Field Evaluation of a Dual-Channel Microwave Radiometer Designed for Measurements of Integrated Water Vapor and Cloud Liquid Water in the Atmosphere

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ABSTRACT

The dual-channel microwave radiometer is evaluated in regard to the measurement of integrated water vapor and supercooled liquid water. The study includes comparisons of integrated vapor content measured by the radiometer and rawinsondes as part of the Sierra Cooperative Pilot Project in the central Sierra Nevada. In addition, two radiometers with virtually identical characteristics were brought together on the Colorado Orographic Seeding Experiment at Steamboat Springs, Colorado, in order to study the stability and comparability of integrated vapor and liquid measurements.

Comparison of vapor measurements by the radiometer and by rawinsonde yielded a correlation coefficient of 0.94, and a rms difference of 0.08 cm. There were no significant differences between results for paired data gathered in storms in the presence of supercooled liquid water and for paired data gathered on clear days under more ideal conditions. The collocated-radiometer experiment showed slightly closer agreement than did the comparisons of radiometer data with rawinsondes. Comparisons of paired data from the vapor channel yielded a correlation coefficient of 0.95 with a rms difference of 0.05 cm, while the liquid water channel data yielded a correlation coefficient of 0.99 with a rms difference of 0.02 mm.

The study lends further credence to other theoretical estimations of the accuracy of the radiometer measurement, in that the measured values of integrated vapor are probably within 15% of truth. Measurements of supercooled liquid water are reproducible and very stable.

1. Introduction

The dual-channel microwave radiometer (Hogg et al., 1983) has become an important study and evaluation tool for weather modificaton research, particularly for wintertime storms that occur over the western United States (e.g., Holroyd and Super, 1984; Long and Walsh, 1984; Heggli, 1985; Sassen et al., 1986; Rauber et al., 1986). The radiometer provides continuous measurements of both liquid water and vapor integrated through the depth of the atmosphere. At present, there are only two dual-channel radiometers with full scanning capability in the United States: one operated by the Bureau of Reclamation (USBR) and the other by the National Oceanic and Atmospheric Administration (NOAA) Wave Propagation Laboratory. A third unit is currently under construction at the University of Nevada, Desert Research Institute.

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Before radiometric measurements can be confidently applied to analyses, field evaluations of performance specifications must be undertaken, so that limitations and deficiencies of radiometric measurements can be recognized and understood. This paper presents results from field evaluations conducted during the Sierra Cooperative Pilot Project (SCPP) and the Colorado Orographic Seeding Experiment (COSE).

The SCPP has incorporated a microwave radiometer to study the potential for precipitation enhancement of wintertime storms in the central Sierra Nevada. The COSE program is a similar study designed to evaluate the precipitation augmentation potential of wintertime cloud systems that occur over the northern Colorado River Basin. Both of these programs have used microwave radiometric measurements extensively to interpret the physical processes in these cloud systems (Heggli, 1985; Rauber et al., 1986). As part of this research, these programs have taken steps to compare measurements made by microwave radiometers with independent in situ instrumentation.

The field evaluation was performed in two phases. The first, carried out in the SCPP, compared radiometric measurements of water vapor with precipitable water vapor measurements made by a collocated rawinsonde unit. The second phase was conducted during COSE. During this experiment two radiometers were brought together for an intercomparison test. A limited number of rawinsondes were also launched during routine radiometer calibrations to compare vapor measurements.

A third phase of the experiment, not reported here, attempted to compare radiometric liquid measurements with in situ measurements by aircraft. To date, this later experiment has met with limited success, primarily because variations in cloud integrated liquid occur on time scales shorter than that required for an aircraft to descend through the cloud (e.g., Heggli and Reynolds, 1985; Rauber et al., 1986).

2. Instrumentation

a. Dual channel microwave radiometer

The dual channel microwave radiometer is a ground-based passive instrument which determines the brightness temperatures emitted by water vapor and cloud liquid water. The quantity of vapor and liquid is determined by the magnitude of the brightness temperature at specific microwave frequencies. The principles of microwave thermal emission from Rayleigh attenutating clouds have been described by Westwater (1972). The design and operation of the dual-channel ground based microwave radiometer have been presented by Hogg et al., (1983) and Guiraud et al., (1979). The SCPP radiometer was designed by NOAA and manufactured by the Hughes Corporation.

The radiometer operates at two frequencies: 20.6 GHz, sensitive primarily to water vapor, and 31.65 GHz, sensitive primarily to liquid water. The antenna beam width is 2.5°. Path-integrated amounts of water vapor and liquid water, expressed as depth in centimeters and millimeters, respectively, are calculated from the radiometer measurements of brightness temperature using statistical retrieval algorithms (Hogg et al., 1983). The coefficients in these algorithms are derived from a set of radiosonde data appropriate to the area in which observations are made. The coefficients include the effects of the small absorption by oxygen at each operative frequency. For nonprecipitating clouds or clouds with relatively low amounts of liquid water (i.e., <1.5 mm zenith-equivalent), the retrieval coefficients are self-correcting and limit the algorithm induced measurement uncertainty to less than 5% (Westwater and Guiraud, 1980). This measurement uncertainty can be further reduced through the use of adaptive coefficients, which are a function of the initial estimates of the amounts of vapor and liquid present during the observation. However, due to the low amounts of liquid water present in the clouds reported here, adaptive coefficients were not employed.

