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Brightness Temperature and Attenuation Diversity Statistics at 20.6 and 31.65 GHz for the Colorado Research Network

by

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Abstract--A limited network of four dual-channel microwave radiometers, with frequencies of 20.6 and 31.65 GHz, was operated in the front range of eastern Colorado from 1985 to 1988. Data, from November 1987 through October 1988 are analyzed to determine both single-station and joint-station brightness temperature and attenuation statistics. Only zenith observations were made. The spatial separations of the stations varied from 50 km to 190 km. Before the statistics were developed, the data were screened by rigorous quality control methods. One such method, that of 20.6 vs. 31.65 GHz scatter plots, is analyzed in detail, and comparisons are made of measured vs calculated data. At 20.6 and 31.65 GHz, vertical attenuations of 5 and 8 dB are exceeded 0.01% of the time. For these four stations and at the same 0.01% level, diversity gains from 6 to 8 dB are possible with the 50 to 190 km separations.

I. Introduction

During 1985 through 1988, the Wave Propagation Laboratory (WPL) of the National Oceanic and Atmospheric Administration (NOAA) operated a limited network of four dual-channel microwave radiometers. The radiometers, operating at 20.6 and 31.65 GHz, were deployed for the meteorological purposes of measuring precipitable water vapor (PWV) and integrated cloud liquid water (CLW). Data from ground-based microwave radiometers are commonly used to derive attenuation statistics (Ortgies et al., 1990; Vogel et al., 1991; Fionda et al., 1991). Using the radiometric technique, these authors have shown that attenuation levels up to about 12 dB can be derived with good accuracy. Since attenuation is the sum of absorption and scattering, and since scattering is not negligible when rain rates are in the 5 to 10 mm/hr region, radiometrically-derived absorption is not representative of attenuation under such rain conditions. Data from two of the Colorado stations, Denver and Platteville, have previously been used to derive single-station and two-station attenuation statistics for 2 three-month periods during 1988 (Fionda et al., 1991). Here, we greatly extend that work by deriving attenuation and attenuation-diversity statistics for an entire year's data taken at each of the four stations. For completeness, we also present complementary statistics on the basic measured variable - brightness temperature T_b. Since operations at two of the stations, Fleming and Flagler, were discontinued during November of 1988, we used data starting from November 1, 1987, and ending at October 31, 1988, to derive a complete year's statistics.

II. Description of Radiometers in the Colorado Research Network

A. Location

A description of Wave Propagation Laboratory radiometers was given by Westwater and Snider (1987); here we will only describe in limited detail the dual-channel radiometers of the Colorado Research Network. Their geographical coordinates and the separation distances are given in Table 1.

B. Radiometer Characteristics

The dual-channel radiometers were designed, constructed, and field-tested by WPL; a complete description of the systems is given by Hogg et al.(1983). The instruments were designed to run continuously, to provide unattended operations, and to operate in almost all weather conditions. The salient characteristics of the instruments are shown in Table 2. Note that the antenna beamwidth at Denver differs from those of the other three stations. Field experiments (Snider, 1988), in which a steerable radiometer with a 2.5 deg beamwidth was compared with the network radiometers with their 5 deg beamwidths, showed a 0.99 correlation between the systems. The receivers of all four radiometers are of the same construction. The internal calibration of the radiometers is done by switching between the antenna and two hot blackbody loads; external calibration is done approximately every two weeks using the "tip cal" method (Hogg et al., 1983; Decker and Schroeder, 1991).

C. Methodology to Derive Attenuation from Emission

The basic quantity measured by a radiometer is brightness temperature, which is closely related to input power present at an antenna (Ulaby et al., 1981). Although the probability distributions of T_b are of interest in themselves, the quantities needed by communication engineers are the distributions of attenuation. We derive attenuation τ(dB) from T_b by using the well-known formula (Westwater et al., 1990)

$$\tau(\mathrm{dB}) = 4.34 \ln\{(T_m - T_c)/(T_m - T_b)\} \quad , \qquad (1)$$

where T_m = mean radiating temperature (K),

and T_c = cosmic background temperature = 2.75 K.

In deriving τ, we used monthly mean values of T_m (see Table 3) that were calculated from our radiative transfer and cloud models. With monthly mean values of T_m, estimated rms errors of about 7^0C occur. These errors become important when deriving attenuation from the higher values of T_b, say those greater than 150 K.

III. Quality Control

The radiometric data were taken by radiometers that operated in an unattended mode, although bimonthly on-site calibrations were done. For the most part, the data were of high quality, although occasional outliers had to be removed from the data. Such outliers can arise from liquid and ice buildup on the antennas, spurious signals of electromagnetic origin, calibration drifts in the receivers, and data transmission errors. To eliminate obvious erroneous data, we plotted and inspected daily time series of the following quantities: brightness temperature T_b at 20.6 and 31.65 GHz; derived values of PWV and CLW. If a record had an obvious error at either frequencies, data from the entire record were removed. Next, scatter plots of T_bs at both frequencies were constructed; usually, suspicious points were easily identified from these plots. Westwater and Falls (1991) described the method in more detail and gave examples of the method. That method was applied to all the data analyzed in this report.

One other consideration is necessary before we present our results. Westwater et al. (1990) have shown that calculations of clear air brightness temperature, based on coincident radiosonde soundings and contemporary absorption algorithms (Liebe and Layton; 1987), differed from T_b measurements that were calibrated by the tip cal method. Consequently, we adjusted our calculated values $T_{b,cal}$, based on their absorption algorithms, to be consistent with those determined by a tip cal procedure. These adjusted values $T_{b,adj}$, based on the data set described by Westwater et al. (1990), are

$$\begin{aligned} &20.6\ \text{GHz:} && T_{b,adj} = 1.144\ T_{b,cal} - 0.049 \\ &31.65\ \text{GHz:} && T_{b,adj} = 0.970\ T_{b,cal} + 1.407\ . \end{aligned} \qquad (2)$$

