Abstract—Zenith sky brightness temperature measurements at 135 GHz and 215 GHz have been made on a semicontinuous basis for a period of seven months in the Gunston Cove area of Northern Virginia. These measurements were made using Dicke receivers with noise figures of 8 dB and 14 dB, respectively. A liquid nitrogen cooled load was used to calibrate the measurements. The 215 GHz sky temperature was on the average about 80 K greater than that at 135 GHz. Clouds were found to cause the sky temperatures to fluctuate as much as 150 K in a few minutes. Graphs are presented to outline general trends of the data as well as representative days, including the blizzard on February 11, 1983. In addition, empirical relations between precipitable water vapor, atmospheric water density at the surface, sky brightness temperatures, and zenith attenuation are given for visually clear days.

I. INTRODUCTION

The Earth’s atmosphere has four extremely high frequency (EHF) windows around 35, 95, 135, and 215 GHz. These windows are framed by rotational absorption lines of oxygen and water molecules and their transparencies vary with the atmospheric water content. Excellent reviews of the atmospheric propagation in this spectral region can be found in [1]–[3]. The two lower frequency windows have been more extensively characterized and utilized due mainly to availability of equipment. However, with the continuing improvement of technology in the millimeter wave region the upper two windows are becoming increasingly important for application in radio astronomy, remote sensing, and communications [4]–[6].

In this paper we report the measurement of zenith downwelling radiation at 135 GHz and 215 GHz over a seven-month period from January through July 1983, in the Gunston Cove area of Northern Virginia (longitude, 77°07′W; latitude, 38°41′N). This radiation is described in terms of an equivalent sky brightness temperature which at these frequencies is simply related to a black-body source by the expression $T = kT_{af}$, where $P$ is the detected power [7]. These sky brightness temperatures on clear days are caused almost entirely by atmospheric molecular emissions and can be used to calculate the zenith attenuation or absorption [8]–[11].

These measurements were made using an unique uncooled dual frequency Dicke radiometer [12] that provided near simultaneous measurements at the two frequencies ($\sim$3 ms switching time). Initially, data were recorded only during the daytime until system stability and reliability were established. Subsequently, they were taken continuously during the week from Monday morning to Friday evening. Corresponding weather data were obtained from two sources. Dew point, relative humidity, and surface temperature measurements at Washington National Airport (14 mi NNE) were supplied by the National Weather Service. Precipitable water data for this area were taken from contour maps supplied by the U.S. Air Force Environmental Technical Applications Center in Asheville, NC.

II. APPARATUS

Uncooled GaAs Schottky barrier diodes were used as the mixing elements for both of the receivers. The 215 GHz receiver was constructed at the Engineering Experiment Station

Sky Brightness Temperature Measurements at 135 GHz and 215 GHz

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at the Georgia Institute of Technology. It consisted of a Gunn diode local oscillator at 35.83 GHz which was tripled and then subharmonically mixed with the signal [13]. The mixer contained two antiparallel point contact diodes [14], [15]. A variable attenuator between the local oscillator and the mixer was set to obtain the maximum sensitivity. The 135 GHz receiver was purchased from Alpha/TRG. It also used a Gunn diode for the local oscillator which was tripled to the fundamental frequency of 135 GHz. The mixer contained two beam lead diodes (balanced type) [16]. Both receivers had IF bandwidths of 1 GHz. The receiver noise figures (DSB) were 14 dB for the 215 GHz system and 8 dB for the 135 GHz system. The signals from the square-law detectors were sent to lock-in amplifiers with time constants of 1 second and then recorded on a chart recorder. The chopping rate varied from 400 Hz initially to 300 Hz at the end due to wear in the chopper wheel bearings. The lock-in amplifiers were able to track the observed variations in the chopping rate.

The radiometer and the electronic equipment were housed in a truck which had a 5 cm thick styrofoam window and zenith reflector. The two receivers were arranged in the configuration shown in Fig. 1. The chopper was a 45 cm diameter polished aluminum wheel which acted both as a mirror and a window, allowing the receivers to alternately view the Dicke load and the sky. The Dicke load was made of Eccosorb CR-117 [17] and kept near ambient temperature (15-25'). The TPX (Poly 4-Methyl-Pentene-1) lens was 28 cm in diameter, causing a beam 140 cm aluminum wheel which acted both as a mirror and a window, allowing the receivers to view the primary calibration load. These structures included the two reflectors, the styrofoam window, and the lens. The effect of each of these objects is accounted for by using the following equation [2], [10]:

$$T_R = mV_R + T_D.$$  

(1)

Here $T_R$ represents the "output" radiation from the structure, $T_D$ is the "input" radiation, $T_A$ is the temperature of the structure, and $L$ is the loss factor. The first term on the right corresponds to the energy lost by absorption in the material and the second term is the energy emitted or reflected by the material. This equation assumes that the background energy reflected off the material equals the energy emitted by the material [18]. The sky temperature was calculated from $T_R$ by using (2) sequentially at each structure. The loss factor for the 5 cm styrofoam window was measured to be 1.05 for both frequencies and the loss factor for the lens was 1.26 at 215 GHz and 1.15 at 135 GHz. The losses due to the reflectors were negligible.

