun to decrease more at low elevations than one expects from atmospheric absorption. These effects fortunately are quite repeatable from one day to the next so that clear weather days provide a reference level below which excess attenuation is measured.

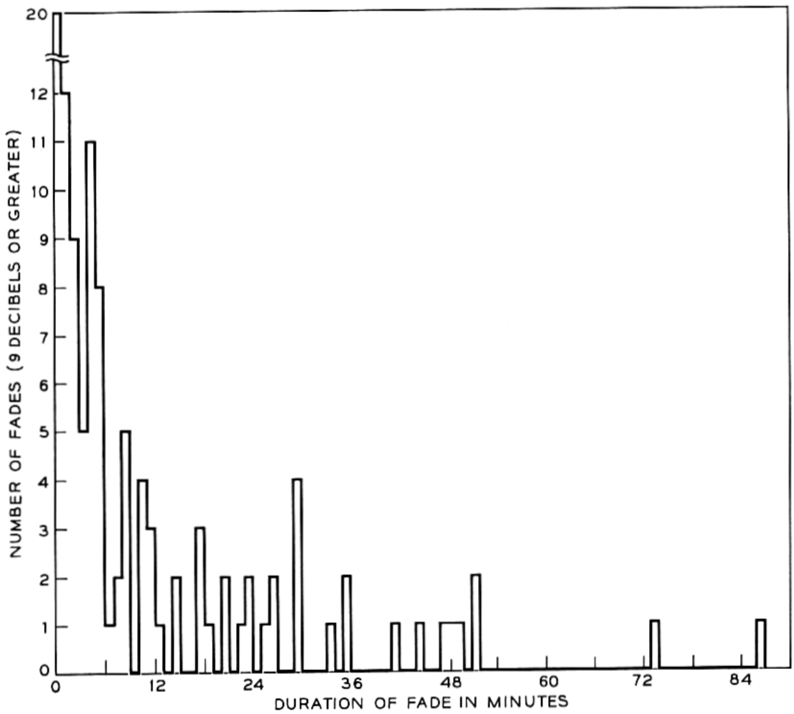

Fig. 7 — Number versus duration for fades of 9 dB or greater at 16 GHz from December 1967 to August 1968.

(*iii*) The brightness of the sun may not be constant. Clear weather records to date show no noticeable variations from day to day, except for a large increase for 40 minutes during the solar event of July 8, 1968 and increases of 1 dB or less lasting only a few minutes on several other occasions.

(*iv*) Part of the received signal might result from forward scattering by the precipitation. The scattered energy might therefore be collected by the relatively broad beam of the antenna and be indistinguishable from the direct signal. However, since rain drops are not large compared with a wavelength, the forward scattering lobe will be relatively weak and large in angular diameter. Moreover, approximately equal scattered power will be picked up in the direction of the sun and in the reference direction 2.6° away. Forward scattered energy should therefore cancel out, resulting in a proper measurement of attenuation. In measuring sky brightness at low attenuations, how-