Sources of error in radiometric measurements of liquid and vapor are associated with estimation of the mean radiating temperature of the emitter, the determination of brightness temperature, uncertainties in dry attenuation, and uncertainty in the vapor and water attenuation coefficients (Westwater, 1978). Westwater estimated that with these uncertainties in the absorption calculation, liquid retrieval accuracies better than 15% can be achieved for a wide range of liquid water contents. Rain or mixed phase precipitation also may obscure the measurement of cloud liquid. False signals can also be caused by melting hydrometers and/or a water coated reflector. Periods when melting occurred or the reflector was wet were removed from the dataset prior to this analysis. Ice crystals, on the other hand, have no discernible effect on the emissions by water vapor and liquid, whether it be falling or resting on the reflector.

During SCPP, the USBR radiometer was located in the high alpine environment of the central Sierra Nevada at Kingvale, California, elevation 1857 m (all heights are relative to mean sea level). This radiometer was operated during the winter months of December 1984 through March 1985. Rawinsonde observations were taken concurrently during storms at Kingvale.

The USBR and NOAA radiometers were collocated in COSE. The elevation of the radiometers was 2050 m. The two radiometer systems operated independently. However, the mean radiating temperatures and atmospheric attentuation coefficients used to retrieve vapor and liquid were identical. Retrieval coefficients were calculated from a sample of 352 soundings released in previous COSE experiments from Craig, Colorado.

b. Rawinsondes

Upper air observations were made during the SCPP and COSE. The Sierra Cooperative Pilot Project launches were made at Kingvale, where the radiometer was operated. The Colorado Orographic Seeding Experiment launched rawinsondes ~ 8 km from the collocated radiometers.

The VIZ Acculok rawinsonde was used at both field sites. The VIZ package is used in upper air measurements in more than 20 countries, and also by the National Weather Service. The rawinsondes were factory calibrated by VIZ at a temperature of 30°C and 33% relative humidity, which is considered to be within the optimal calibration range. The humidity sensors were the most current sensor at the time. Relative humidity attained from these sensors at saturation was slightly lower than previous models. This is discussed by Shaffer (1982) and Nordahl (1982). Under these baseline conditions the relative humidity was expected to be determined within 3 over the range from 50 to 97% relative humidity (personal communication, Potts, 1985). Richner and Phillips (1981) concluded that the reproducibility of the VIZ sonde is quite satisfactory. Deviations in multiple sonde accents were found to lie within the accuracies specified by the respective sensor manufacturer.

3. Field evaluation analyses

a. Rawinsonde and radiometer comparison

During SCPP, rawinsondes were launched from Kingvale during the storm periods at 3-h intervals for one shift per day (up to 12 h, four launches). Launches also were made on clear days to compare the vapor observations under optimal conditions. Eighty-nine rawinsonde soundings were analyzed for the 1984–85 season. The comparison between the rawinsonde and the radiometer water vapor measurements is shown in Fig. 1. The radiometer data used in plotting Fig. 1 were averages over the first 20 min following the rawinsonde launch.

Three sets of statistics were calculated from the dataset. Separate statistics were calculated for pairs of observations measured in the presence of liquid water, pairs without liquid water and all pairs. The scatter diagram and accompanying statistics shown in Fig. 1 were determined from the 89 rawinsonde/radiometer vapor observation pairs. Pairs evaluated in the absence of liquid water provided the greatest correlation coefficient at 0.96, with a root-mean-square (rms) difference of 0.05 cm. Based on the means, slopes and y-intercepts, the radiometer generally measured less vapor than the rawinsonde. The bias was near 0.03 cm. Pairs with liquid water showed slightly lower correlation and slightly larger rms differences. The combined data (all pairs) yield a correlation coefficient of 0.94 with a rms difference of 0.07 cm. These differences were between 13 and 15% of the mean. Hogg et al. (1983), also compared radiometer and rawinsonde data. They found a 0.17 cm rms difference for a 6-month dataset taken at Denver, Colorado, and a 0.26 cm rms difference for a 3-month field test at Sterling, Virginia. These differences were over twice that found with the Kingvale dataset. Since the radiometer used at both Denver and Sterling was nearly identical to the one used in Kingvale, causes for the differences must be attributed to differences in rawinsonde sensors or data reduction techniques.

b. Radiometer-radiometer comparisons

During the 1984–85 COSE program, the USBR and NOAA radiometers were collocated for a period of 3 weeks for direct comparisons. The radiometers were placed adjacent to each other at the base of the Park Range in northwest Colorado, near the town of Steamboat Springs. Due to physical restraints within the local parking area, the radiometer trailers had to be aligned perpendicular to each other. The distance between the reflectors was 20 m.