Sidelobe contributions from the receiver horn were not accounted for in the analysis but could add as much as 3 K to the measured temperatures. In addition, water accumulation on the window and reflector affected the readings during rainy weather. The absolute accuracy in these measurements is estimated to be ±10 K, due mainly to the uncertainty in the primary calibration standard.

IV. RESULTS

Fig. 2 shows the sky temperature data for a representative day. The weather for this particular day included rain which ended in the morning followed by a clear sky with scattered clouds in the afternoon. This weather is clearly indicated by the sky temperatures at both frequencies; the rain and clouds yield high sky temperatures because of their water content whereas clear skyes are relatively cool. Fig. 2 also illustrates some general results. For one, the 215 GHz sky temperature was almost always greater than the 135 GHz sky temperature, as expected. In addition, Fig. 2 shows the rapid fluctuations in temperature which can occur due to clouds. Changes in temperature of as much as 150 K in less than five minutes were sometimes measured. These fluctuations were caused by cumulus or stratus type clouds; high cirrus type clouds had little effect on the sky temperature.
Fig. 2. 135 GHz/215 GHz sky temperatures for June 8, 1983.

Fig. 3. Correlation of 135 GHz and 215 GHz sky temperatures. The equation of the fitted curve is $T_{135} = (2.08 \pm 0.12) \times 10^{-3} T_{215}^2 - (8.85 \pm 4.57) \times 10^{-2} T_{215} + (36.2 \pm 4.0)$. $\sigma = 7$ percent for this fit.

The analyses for Figs. 3–7 following contain only uniform sky data, i.e., days which were visually clear with the possible exception of high cirrus clouds. For these conditions the water density measurements at National Airport produced 263 data points, selected at equal time intervals. The precipitable water measurements were taken every 12 h and produced useful data for 92 of the 263 points. For Figs. 3–7 both linear and quadratic least squares fits were compared and the best one chosen. The accuracy of each fit is expressed as the root mean square (rms) deviation of the residuals $\sigma$ given as a percentage of the mean of the dependent ($y$-axis) variable.

Fig. 3 shows the correlation of the sky temperatures for the two frequencies including all 263 measurements. Fig. 4 shows the sky temperatures at both frequencies plotted against the atmospheric water density at the surface. Note in this case the 135 GHz data was best fit by a linear curve while the 215 GHz data was fit by a quadratic. The sky temperatures in Fig. 4 are in general agreement with those presented by Smith [11], however, this graph should be compared to Fig. 5 which shows sky temperatures plotted against the total precipitable water vapor. Here both the 215 GHz and 135 GHz data were best fit with quadratic curves. The sky temperatures are better correlated to the precipitable water than the surface water density, as expected [19]. It should be noted that the fitted curves in Figs. 4 and 5 have no physical basis; they are purely mathematical representations. The differences in the two fits can be explained by Fig. 6, which shows a

Fig. 4. Sky temperature versus surface water density. The equations of fitted curves are $T_{135} = (7.24 \pm 0.17)p + (38.6 \pm 1.5)$ for the 135 GHz data and $T_{215} = (-0.415 \pm 0.047)p^2 + (18.4 \pm 1.0)p + (74.4 \pm 3.7)$ for the 215 GHz data. $\sigma_{135} = 15$ percent and $\sigma_{215} = 11$ percent for these fits.

Fig. 5. Sky temperature versus total precipitable water. The equations of the fitted curves are $T_{135} = (-3.75 \pm 0.58)p^2 + (53.8 \pm 2.5)p + (30.4 \pm 2.1)$ for the 135 GHz data and $T_{215} = (-13.6 \pm 0.8)p^2 + (107.5 \pm 3.5)p + (71.7 \pm 2.8)$ for the 215 GHz data. $\sigma_{135} = 8$ percent and $\sigma_{215} = 6$ percent for these fits.
The sky brightness temperatures for the blizzard of February 10-11, 1983, are shown in Fig. 7. Also shown in this figure are representative points at 0 cm, 1.44 cm, and 2.87 cm derived from the NTIA millimeter wave propagation model for the U.S. Standard Atmosphere [20].

In Figs. 8 and 9 the hourly sky temperatures are presented in terms of frequency of occurrence by month for February through July. Only complete 24 hour cycles, generally Monday through Friday morning, were included in this data set. Both these figures indicate that this area had a short spring in 1983; February through May represent winter months and June and July represent summer.