A scatter plot of adjusted calculated data is shown in Fig. 1. We note that the range of calculated T_b's is considerably less than that of the measured values, presumably because we underestimate the range of cloud liquid that occurs. This is not surprising, because our cloud calculations, based on the Rayleigh approximation, do not contain a rain model. However, over the range of calculated T_b's, the slopes and ranges of variation of measured and calculated data are similar. To gain insight into the ranges of variation and their causes, we also calculated T_b's as a function of (a) PWV for clear conditions, (b) CLW for cloudy conditions, (c) PWV during both clear and cloudy conditions, and CLW for both clear and cloudy conditions. These results are shown in Figs. 2 and 3 for 20.6 and 31.65 GHz. We note from these figures that for clear conditions, T_b's at both frequencies vary linearly with PWV over the range of 0.3 to 4.0 cm. The interesting behavior occurs when clouds are present; for a given vapor, there is a considerable range of variation in T_b due to the allowable range of CLW. Conversely, for a given amount of CLW, there is a considerable range of variation in T_b due to clouds. These figures also clearly show the relative sensitivity of the two channels to vapor (20.6 GHz is more sensitive) and to liquid (31.65 GHz is more sensitive). Finally, we show in Fig. 4, scatter plots of calculated T_b's, during clear and cloudy conditions. Thus, the lower straight line borders in the scatter plots are determined by the amount of PWV, and the more diffuse upper boundaries are determined by the amount of CLW.

IV. Single-Station Attenuation Statistics

After the quality control methods discussed above were applied to the data, cumulative distributions of brightness temperature and radiometrically-derived attenuation were derived for each of the four stations. In addition, the composite of all stations was also computed. The results for brightness temperature and attenuation are shown in Figs. 5 and 6. Perhaps not too surprisingly, there is not a substantial difference between any of the four stations. At both frequencies, Denver is slightly colder in T_b and is slightly less attenuating than the other three stations. For both frequencies, attenuation is less than 1 dB at the 1% level, and is less than 7.5 and 9.5 dB at the 0.01% level for 20.6 and 31.65 GHz. Finally, the four-station composite values are plotted in Fig. 7. It will be of interest to compare these radiometrically derived values of attenuation with forthcoming beacon measurements from ACTS (Chakraborty and Davarian, 1991).

V. Joint-Station Attenuation Statistics

At the time these data were taken, the sampling times for each station were not synchronous, and starting times could differ by up to 1 1/2 minute. To compute joint-station diversity statistics, it is necessary to put time series from each station into one-to-one temporal correspondence. For our data, we set up a 2-minute window, and when starting times from each of the two stations fell within this window, the data were placed in correspondence. If a complete pair of data was not available, the 2-minute sample was eliminated. Over a year's time, we were able to obtain a significant sample size for analysis: a minimum of 155,739 data pairs (Platteville - Flagler) and a maximum of 218,521 data pairs (Denver - Fleming).

The results for the joint-station diversity analyses are given in Fig. 8. We note that the diversity curves are all quite similar for the stations that are separated by ≈ 150 km, but that the closer pair, Denver - Platteville, differ significantly from the other five station pairs. Roughly, at the 0.01% level, the diversity gains for Denver - Platteville are about 6 dB at both 20.6 and 31.65 GHz; at the 150 km separations, the corresponding gains are about 6-7 and 8 dB at the lower and upper frequency.

VI. Summary and Plans

We have derived yearly cumulative distributions of brightness temperature and attenuation for all four stations of the Colorado Research Network. Both single and joint-station distributions were derived for these stations whose separations varied from 49 to 190 km. We plan to publish more detailed versions of the work presented here both as a technical memorandum to the sponsor and as an open literature publication.

We plan to analyze and publish attenuation statistics for a variety of locations at which we have operated dual-channel radiometers. Most recently, we have completed a year's observations at Norman, Oklahoma, and will soon be processing these data.

VII. Acknowledgements

The authors thank Jack Snider for calculations of Table 1 and regression coefficients and also thank Sergei Matrosov for his usefull comments on the manuscript.

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Table 1. Geographical coordinates and spacings of the Colorado Research Network

Site	Latitude (deg.)	Longitude (deg.)	Elevation (msl)
Denver	39.75 N	104.87 W	1.611
Flagler	39.12 N	103.09 W	1.463
Fleming	40.63 N	102.94 W	1.337
Platteville	40.18 N	104.73 W	1.523

Combination	Spacing (km)
Denver-Platteville	49.25
Denver-Flagler	168.04
Denver-Fleming	190.79
Flagler-Fleming	168.28
Flagler-Platteville	183.19
Fleming-Platteville	159.50

Table 2. Characteristics of WPL Dual-channel Radiometers

Operating frequencies (GHz)	20.6 and 31.65 GHz
Viewing	Zenith
Antenna half-power beam width	2.5^0 (Denver), 5.0^0 (other three)
Total bandwidth (double side band)	1 GHz
Integration time	2 min
Sensitivity (for 2-min integration time)	0.05 K rms
Estimated absolute accuracy	0.75 K

Table 3. Monthly-averaged mean radiating temperatures/standard deviations for 20.6 and 31.65 GHz., Denver, Colorado, 1970 - 1985.

Month	1	2	3	4	5	6	7	8	9	10	11	12
20.60	259.7 5.5	260.3 5.3	262.8 5.4	266.4 5.7	270.7 6.2	275.4 5.4	278.3 3.9	277.7 4.3	274.3 5.9	270.9 7.4	264.4 6.5	260.8 5.8
31.65	255.7 5.0	256.3 5.0	258.6 5.4	262.1 5.7	266.3 6.1	270.9 5.6	273.8 4.4	273.3 4.7	269.8 5.9	266.4 7.2	260.1 6.0	256.7 5.2