Two modes of operation, fixed vertical and azimuthal scanning, were utilized for direct comparison. Additional comparisons between the two radiometers and a rawinsonde launched from a local site were made on

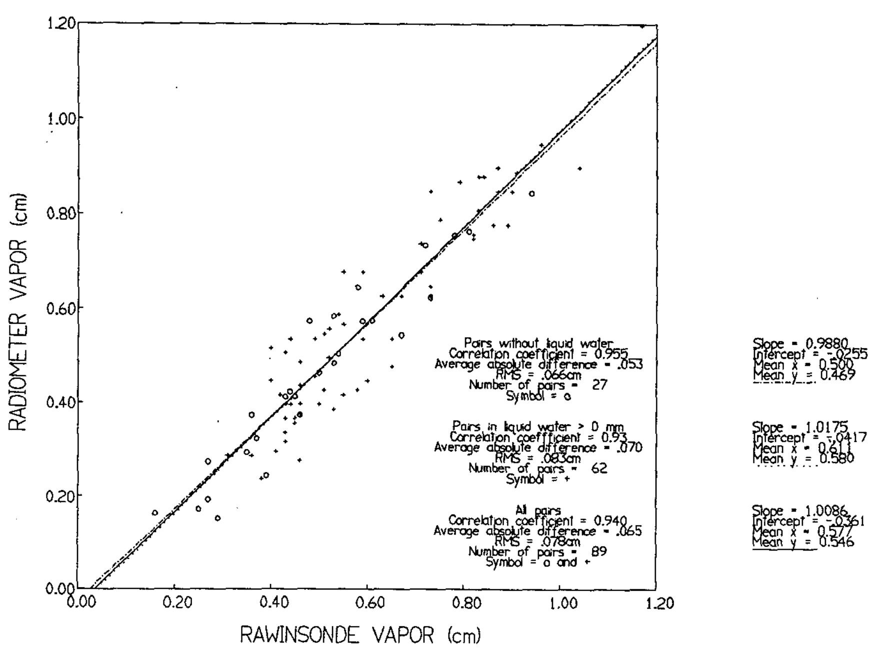

FIG. 1. Scatter plot showing rawinsonde precipitable water vapor (ordinate) vs. radiometer retrieved water vapor measured at Kingvale, California.

three occasions during calibrations. Procedures associated with analysis of data for each of these modes and results of the comparisons are the subject of the following discussion.

1) VERTICAL MODE

The largest portion of the 3-week experiment was reserved for data collection in the vertical mode. This dataset included both cloudy and clear weather events. Due to differences in the operating programs of the two radiometers, data were recorded at different rates. The NOAA radiometer recorded data each minute, the USBR radiometer every 2 min. The NOAA 1-min data points were averaged and compared to the 2-min values obtained by the USBR radiometer. The total 2-min averaging periods for the two radiometers were simultaneous.

Figures 2 and 3 show the comparisons of the measurements of integrated water vapor (centimeters) and liquid (millimeters) for the vertical mode dataset. The vapor data are stratified into three groups: pairs obtained when liquid water was recorded (liquid water ⩾ 0.05 mm), pairs obtained when little or no liquid water was recorded (liquid water < 0.05 mm) and all data points. Statistics are given in Table 1.

A high correlation (0.95) was obtained for the measurement of vapor in the total dataset. However, the correlation was lower (0.79) in periods when liquid was present. The mean absolute difference and the rms difference for no liquid and all points were between 0.05 and 0.07 cm. The values were higher (0.07 and 0.08, respectively) in the presence of liquid. These differences compare favorably with a rms difference of 0.08 cm for two collocated radiometers reported by Hogg et al., (1983).

Measurements of integrated liquid water were considered when either radiometer reported a threshold value of 0.05 mm. For this comparison, a correlation coefficient of 0.99 was obtained with an average absolute difference of 0.02 mm. The rms difference was also only 0.02 mm.

2) SCANNING MODE

Direct comparison of the radiometric measurements during azimuth scans offers two advantages over vertical comparisons. The primary advantage is that the integration path extends over a larger atmospheric path length, resulting in larger values of the measured parameters. This is particularly helpful when only low concentrations of liquid water are present. The second major advantage is that a wide range of values can be obtained, particularly in the liquid measurement, due to the large temporal and spatial variability of liquid water in an orographic environment. This variability, however, requires that the antenna beams be closely coordinated in space and time to make comparisons valid.