The median daily sky temperature difference $\Delta T$ and the rms deviation in kelvins are shown by month in Table I. Rainy days, in which the temperature difference was very small, were not included in these results. In a very few instances, thunderstorms in particular, the 135 GHz temperature became greater than the 215 GHz temperature. In other instances, again rare, the two frequencies would indicate opposite changes, i.e., one would increase while the other decreased. It is not known if these anomalies are real or if the beams intercepted different active areas in the sky because of spot size or beam misalignment. Before installation in the truck the beams were aligned within 1° of each other.

The minimum and maximum sky temperatures are also shown in Table I for these measurements. Although there were more cold days in January, the coldest sky temperatures occurred on March 25, in the presence of high cirrus type clouds. There is a sharp jump in the minimum sky temperature between May and June, another indication of the short spring in this area. The warmest temperatures were near 300 K at both frequencies during heavy overcast or rainy conditions each month.

The sky temperatures for the blizzard of February 10-11, 1983, are shown in Fig. 70. Although the sky temperatures began to increase on the 10th, heavy snow fall did not begin until 0700 on the 11th and lasted about 10 h. In terms of total snowfall, this was the third worst storm in the history of this area.
This was a "dry" snow which did not collect on the reflector or window.

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Effect of Jammer Power on the Performance of Adaptive Arrays

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Abstract—The effect of jammer power on the performance of adaptive arrays is studied. It is shown that the output signal-to-interference-plus-noise ratio (SINR) of an adaptive array is a function of jammer power. In the presence of a wide-band jammer, the output SINR of the array decreases with an increase in jammer power and eventually goes to zero. Unlike continuous wave (CW) jammers, a wide-band jammer does not go through power inversion. Instead, as the jammer power is increased, the interference-to-noise ratio (INR) at the array output shows oscillations. For large jammer power, the output INR increases with an increase in jammer power.

I. INTRODUCTION

IN RECENT YEARS, adaptive antenna arrays have been receiving a great deal of attention in the areas of radar, sonar, communication, and seismic systems. One of the primary reasons for this fast growing interest is the protection it provides against undesired signals (jammers, unintentional RF interferences, etc.). An adaptive array automatically steers pattern minima onto sources of undesired signals, thereby reducing undesired signals at the array output. The stronger an undesired signal, the lower is the pattern minimum, and thus the undesired signals go through power inversion [1], [2] and the output signal-to-interference-plus-noise ratio (SINR) does not vary much with jammer power. These concepts of steering pattern minima and power inversion apply to narrow-band signals, but not to wide-band signals where different frequency components arrive with different phases at the array elements; and consequently a pattern minimum at one frequency may not be a pattern minimum at another frequency. Thus, it is difficult to assess the output SINR and the output interference-to-noise ratio (INR) as jammer power varies.

In this paper, analytic expressions for the output SINR and INR of an adaptive array in the presence of wide-band jammers are derived. The expressions give the output SINR and INR in terms of the eigenvalues and the corresponding eigenvectors of the covariance matrix of undesired signals (jammers and thermal noise) present at the array elements. Thus, knowing the jammer characteristics, one can assess the adaptive array performance.

It is shown that the output SINR of an adaptive array is a function of jammer power. The output SINR decreases with increasing jammer power and, for a wide-band jammer, it eventually goes to zero. Unlike continuous wave (CW) jammers, a wide-band jammer does not go through power inversion. Instead, as the jammer power is increased, the INR at the array output undergoes oscillations. Beyond a certain jammer power level, the output INR monotonically increases with increasing jammer power. At this point the array is fully constrained and the array output SINR drops sharply.

The expressions for the output SINR and INR are derived in Section II. Adaptive array performance in the presence of a CW signal is discussed in Section III. Section IV deals with a wide-band jammer.

II. OUTPUT SINR OF AN LMS ADAPTIVE ARRAY

The steady state weight vector \( w \) of the least mean square (LMS) adaptive array due to Widrow et al. [3] is given by

\[
\mathbf{w} = \Phi^{-1} \mathbf{S}
\]  

where \( \Phi \) is the covariance matrix of the signals present in the array elements, and \( S \) is the reference correlation vector. In the presence of a single CW desired signal and \( m \) jammers, the covariance matrix \( \Phi \) can be written as

\[
\Phi = \sigma^2 I + \Phi_d + A_d^2 U_d^T U_d T
\]

where \( \sigma^2 \) is the thermal noise power in each antenna element, \( I \) is an \( N \times N \) identity matrix, \( \Phi_d \) is the covariance matrix due to the jammers, \( A_d \) is the desired signal amplitude, \( U_d \) is the desired signal vector, and superscripts asterisk and \( T \) denote complex conjugate and transpose, respectively. In (2), it is assumed that the thermal noise voltages from the array elements are Gaussian with zero mean and variance \( \sigma^2 \) and are uncorrelated with each other and with other signals incident on the array. The desired signal is assumed to be a narrow-band signal uncorrelated with jammers. Further, assuming that the reference

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