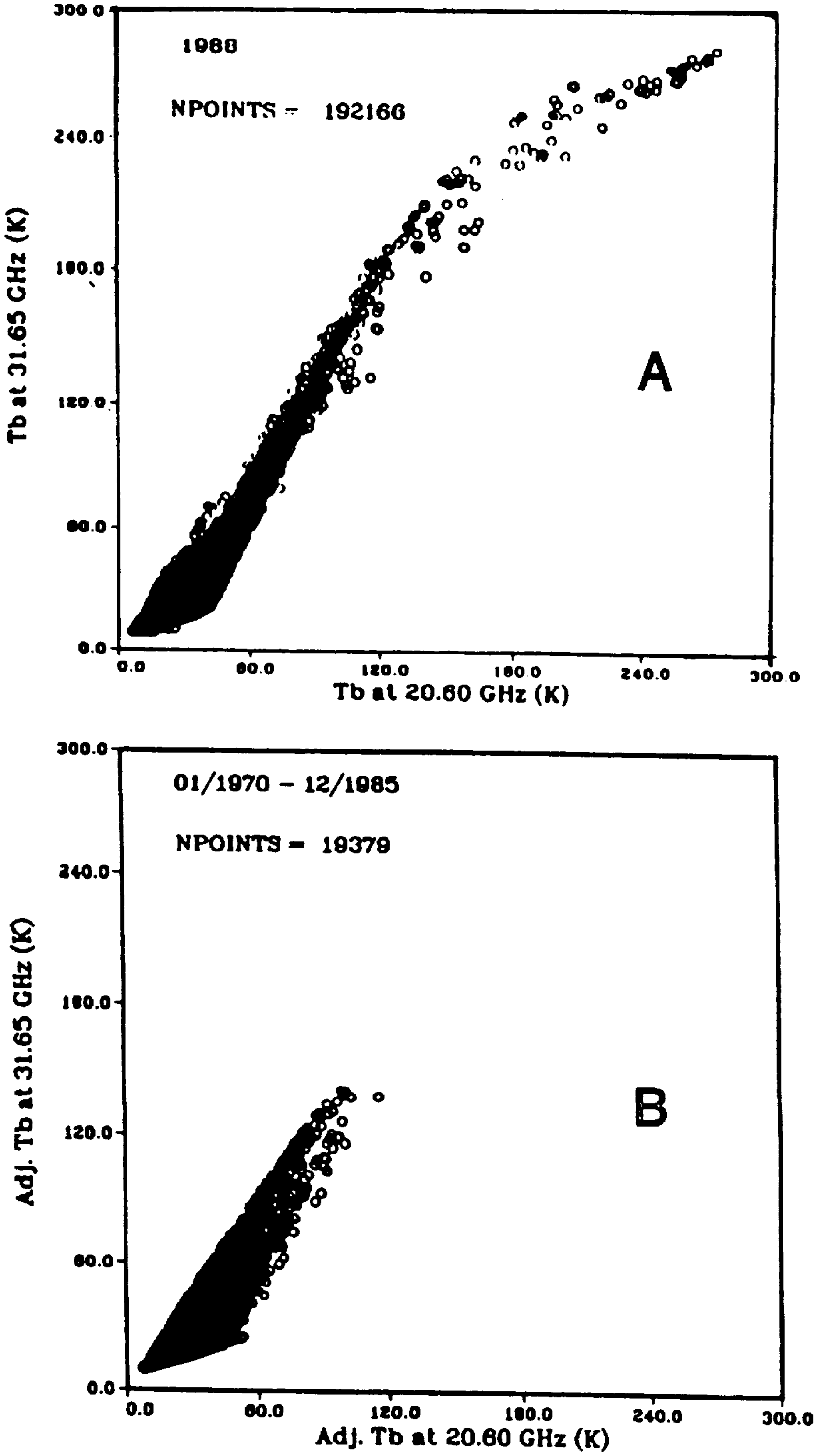

Fig. 1. Scatter plots of measured (A) and calculated (B) T_b at 20.6 and 31.65 GHz from Denver, Colorado. The measured data were taken in 1988; the calculated data were based on radiosondes taken during 1970-1985. The calculated T_b values have been adjusted to be consistent with those determined by the tip cal procedure (see Section III for details).