Six coordinated scans were made during a 3-h storm period on 28 November 1984. The scans were done at a 15° elevation angle between the azimuths of 173°

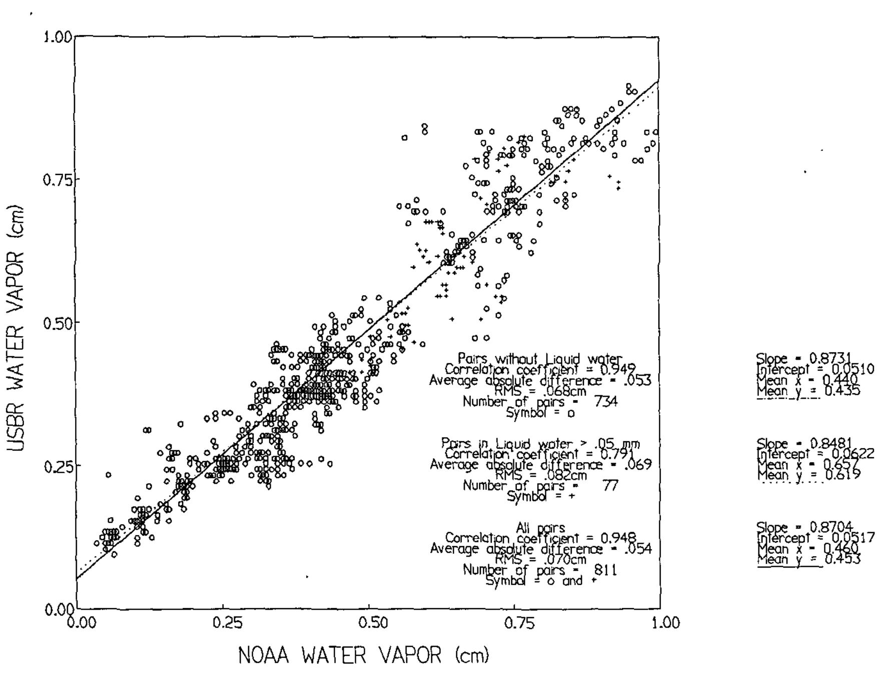

FIG. 2. Scatter plot of integrated water vapor retrieved by the NOAA and USBR radiometers from data taken at Steamboat Springs, Colorado. Statistics are provided for vapor retrieved in the absence of liquid water (O), in liquid water (+), and all points.

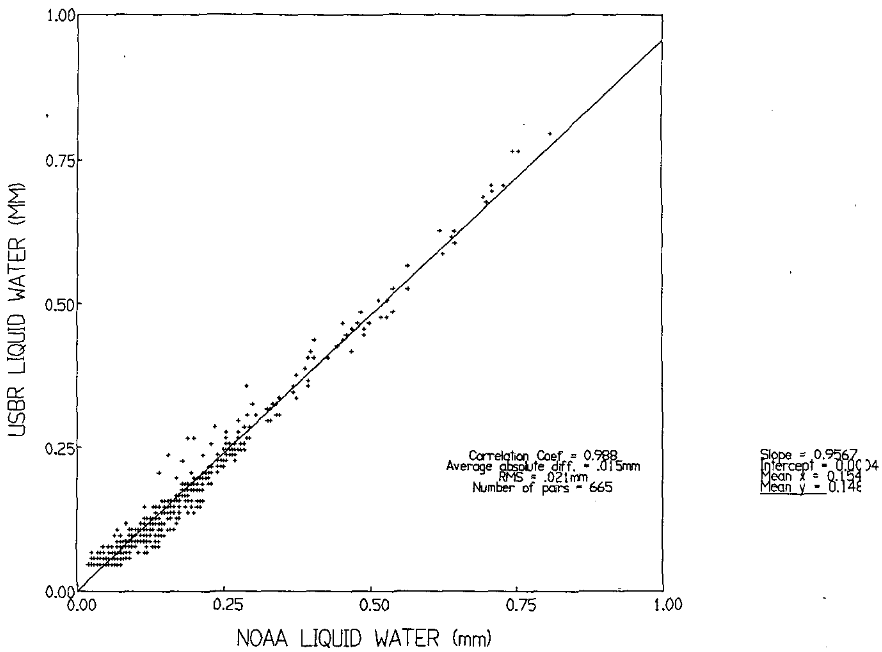

FIG. 3. Scatter plot of integrated liquid water as measured by the NOAA and USBR radiometers from data taken at Steamboat Springs, CO. Liquid water measurements less than 0.02 mm are not included in this analysis.

and 101°, rotating clockwise. The remaining angles could not be scanned simultaneously due to the position of the cable stops on the scanning drive mechanism caused by the perpendicular orientation of the radiometer trailers.

Due to the physical separation of the trailers, coordination required some skill on the part of the operators. As a result, the degree of coordination on each of the six individual scans varied. The coordination sequence for each scan is shown on Fig. 4. On the first, the USBR radiometer led the NOAA radiometer by 1.5 min. On the second, the USBR radiometer led NOAA by 4 min. On the remaining four scans, near perfect coordination was achieved. Despite coordination problems associated with the first two scans, these scans were included in the data analysis.

During the scan sequence, the radiometers average liquid and vapor values over a small range of azimuths (~2.5°). The average over this range is calculated and assigned to the center azimuth of the range. Because of slight variations in the scan rate, the centers of the range for each radiometer do not coincide. Linear interpolations between successive data points were used to estimate the values of liquid water and vapor for each radiometer at each integer azimuth (in degrees), and the data for each integer azimuth angle were then compared.