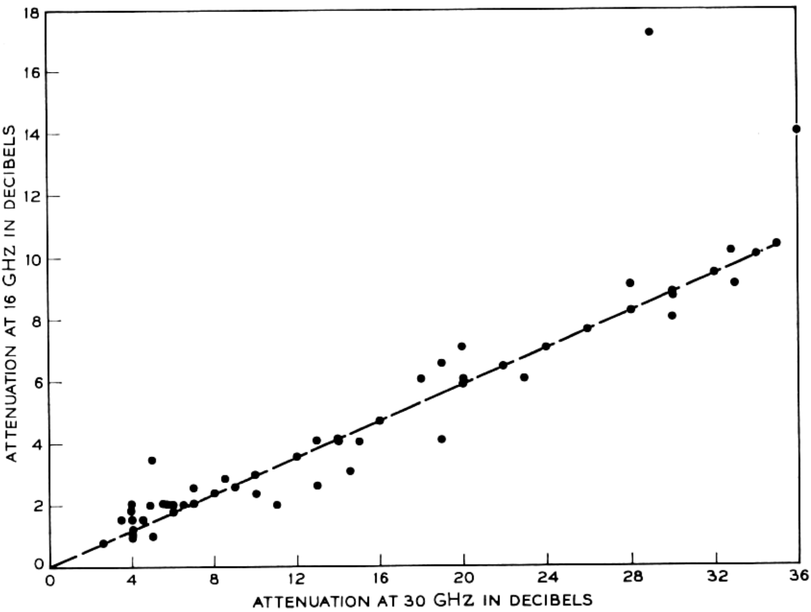

Fig. 8 — Scatter plot of attenuation at 16 GHz against simultaneous attenuation at 30 GHz (December 12, 1967).

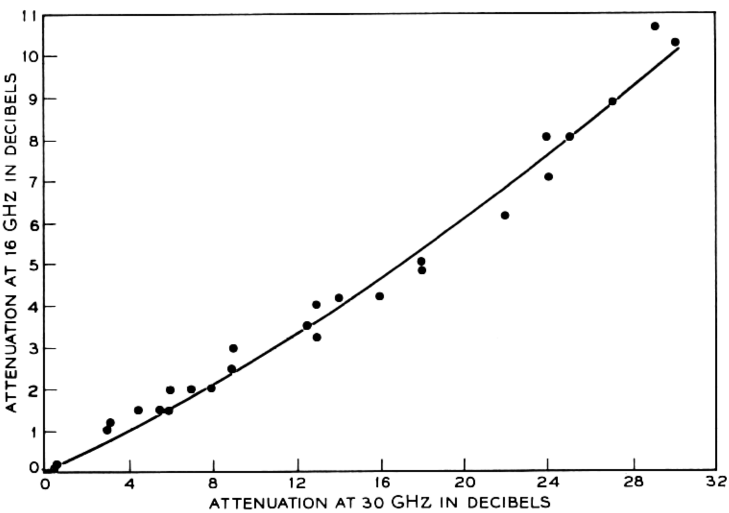

Fig. 9 — Scatter plot of attenuation at 16 GHz against simultaneous attenuation at 30 GHz showing change of ratio with rain rate (August 7, 1968).

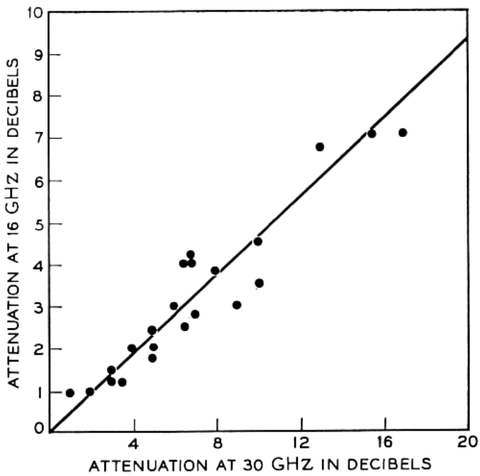

Fig. 10 — Scatter plot of attenuation at 16 GHz against simultaneous attenuation at 30 GHz for rain with noticably large drops (June 3, 1968).

ever, forward scattering will scatter energy from the cold sky into the antenna beam; in other words, it will not contribute to sky brightness in the same way that absorption does. The apparent value of T_c in equations (1) to (3) will be lower than the actual temperature of the absorbing water, consistent with the low values shown in Fig. 12 for small attenuations. The presence of the hot sun in the cold sky does not alter this conclusion since the sun's contribution averaged over the upper hemisphere will be much less than 1°K.