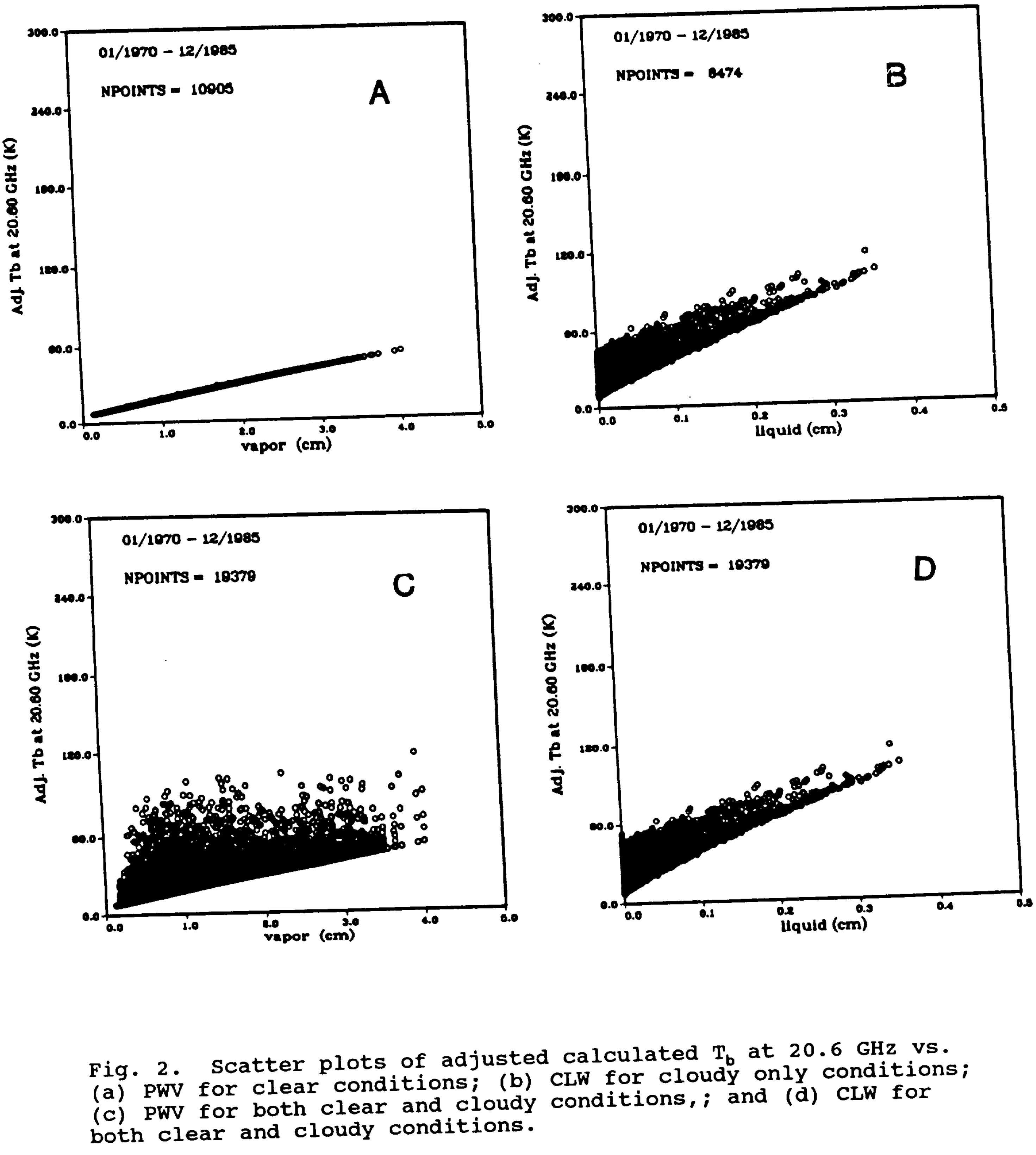

Fig. 2. Scatter plots of adjusted calculated T_b at 20.6 GHz vs. (a) PWV for clear conditions; (b) CLW for cloudy only conditions; (c) PWV for both clear and cloudy conditions,; and (d) CLW for both clear and cloudy conditions.

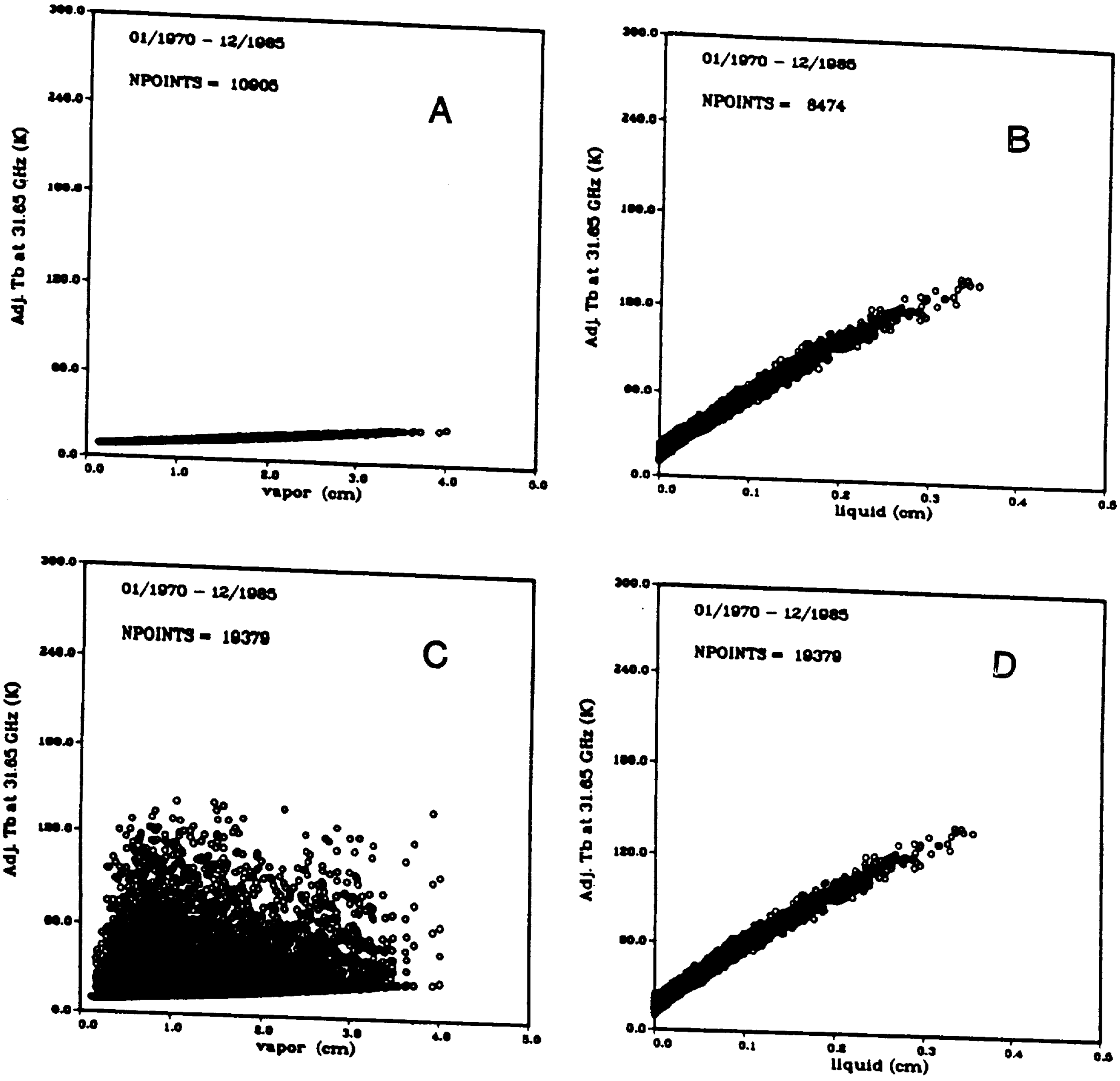

Fig. 3. Scatter plots of adjusted calculated T_b at 31.65 GHz vs. (a) PWV for clear conditions; (b) CLW for cloudy only conditions; (c) PWV for both clear and cloudy conditions,; and (d) CLW for both clear and cloudy conditions.