Figure 5 shows the vapor measurements collected by each radiometer as a function of azimuth angle for the six scans. Figure 6 shows similar plots for the liquid water measurements.

On the first scan, vapor measurements from both radiometers followed closely with a slight bias in the northern quadrant (USBR greater) and southern quadrant (NOAA greater). The liquid water values were the system noise level (~ ±0.03 mm) throughout the

TABLE 1. Comparison of measurements by two radiometers in vertical modes.

	Vapor SLW > 0.05	Vapor SLW < 0.05	Vapor all points	Liquid all points
Correlation coefficient	0.79	0.95	0.95	0.99
Absolute average differential	0.07	0.05	0.05	0.02
Root mean square differential	0.08	0.07	0.07	0.02
Number of pairs	77	734	811	665
Slope	0.85	0.87	0.87	0.96
Intercept	0.06	0.04	0.05	0.00
Mean (NOAA)	0.66	0.44	0.46	0.15
Mean (BOR)	0.62	0.44	0.45	0.15

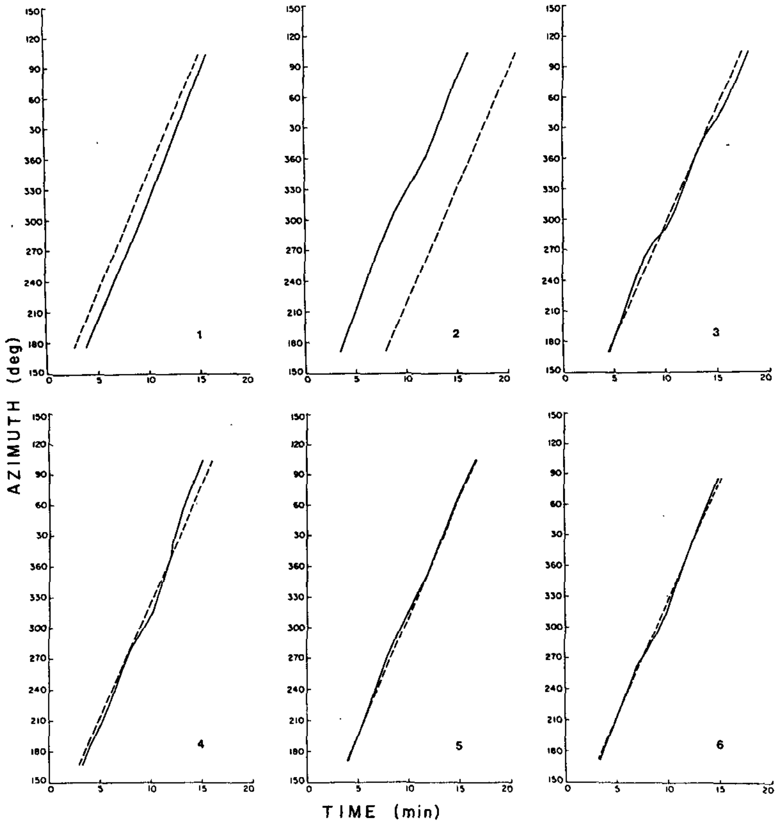

FIG. 4. Coordination of scanning radiometers as measured by the difference in time that the two radiometers made observations at particular azimuths. The scan numbers are shown in each figure.

