An Evaluation of Wind Profiler, RASS, and Microwave Radiometer Performance

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Abstract

Several ground-based remote sensors were operated together in Colorado during February and March 1991 to obtain continuous profiles of the kinematic and thermodynamic structure of the atmosphere. Instrument performance is compared for five different wind profilers. Each was equipped with Radio Acoustic Sounding System (RASS) capability to measure virtual temperature. This was the first side-by-side comparison of all three of the most common wind-profiler frequencies: 50, 404, and 915 MHz. The 404-MHz system was a NOAA Wind Profiler Demonstration Network (WPDN) unit. Dual-frequency microwave radiometers that measured path-integrated water vapor and liquid water content were also evaluated. Frequent rawinsonde launches from the remote-sensor sites provided an extensive set of in situ measurements for comparison. The winter operations provide a severe test of the profiler/RASS capabilities because atmospheric scattering is relatively weak and acoustic attenuation is relatively strong in cold, dry conditions. Nevertheless, the lower-frequency systems exhibited impressive height coverage for wind and virtual temperature profiling, whereas the high-frequency units provided higher-resolution measurements near the surface. Comparisons between remote sensor and rawinsonde data generally showed excellent agreement. The results support more widespread use of these emerging technologies.

1. Introduction

The U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program seeks to improve general circulation models (GCMs) for predicting climate changes. The program's primary emphasis is on improving the treatment of radiative transfer in GCMs by combining measurements and modeling. The program will attempt to assess all features of the atmosphere that significantly influence the radiative budget at a few climatically strategic sites (DOE 1990). Remote sensing will play a central role in this effort. Long-term continuous measurements of the atmospheric structure and radiative fluxes will be taken at these cloud and radiation testbeds (CART).

Many of the instruments proposed for use in CART operations represent emerging technology that is currently in the form of specialized research prototypes. Therefore, ARM sponsored an intensive Colorado field project in 1991 to assess the suitability and readiness of instruments and techniques for profiling the thermodynamic and kinematic structure of the atmosphere. This work was a precursor to the design and operation of CART sites. Additional, longer-term ARM research will use these 1991 data to explore various combinations of instruments. They will also be used in data assimilation models to extrapolate single-site data to cohesive, dynamically consistent, four-dimensional fields at GCM subgrid scales. The result will be an integrated system for atmospheric observation tailored to ARM's requirements. The research is being conducted by scientists from the National Oceanic and Atmospheric Administration's (NOAA) Wave Propagation and Aeronomy laboratories (WPL and AL, respectively), the National Center for Atmospheric Research (NCAR), and the University of Wisconsin (UW) (see Dabberdt et al. 1991).

The month-long field project was the first time that all three of the most commonly used wind profilers were operated side by side. Each profiler included a Radio Acoustic Sounding System (RASS) for measuring profiles of virtual temperature (May et al. 1990). The remote sensors were collocated with rawinsonde launch sites from which frequent soundings were obtained. The project's instrumentation, duration, and scope far surpassed those of the related Ground-based Atmospheric Profiling Experiment (GAPEX) of 1988 (Smith et al. 1990).

This article summarizes measurements obtained with the wind profilers, RASS, and microwave radiometers operated by NOAA in the 1991 project. Meteorological measurements from these systems were displayed in real time. Analyses of data collected with several other systems are in progress. The performance of each wind profiler and RASS is examined and compared. Remote sensing measurements of wind, virtual temperature, and precipitable water va-