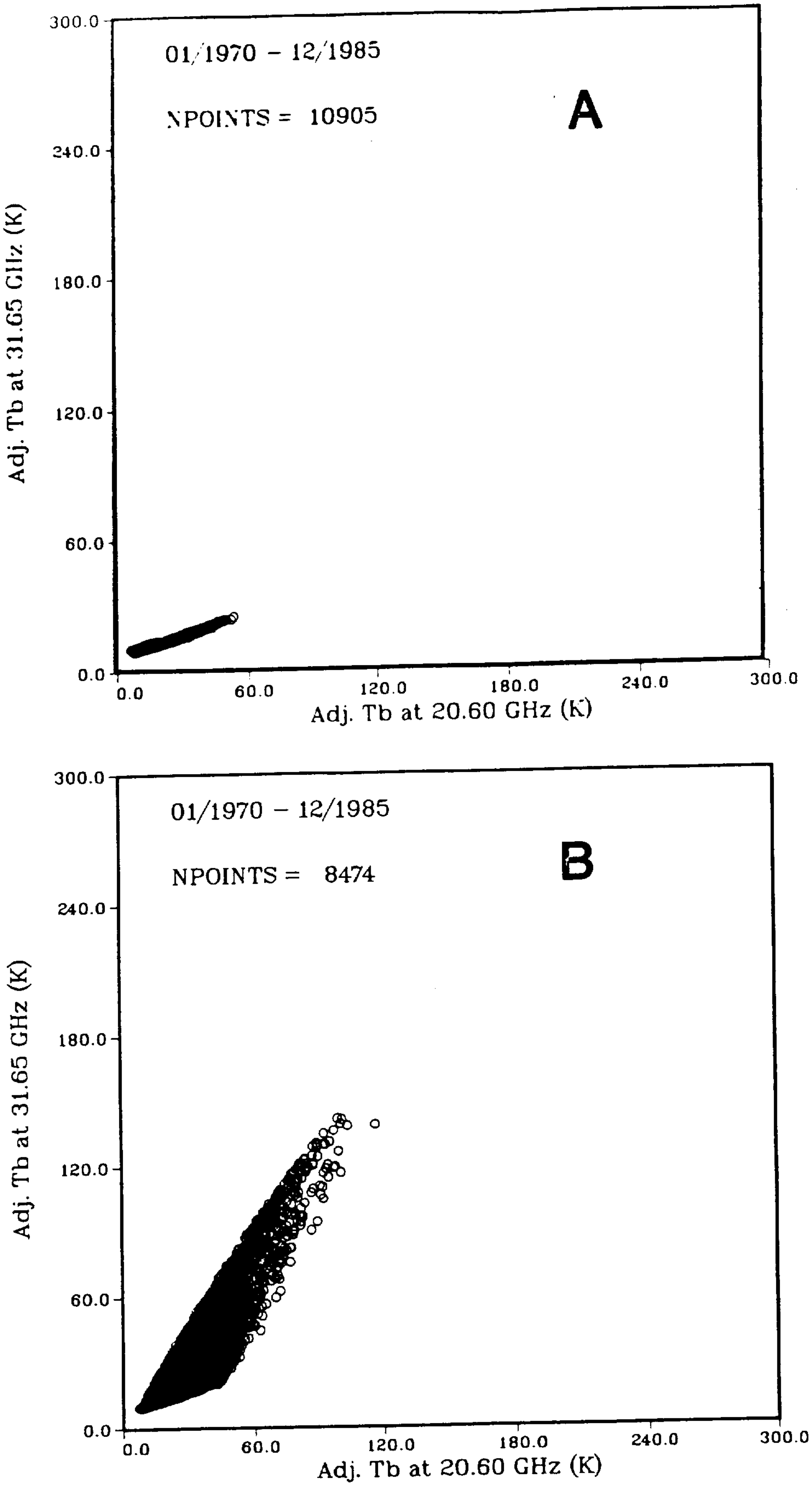

Fig. 4. Scatter plots of adjusted calculated T_b at 20.6 and 31.65 GHz for (a) clear conditions; (b) cloudy conditions only.