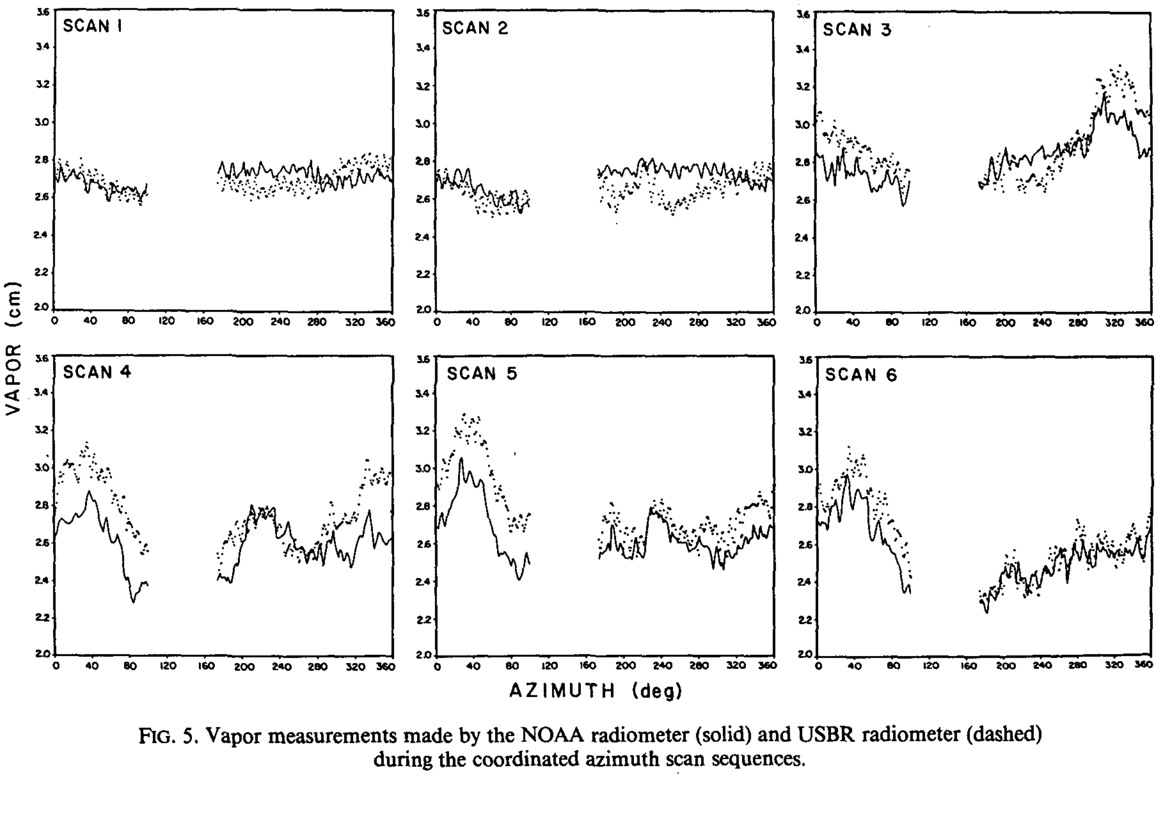

FIG. 5. Vapor measurements made by the NOAA radiometer (solid) and USBR radiometer (dashed) during the coordinated azimuth scan sequences.

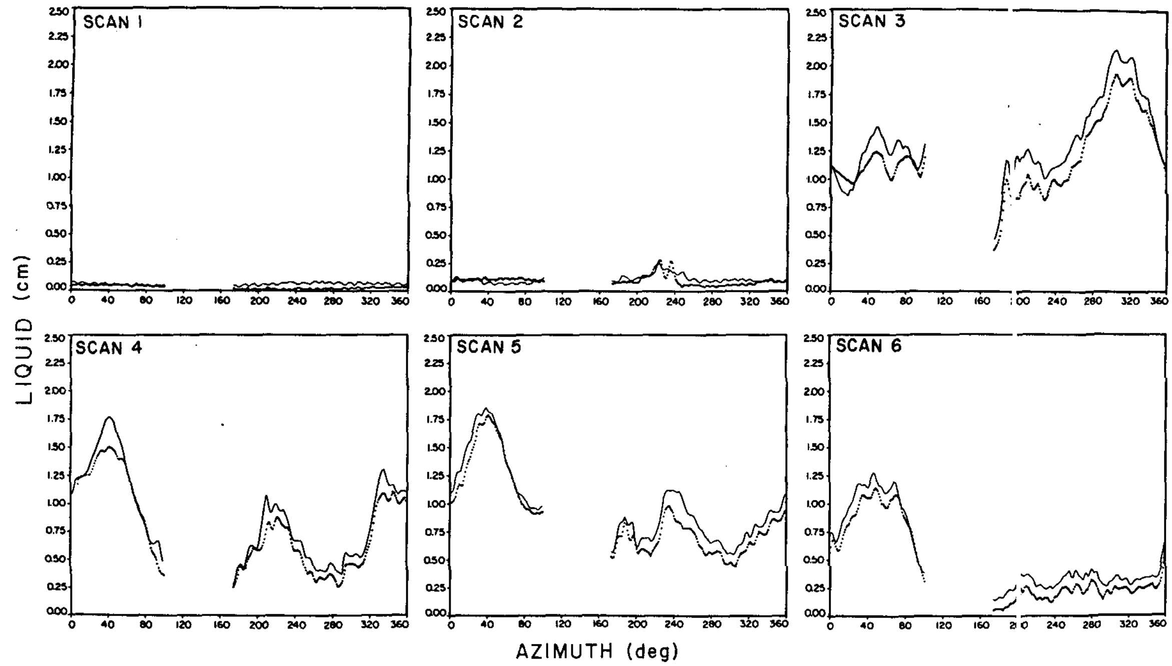

FIG. 6. As in Fig. 5 except for liquid water.

hemisphere. The second scan was the least coordinated and consequently may have been affected by temporal variations in the cloud system. Values in the vapor channel were similar in the 320° to 120° quadrant but differed significantly at other azimuths. An exception was in the region of liquid water peaks near 230° where vapor values approached each other. During this scan the liquid water was above the noise level, but not as high as in later scans. The Bureau of Reclamation liquid values were higher in the eastern quadrant and lower in the western quadrant. A double peak in liquid water was observed near 230° azimuth by USBR, but only one peak was seen by NOAA.

Liquid water values during the remaining scans increased significantly. Close coordination was achieved on these scans. In the vapor channel, a trend similar to scan 1 was again observed in the northern quadrant (USBR higher). Such a bias was observed in all remaining scans in the vapor channel. Both radiometers duplicated peaks and valleys associated with the liquid water distribution. However, with few exceptions, the USBR radiometer measured consistently higher values.