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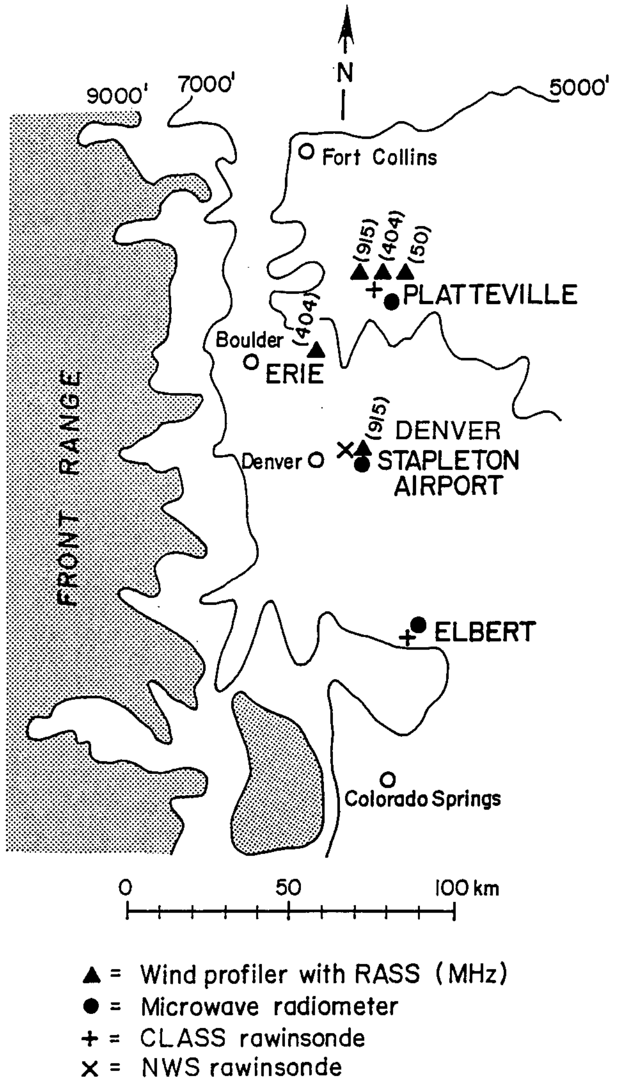


Fig. 1. Locations of wind profilers, RASS, microwave radiometers, and rawinsondes used in ARM-91 and WISP. This is a subset of the complete suite of instrumentation.

por are also compared with those of the collocated rawinsondes. Measurements obtained by the ARM Colorado field experiment, and related concurrent field projects in the same locality, provide a rich dataset for testing data assimilation and integration techniques.

2. Field operations

The field work conducted for ARM was part of an Integrated Data Assimilation Sounding System (ARM/IDASS) research project, referred to here as ARM-91. The instrumentation was concentrated near Platteville, Colorado, about 50 km northeast of Denver. Figure 1 shows the locations of the instruments discussed here. Data were collected from 15 February to 16 March 1991 in cooperation with the Winter Icing and Storms Project (WISP) (Rasmussen et al. 1992).

The wind profilers, RASS, and radiometers were designed for unattended, continuous operations. ARM-91 augmented these continuous measurements with operations of more labor-intensive instruments during short (about 24–36-h) intensive operating periods (IOPs). Seven IOPs were declared. These included a variety of weather, ranging from cold frontal snow and rain showers to variable cloudiness and clear skies.

The comprehensive edited datasets from all ARM-91 instruments are archived on NCAR's Mass Storage System. Both netCDF and ASCII format versions of the data are available through NCAR to all participants of ARM and WISP, and by special arrangement to other interested scientists (Martin 1991).

3. Instrumentation

In addition to the instruments shown in Fig. 1, ARM-91 also operated a laser ceilometer, an infrared high-resolution interferometer, an Atmosphere–Surface Turbulent Exchange Research (ASTER) system, nine portable automated mesonet (PAM-II) stations, and a Doppler sodar at Platteville. The proximity and simultaneous operation of these systems provided a unique opportunity to compare their measurements and ranges.

a. Wind profilers and RASS

Wind profilers are long-wavelength Doppler radars designed primarily for measuring winds in all weather conditions. These radars detect signals backscattered from turbulence-induced refractive index variations with a scale of half the radar wavelength. As the turbulent eddies drift with the mean wind, their translational velocity provides a direct measure of the mean wind vector. Typically, profilers are designed to operate in two modes, one for low-altitude sampling with high vertical resolution and another for higher-altitude sampling with reduced vertical resolution.