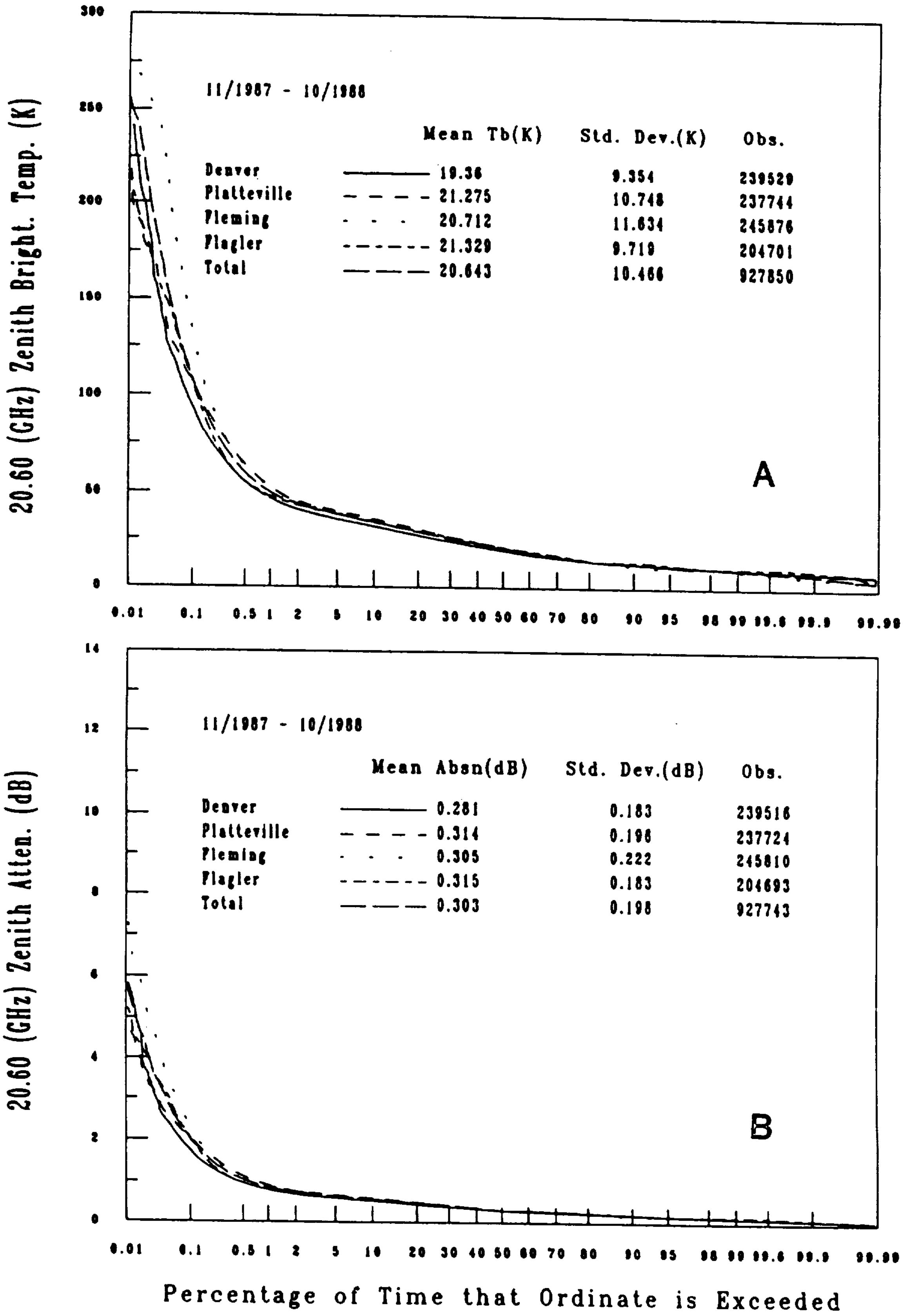

Fig. 5. Cumulative brightness temperature (A) and zenith attenuation (B) statistics for the four stations of the Colorado Research Network at 20.6 GHz.

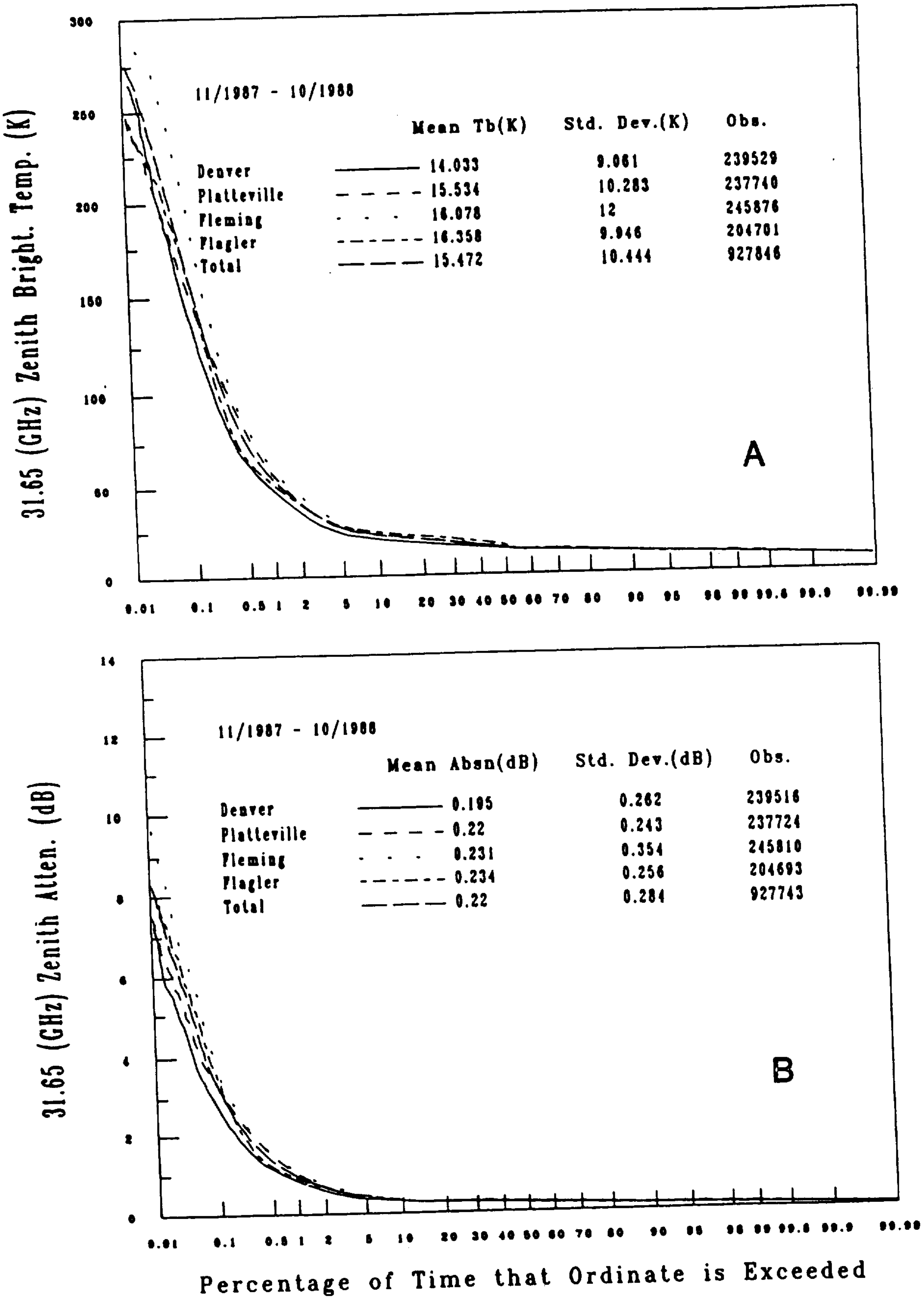

Fig. 6. Cumulative brightness temperature (A) and zenith attenuation (B) statistics for the four stations of the Colorado Research Network at 31.65 GHz.