The complete statistics for each scan are presented in Table 2. During all six scans, the vapor throughout the viewing region underwent only minor variations. The mean value of vapor measured by either radiometer in any scan varied from 2.55 to 2.89 cm. Little variation with azimuth was noted as evidenced by the small standard deviations. In general, the rms and mean absolute differences between radiometers were small over all scans; the correlation coefficient for all scans was 0.71. A scatter plot of all vapor points determined during the scanning portion of this study is shown on Fig. 7.

Values of liquid water throughout the hemisphere varied considerably in space and time. Despite these large variations, measured values of liquid water by the radiometers correlated extremely well (0.99). However, a consistent offset was present throughout the dataset with NOAA values exceeding those measured by the USBR. Root-mean-square differences between the two radiometers for the complete scan data varied between 17 and 19% of the mean liquid values measured. The mean absolute difference between radiometer measurements varied between 14 and 16% of the means. The scatterplot for all liquid water values determined during the scanning portion of this study is shown on Fig. 8.

3) Radiometer calibrations

Calibration of the instrument, including the antenna system, is accomplished using the clear, stable atmosphere as a signal source by means of elevation scan observations, commonly called "tipping curves." In the calibration procedure, the absolute absorption of the atmosphere at each operating frequency and in the zenith direction is determined from the slope of the relative values of absorption measured by the radiometer as a function of antenna elevation angle. Absolute absorption, τ (in nepers) is related to the zenith brightness temperature, T_b, by the expression

$$\tau = \ln[(T_m - 2.9)/(T_m - T_b)] \quad (1)$$

TABLE 2. Comparison of data from two radiometers during six azimuthal scans.

Scan	No. points	NOAA mean (cm)	NOAA SD	USBR mean (cm)	USBR SD	RMS diff (cm)	Mean ABS diff (mm)
				Vapor			
1	287	2.70	0.05	2.70	0.06	0.07	0.06
2	287	2.71	0.07	2.65	0.07	0.10	0.08
3	287	2.82	0.12	2.89	0.18	0.14	0.12
4	287	2.61	0.13	2.77	0.16	0.21	0.18
5	287	2.64	0.13	2.79	0.18	0.18	0.15
6	287	2.55	0.15	2.62	0.20	0.11	0.08
All	1722	2.67	0.14	2.73	0.18	0.14	0.11
				Liquid			
1	287	0.06	0.01	0.03	0.01	0.04	0.03
2	287	0.10	0.04	0.10	0.04	0.04	0.03
3	287	1.34	0.36	1.19	0.33	0.18	0.16
4	287	0.89	0.39	0.79	0.37	0.12	0.10
5	287	1.00	0.35	0.89	0.36	0.12	0.10
6	287	0.53	0.34	0.43	0.34	0.11	0.10
All	1722	0.65	0.55	0.57	0.51	0.11	0.09

Correlation coefficient, all scans: Vapor 0.71
Liquid 0.99

where T_m is the mean radiating temperature of the atmosphere, and 2.9 the cosmic background brightness temperature. All temperatures are in Kelvin. The temperature, T_m, is estimated from the ensemble of soundings used to calculate the statistical retrieval coefficients.

Tipping curve calibrations are performed during periods of clear weather when atmospheric conditions are nearly homogeneous over the scanning volume. During three occasions in COSE, tipping curve calibrations were performed simultaneously by both radiometers during a rawinsonde release. The release site

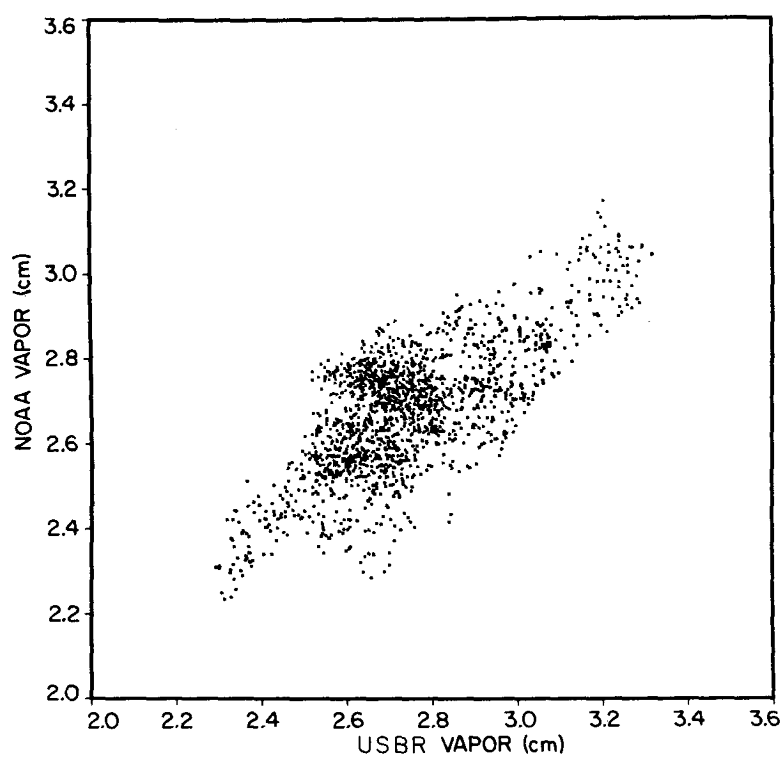

FIG. 7. Scatter plot of all vapor points taken during the scanning portion of the evaluation.