RASS combines acoustic sources with wind profilers to measure the profile of virtual temperature (Peters et al. 1983; May et al. 1990). The wind profiler's Doppler radar measures the speed of refractive index perturbations induced by the acoustic waves (approximately matched to the radar's half-wavelength) as they ascend at the local speed of sound, which is proportional to the square root of the virtual temperature. Virtual temperature measurements are usually obtained at

Table 1. Wind profiler and RASS characteristics during ARM-91.

System characteristic	915 MHz at Platteville	915 MHz at Denver	404 MHz (WPDN) at Platteville	404 MHz at Erie	50 MHz at Platteville
Wind profiler					
Operator	**AL**	**WPL**	**FSL**	**WPL**	**WPL**
Radar frequency (MHz), λ, (m), and band	915.0, 0.33 UHF	915.0, 0.33 UHF	404.37, 0.74 UHF	404.37, 0.74 UHF	49.82, 6.0 VHF
Mean power (W)	7	145	1500	45	200
Antenna size (m^2)	4	100	144	57	10 000
Beamwidth (°)	9	2	4	6	3
Lowest height (km AGL)	0.15	0.30	0.50	0.40	1.80
Height resolution (m)	100	200	320–900 low–high alt. modes	200 vertical wind only	300–870 low–high alt. modes
RASS					
Operator	**AL**	**WPL**	**WPL**	**WPL**	**WPL**
Acoustic frequency (Hz)	2000	2000	900	900	110
Acoustic power: total electrical input (W)	50	200	125	125	2400
Acoustic beamwidth (°)	8	8	18	19	60

the same heights as the wind measurements up to the point at which the acoustically induced signal becomes too weak to detect.

Because different frequencies have advantages and limitations (Balsey and Gage 1982), a combination of profilers using different frequencies may be required to maximize the availability of wind and temperature profile data for a wide range of heights and conditions. At Platteville, ARM-91 used three different frequencies to obtain overlapping height coverage and differing vertical resolutions. These included a 50-MHz VHF system (= 6.0 m) and UHF systems at 404 MHz (75 cm) and 915 MHz (33 cm). Additional wind profiler systems equipped with RASS operated at Denver's Stapleton Airport and Erie (Fig. 1). Characteristics and operating parameters for these systems are summarized in Table 1. There are significant differences between the systems; thus, one would expect large variations in their capabilities.

The 404-MHz wind profiler at Platteville was one of the new NOAA Wind Profiler Demonstration Network (WPDN) units manufactured by Unisys, Inc. (now called Paramax), and operated by the NOAA Forecast Systems Laboratory (FSL) as part of a 31-station network across the central United States (Chadwick and Hassel 1987). WPL added RASS capability to this profiler for the ARM-91 research.

The AL RASS-equipped, 915-MHz boundary-layer wind profiler (Ecklund et al. 1988) at Platteville used a small, flat microstrip antenna on a mechanical positioner. It employed a new RASS technique (Angevine et al. 1991) based on a 2048-point fast Fourier transform to simultaneously measure both the acoustically generated signals at the local speed of sound (near 320 m s^{-1}) and the vertical wind speed (near 0 m s^{-1}). This allows the observed sound speed to be corrected by the observed vertical wind speed, thereby yielding more accurate derived virtual temperatures. The four RASS units operated by WPL lacked this capability, and their virtual temperature data presented in section 4 have not been corrected for vertical air motions.

Table 2. Characteristics of WPL microwave radiometers.

Operating frequencies (wavelengths)	20.6 and 31.65 GHz (1.46 and 0.95 cm)
Viewing direction	Zenith
Antenna half-power beamwidth	2.5° (Denver) 4.0° (Platteville, Elbert)
Total bandwidth (double side band)	1 GHz
Integration time	2 min
Radiometric sensitivity (for 2-min integration time)	0.05 K, rms
Estimated absolute radiometric accuracy	0.75 K

b. Microwave radiometers

WPL operated zenith-pointing, dual-channel (20.6- and 31.65-GHz) microwave radiometers at Platteville, Denver, and Elbert during the ARM-91 and WISP experiments (Fig. 1). Major characteristics of these passive instruments are given in Table 2. The radiometers measure down-welling radiation. Path-integrated total water vapor and cloud liquid are derived from the emission at 20.6 GHz (more sensitive to vapor) and 31.65 GHz (more sensitive to liquid) using retrieval algorithms (Hogg et al. 1983). For data from the zenith direction, the radiometer's path-integrated vapor value is a direct measure of the atmosphere's precipitable water vapor (PWV).