(*v*) In clear weather the transmissivity of the standard atmosphere will, in general, be different in the directions of the sun and of the reference region because of the difference in elevation angle of the two regions. Thus, even when not tracking the sun, the output of the sun tracker is not zero. At 30 GHz it can be as high as 25 dB below the sun at the low elevation cutoff of our observations. This effect does not limit the measuring range of the sun tracker because the false signal is attenuated as the sun is attenuated. If the high attenuation region caused by rain were concentrated near the sun tracker, the false signal from the atmosphere would be attenuated by the same amount as the sun. Also if the high attenuation region had the same temperature as the rest of the atmosphere, its position in the atmosphere would not matter; by the same argument the false signal would be attenuated by the same amount as the sun. In the unlikely case that the high attenuation region is beyond the atmosphere, the effect of the false signal would still be reduced with attenuation, but the maximum reduction would be the ratio of the average atmospheric temperature to the difference between the average atmospheric temperature and the temperature of the high attenuation region. In the actual case, precipitation will at worst be distributed through the atmosphere and have nearly the same temperature as the atmosphere leading to the conclusion that the false signal is not a practical limit to the measuring range of the sun tracker.

(*vi*) Precipitation collecting on the surfaces of the antenna can cause attenuation especially if the radio waves pass through a wetted surface such as a weather cover. This attenuation should not be attributed to the atmosphere. For tests on the effect of water on the surfaces, a fire truck with a fine spray nozzle was used. At a water fall rate of 15 inches per hour, 3 dB attenuation was observed at 30

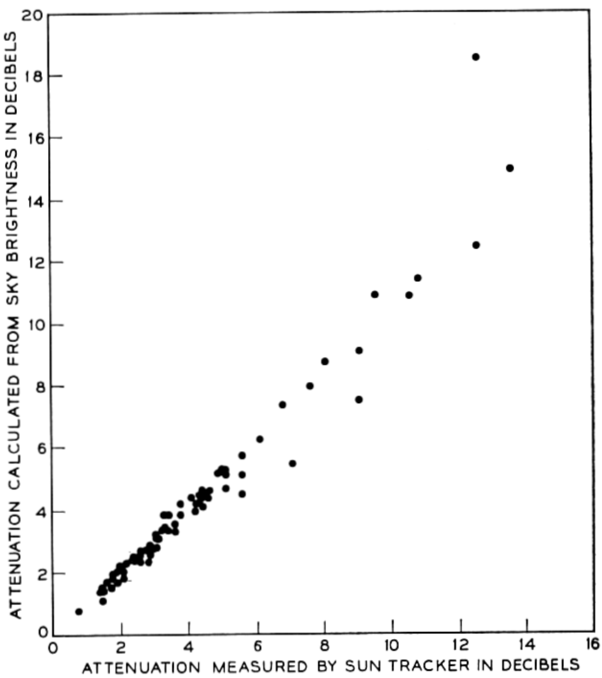

Fig. 11 — Scatter plot of attenuation calculated from sky brightness against the value measured simultaneously using the sun (16 GHz; $T_c = 272°K$; June 12, 1968).