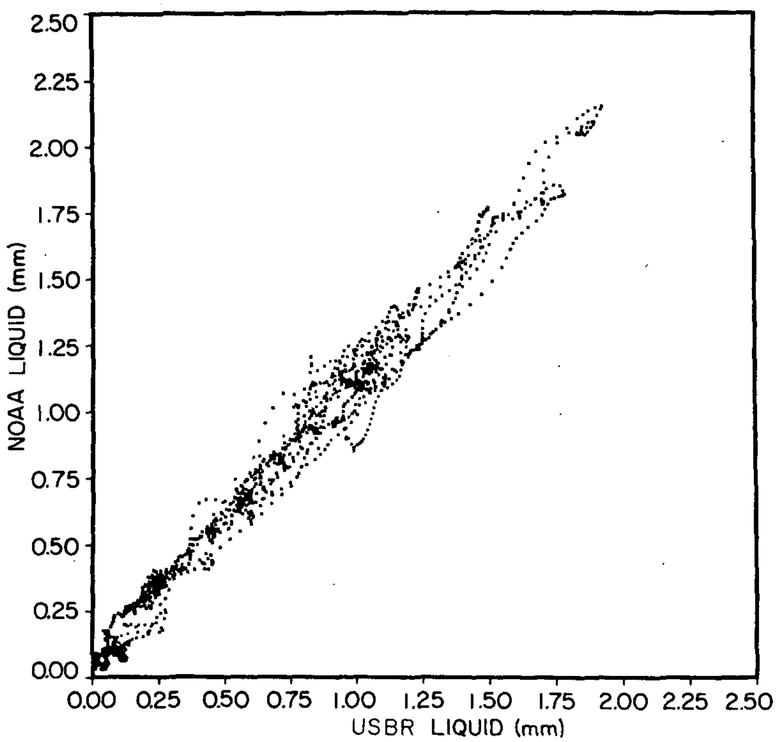

FIG. 8. As in Fig. 7, but for liquid water.

on these occasions was approximately 8 km upwind of the radiometer site. This separation ensured that the rawinsonde would not pass to the lee of the mountain during the ascent. Two tipping curves were performed during each rawinsonde release.

The results of the tipping curve/rawinsonde calibration measurements of integrated vapor are presented in Table 3. During all measurements, the maximum departure in measured vapor was 0.05 cm. The largest discrepancy differences between rawinsonde and either radiometer occurred during the 1800 UTC December 1984 comparison. The radiometer measurements in this case were identical. Half of the measurements by the radiometers departed from the rawinsonde measurements by 0.02 cm or less. In general, agreement between the different instrumentation systems was very good.

TABLE 3. Tipping curve calibrations.

Date	Time (UTC)	NOAA vapor (cm)	USBR vapor (cm)	Rawinsonde vapor (cm)
4 Dec 1984	0600	0.33	0.35	0.36
		0.33	0.32	
4 Dec 1984	1800	0.14	0.14	0.19
4 Dec 1984	2100	0.17	0.16	0.16
		0.18	0.18	

4. Summary and discussion

Two studies have been performed to check the validity of radiometer measurements. One was designed to determine independently the accuracy of the vapor channel of the radiometer. A second study, an intercomparison of radiometers, was not a test of accuracy, but rather of stability, reliability, and general system integrity.

The study comparing vapor measurements from rawinsondes and the radiometer showed excellent agreement. The rms difference between the two instruments was 0.07 cm, with a slight bias (0.04 cm) towards the rawinsonde measurement. These differences were less than 15% of the means, which was less than the theoretical estimation of error for radiometer-retrieved values calculated by Westwater (1978).

The collocated radiometer study examined the system stability. The vapor and liquid channels were found to exhibit similar trends between radiometers, though a small bias often existed. Comparisons of paired data from the vapor channel yielded a correlation coefficient of 0.95 with a rms difference of 0.05 cm, while the liquid water channel data yielded a correlation coefficient of 0.99 with a rms difference of 0.02 mm.

For determining integrated amounts of vapor and liquid, the radiometer appears to be an appropriate device capable of operation over a wide range of severe wintertime conditions. Comparison with rawinsonde data indicates that radiometric measurements of integrated vapor are probably within 15% of the true integrated vapor. The radiometer comparison indicates that the data are reproducible and the radiometric system possesses a high degree of stability. Definitive studies are still required to evaluate the liquid channel. These studies are continuing in both SCPP and COSE.

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