The microwave receivers are enclosed in shelters whose internal temperatures are strictly controlled (±1°C over 1 yr). An exterior flat-plate reflector directs zenith radiation through a microwave-transparent window to the radiometer's parabolic antennas. Similar radiometers of independent design were also operated during ARM-91 by the Jet Propulsion Laboratory (JPL) (Keihm 1991). The JPL instruments had less stringent temperature controls than the WPL devices. Side-by-side operation and comparisons of these radiometers were conducted at Platteville.

The WPL radiometers operated continuously from 15 January to 31 March. They provided high-quality data, except for occasional periods (about 12% of the time) when they suffered performance degradations from rain or melting snow and ice on the reflector surfaces. The data presented in section 5 were edited to remove these effects.

c. Rawinsondes

The continuous remote sensor profiles were supplemented by and compared with periodic in situ profiles from collocated rawinsondes. This combined or integrated dataset can be used to overcome inherent shortcomings of each system. These shortcomings include the relatively coarse vertical resolution of profilers and RASS, height limitations of RASS, the coarse time resolution of sonde launches, and the absence of liquid water measurements by the rawinsondes. In the case of instruments located at Denver, routine launches of the NWS sondes at 12-h intervals served this purpose. At Platteville and Elbert, NCAR's Cross-chain Loran Atmospheric Sounding System (CLASS) units launched sondes at frequent intervals during IOPs. The period between CLASS launches was usually 3 h, but it was as short as 1.5 h on some days. There were 87 launches at Platteville, 41 at Elbert, and 20 at Denver during the seven IOPs.

Basic operating characteristics of CLASS are summarized in Table 3. The system tracks a conventional balloon-borne radiosonde augmented with the ability to receive and retransmit navigation signals from several Loran ground stations (Lauristen et al. 1987). The ground unit is housed in a self-contained, towable trailer with an internal balloon-inflation apparatus and a ceiling hatch for all-weather launching. Real-time data are recorded at 10-s intervals. CLASS advantages over conventional radar-tracked rawinsondes include a) greater vertical resolution at low elevation angles, b) longer maximum range in strong winds, c) easier operation, and d) lower initial equipment cost.

Table 3. CLASS Characteristics.

Sonde	Väisälä model RS-80-15L
Loran navigator	ANI-7000
Data system	DOS 486 PC
Sonde telemetry frequency	401–406 MHz
Maximum altitude	50–60 mb with 200-g balloon
Temperature	Sensor: thermocap (capacitive) Accuracy: 0.5°C Precision: 0.1°C
Winds	Method: cross-chain Loran Accuracy: 0.5 m s^{-1} for 60 s avg. Precision: 0.1 m s^{-1}
Relative humidity	Sensor: humicap (capacitive) Accuracy: 5% Precision: 1%
Pressure	Sensor: aneroid Accuracy: 1–2 mb Precision: 0.1 mb

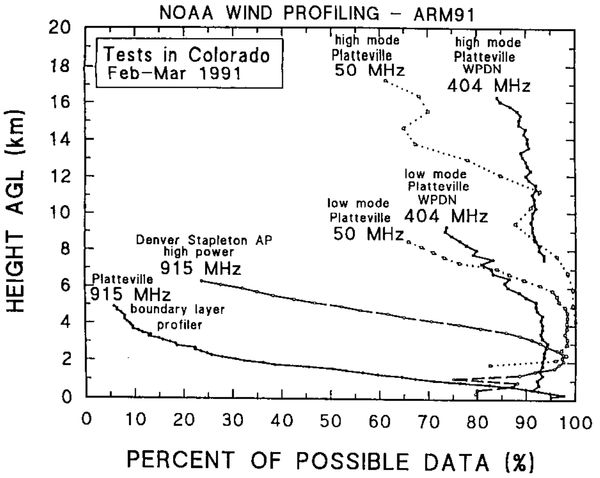


FIG. 2. Height coverage statistics for wind profilers used in ARM-91. The curves show the percent of time horizontal wind measurements were obtained to the indicated heights. The data passed consensus averaging and time–height continuity tests described in the text.