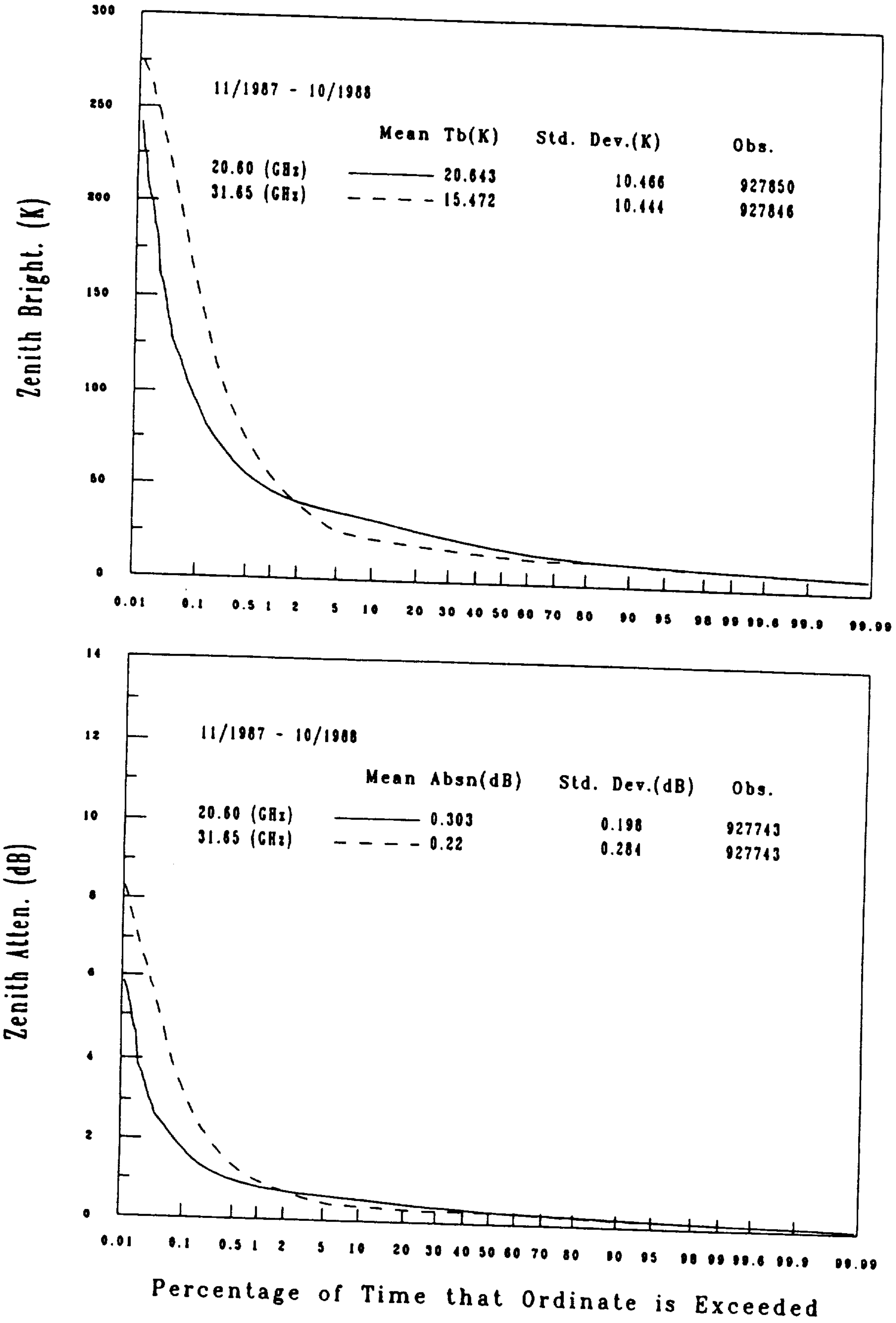

Fig. 7. Composite brightness temperature (A) and zenith attenuation (B) statistics for the four stations of the Colorado Research Network.