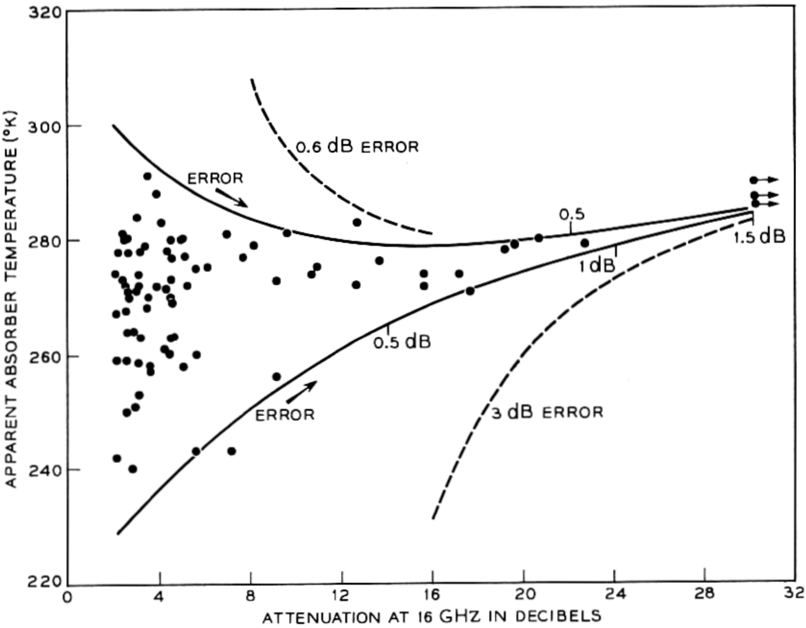

Fig. 12 — Apparent absorber temperature derived from sky brightness measurements plotted against attenuation. The dots are experimental points. The dashed lines show the effect in this plot of 10 dB differences between the attenuation in the direction of the sun and the reference region. The solid lines show the effect of 20 percent differences in attenuation. The resulting error in attenuation measured by the sun tracker is labeled on the curves. A linear change in absorber temperature with attenuation has been assumed in calculating the lines (June 12, 1968).

GHz and 1½ dB at 16 GHz. Snow is also an offender and measurements during snow have been discarded except immediately following removal of the accumulation.*

(*vii*) The high loss region (for example, a raincell) may not be uniform over the 2.6° lobing angle thereby resulting in a difference in brightness between the medium in the direction of the sun and the medium in the direction of the reference region. The main salvation in this case is that the sun produces an antenna temperature much higher than the physical temperature of the atmosphere. If the transmissivity of the medium in front of the sun is t_1 and in front of the reference region t_2, then on subtracting equation (2) from (1) we will have

* However, as discussed in Section V, an inch or so of dry snow on the antenna has only a small effect on antenna temperature.

$$\Delta T_a = t_1 T_s[1 + (t_2/t_1 - 1)(T_c/T_s)].$$

Since T_c/T_s is about 0.1 at both frequencies the maximum over-estimate of t_1 will be about 0.5 db as T_2 becomes much smaller than t_1. In the cast $t_2 > t_1$ the second term in the brackets would begin to dominate if $t_2/t_1 > 10$. Thus t_2 would be measured instead of t_1 for large ratios. Fluctuations of more than 10 dB in the transmissivity of the atmosphere over the 2.6° lobing angle would cause a significant average under-estimate of attenuation in the path to the sun.

The 16 GHz radiometer data plotted in Fig. 12 can be used to estimate the errors in attenuation measurement resulting from actual differences in attenuation. As shown above, a 10 dB excess of attenuation in the direction of the sun would cause about a 3 dB under-estimate of that attenuation. The expected apparent values of T_c in this condition are shown as the lower dashed line in Fig. 12. The upper dashed line indicates the values of T_c expected in the equally probable opposite case where the attenuation in the reference beam is 10 dB greater than in the direction of the sun. In this case the total error is only 0.6 dB. It is seen from Fig. 12 that the data excludes differences which are this great. In both of these cases and in the one to follow, a linear increase of T_c with attenuation has been assumed, namely from 265° at 0 dB to 285° at 30 dB.

A more realistic model of the fluctuations in attenuation is that they are some fraction of the total attenuation. The solid lines in Fig. 12 show the apparent values of T_c with plus and minus 20 percent differences in attenuation. These lines come remarkably close to being envelopes of the scattered points. The error in measured attenuation implied by this model is shown along the lines at 0.5 dB intervals. The maximum error of 1.5 dB out of 30 dB is acceptably small for the type of measurements intended with the sun tracker. The same type of plot has been made for other rains and with 30 GHz data with similar results.

If the temperature of the attenuating medium is T_1 in front of the sun and T_2 in the reference region, but the transmissivity is a constant value t, on subtracting equation (2) from (1) one obtains

$$\Delta T_a = tT_s\left[1 + \frac{1-t}{t}\frac{T_1 - T_2}{T_s}\right].$$

In this case the temperature difference appears linearly in the correction term so that positive and negative errors are equally likely. Thus if there were significant temperature differences over the 2.6° lobing angle, one would see periods of zero or negative receiver output during times of high attenuation. To date, when large attenuations have occurred, this behavior has not been observed and the output has had the same appearance as receiver noise in the absence of signal.

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