Disadvantages include sparse Loran coverage over some parts of the globe (Passi and Morel 1987) and vulnerability to radio interference (Lauristen 1991).

The CLASS data used in sections 4 and 5 for comparison with the remote sensor measurements are based on interpolations of the raw 10-s data to 5-mb pressure increments. The wind data were smoothed with 60-s running averages.

4. Wind profiler and RASS performance

A number of earlier studies have assessed the performance of various wind profilers. The height coverage of wind profiler measurements in Colorado was documented by Frisch et al. (1986) for WPL's 50-, 405-, and 915-MHz profilers, and by Weber et al. (1990) in summer conditions for the first WPDN profiler. Reinking (1991) discusses wintertime performance in New York of a WPL boundary-layer 915-MHz profiler and of commercially produced 405-MHz profilers. It is difficult to make meaningful comparisons of profiler performance from these studies because the data were collected at different locations, in different seasons, and for differing durations. All of the ARM-91 measurements, however, were obtained simultaneously and in close proximity.

The accuracy and precision of various wind profilers have been investigated through comparisons with nearby rawinsondes and with each other by Fukao et al. (1982), Strauch et al. (1987), Weber and Wuertz (1990), and Weber et al. (1990). Similar analyses are presented in this section for the ARM-91 wind data. There are fewer studies of height coverage and radiosonde comparisons for the relatively new RASS technology. May et al. (1989) compared virtual temperature profiles obtained with two RASS units to those computed from NWS rawinsonde data. Simultaneous data from five different RASS units are analyzed for the ARM-91 project in this section.

a. Height coverage

For long-term operations, such as those to be conducted at the ARM CART locations, it is important to know the height coverage that can be expected with different profiling systems. The ARM-91 wind profiler and RASS data have been analyzed for this purpose. Periods of power interruptions and other hardware failures are excluded from the comparison statistics.

Hourly average wind data at each height were derived from consensus tests of the subhourly measurements (10–12 h^{-1}) of each unit in the manner described by Weber et al. (1990). The hourly data from each profiler, except the WPDN unit, then passed to a time–height pattern-continuity algorithm that further edited the data to remove outlier points (Wuertz and Weber 1989). Virtual temperature data were processed in the same manner. The 404-MHz WPDN data received quality control checks described by Brewster and Schlatter (1988). The remaining data at each height and time represent "good" measurements that met signal-detection thresholds of the hardware and meteorologically reasonable requirements for continuity.

Figure 2 shows the height coverage statistics of horizontal wind measurements obtained by four of the profilers used in ARM-91. The fifth system at Erie measured only vertical motion. Data from both the high- and low-altitude sampling modes of the 50- and 404-MHz systems at Platteville are shown; the 915-MHz systems were operated with a single mode. The figure shows that the 404-MHz WPDN profiler provided the best high-altitude coverage, reaching up to 16 km above ground level (AGL) 84% of the time. Although impressive, this is not as good as the summertime performance (96% coverage to 16 km) of the same profiler documented by Weber et al. (1990). The long-term average transmitted power used during ARM-91 was 2.3 dB less than that of the earlier study. This difference and the weaker reflectivity of wintertime air (Frisch et al. 1990) are responsible for the slightly poorer 404-MHz height coverage in ARM-91.