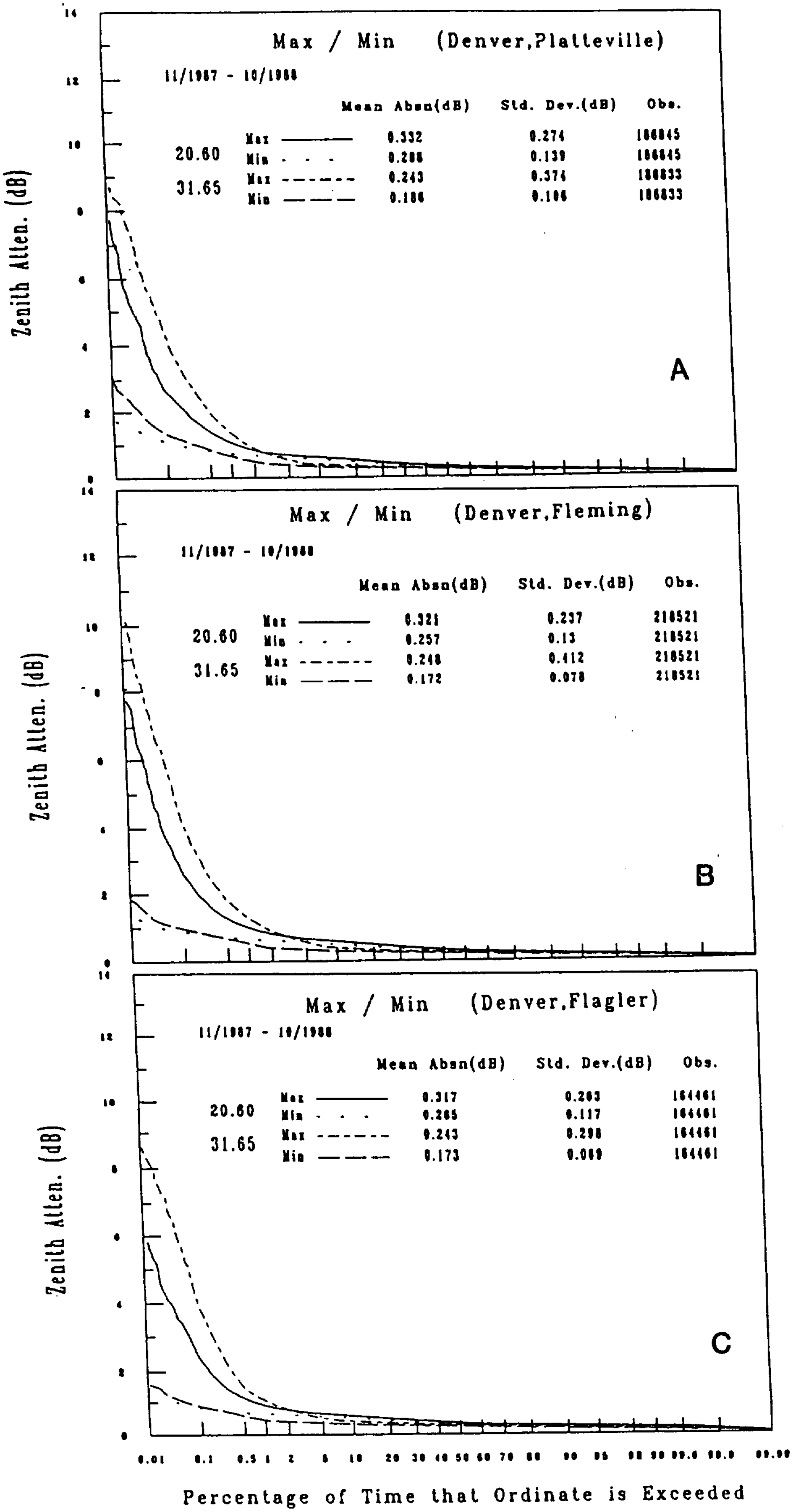

Fig. 8-A. Joint-station zenith attenuation diversity statistics for the Colorado Research Network. Denver with outlying sites.

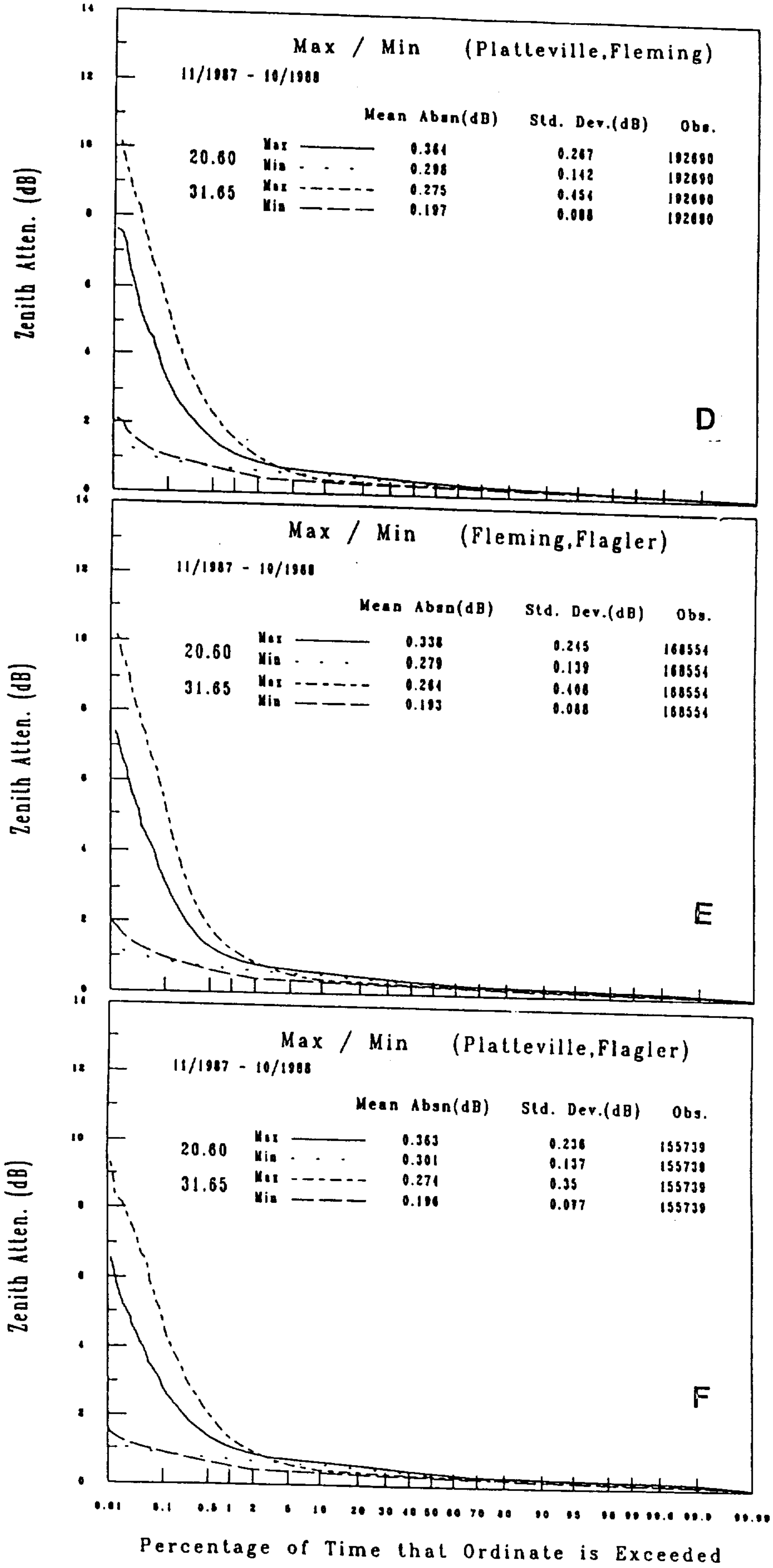

Fig. 8-B. Joint-station zenith attenuation diversity statistics for the Colorado Research Network. Non-Denver sites.