WPL's 50-MHz system had less sensitivity and, therefore, produced somewhat poorer high-altitude coverage than the 404-MHz profiler. Its coverage during ARM-91 was not as good as that documented for January by Frisch et al. (1986); some reduction is caused by the outlier editing used in ARM-91 but not

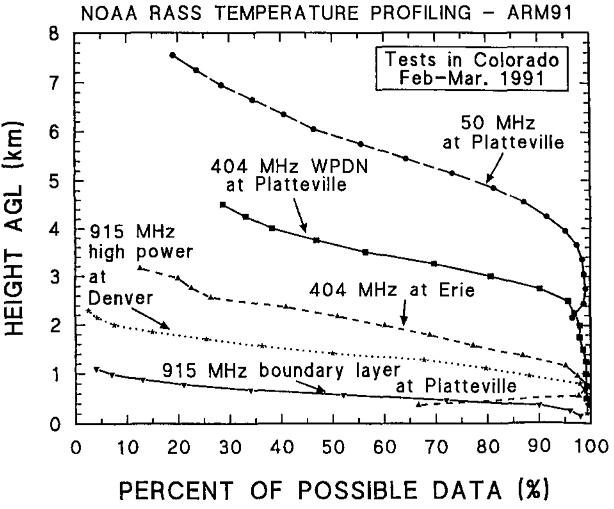


FIG. 3. Height coverage statistics for RASS units used in ARM-91. The curves show the percent of time virtual temperature measurements were obtained to the indicated heights. The data passed consensus averaging and time–height continuity tests described in the text.

in the earlier study. Annual variations of atmospheric reflectivity (Frisch et al. 1990) may also account for some of the difference.

The 915-MHz profiler at Denver obtained wind measurements to 5 km about half the time, whereas the small and much less sensitive boundary-layer 915-MHz system at Platteville reached to only about 1.6 km half the time. The Denver system's ARM-91 statistics are poorer than those observed by Frisch et al. (1986), but the Platteville statistics are about the same as those reported by Reinking (1991) for a similar profiler in winter conditions. Moving ground-clutter problems account for the relatively low percentages below 2 km for the profiler at Denver's airport.

The radar reflectivity of the clear air determines whether it will be detected by a given wind profiler. In general, the wind data height coverage of any of these profilers can be improved by increasing its transmitted power or antenna size or both (see Table 1). Virtual temperature measurements by RASS, however, are affected by additional factors. These include the amount of transmitted acoustic power, acoustic attenuation [a function of frequency, temperature, and humidity (Harris 1966; Bedard 1990)], and the amount of signal defocusing and advection caused by turbulence and winds aloft (Lataitis 1992).

Figure 3 shows the ARM-91 height coverage statistics for the virtual temperature measurements of all five RASS units. The results are consistent with preliminary findings of May et al. (1988) and Moran et al. (1991). The 50-MHz RASS provided the highest coverage (up to 6 km about 50% of the time), but its lowest measurement gate is at 2.15 km. In contrast, half the time the 915-MHz boundary-layer RASS didn't provide virtual temperature data above 0.7 km, but it obtained measurements within 0.15 km of the surface. RASS on the 404-MHz WPDN profiler provided virtual temperature data to about 3.5 km half the time. The improved height coverage with decreasing frequency is primarily the result of weaker acoustic attenuation at lower frequencies.

The first ARM CART will use 50- and 915-MHz RASS units. Figure 3 shows that this combination will frequently suffer from a temperature data gap between about 0.6 and 2.1 km. The gap could be filled by adding RASS capability to a nearby WPDN 404-MHz wind profiler. In ARM-91, the combined three-frequency system provided virtual temperature profiles from near the surface to over 4 km 90% of the time and to about 6 km 50% of the time; slightly better coverage is expected in warmer and more humid seasons or climates. Wind and virtual temperature height coverage statistics for ARM-91 are summarized in Fig. 4, where the performance of the various systems can be readily compared.

It should be noted that the boundary-layer 915-MHz profiler/RASS at Platteville had limited sensitivity because it was designed primarily for measurements in the tropics, where atmospheric reflectivity is higher and acoustic attenuation is less severe. It also suffered from moving-clutter problems at the Platteville

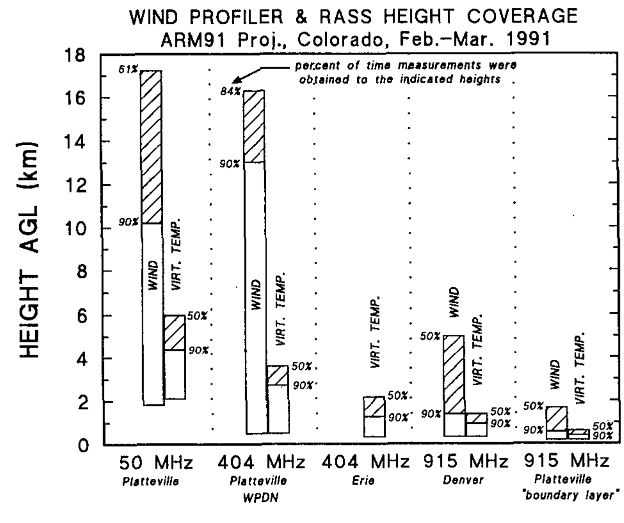


FIG. 4. Summary of wind and virtual temperature height coverage statistics for the ARM-91 project. The percent of time that measurements were obtained to certain indicated heights are shown. The bottom of each bar denotes the lowest measurement height. The combined coverage of the low- and high-altitude sampling modes are shown for the WPL 50- and the WPDN 404-MHz wind profilers at Platteville.

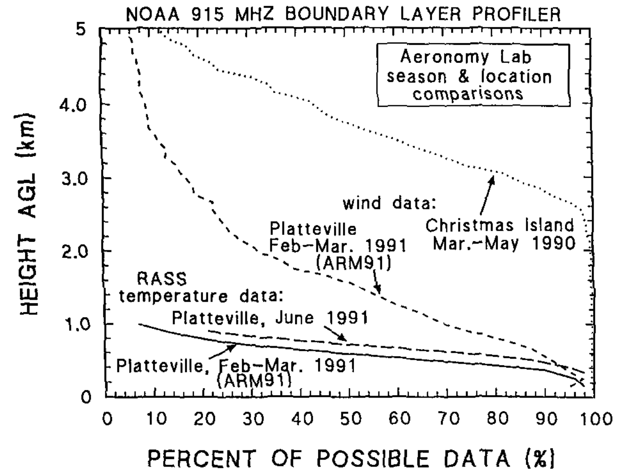


FIG. 5. Height coverage statistics for the 915-MHz boundary layer profiler/RASS obtained under environmental conditions that were more favorable for signal detection than those of the wintertime ARM-91 project, for which the data are also shown.

site, which sometimes made it difficult to obtain measurements at the lower heights. Similar problems were encountered by the boundary-layer profiler described by Reinking (1991). Clutter fences designed to combat this problem have had some success (Russell and Jordan 1991). Figure 5 illustrates slightly improved height coverage for virtual temperature measurements obtained at Platteville in summer with the same system used in ARM-91. Presumably, the improvement is caused in part by the less severe acoustic attenuation expected for the 2000-Hz acoustic frequency in warmer, more moist conditions (Bedard 1990). The figure also shows wind data from a similar profiler at Christmas Island in the tropical Pacific Ocean and indicates significantly better (about 2 km) height coverage for wind than was obtained at Platteville. Neff et al. (1991) show that height coverage to 4 km was common for summertime operation of these profilers with clutter fences in California.

b. Comparisons with rawinsonde data

To evaluate meteorological profiling by remote sensors, it is useful to compare their measurements with those of nearby rawinsondes. Abundant data from ARM-91 are available for these comparisons. The value of such comparisons is limited, however, because different volumes of air are sampled by the two methods. A wind profiler/RASS samples a large volume above its location in an Eulerian sense, whereas the rawinsonde makes a Lagrangian sampling of a smaller volume along the balloon trajectory. Because the balloon drifts, data from initially collocated instruments may actually be obtained at widely separated locations aloft, where meteorological conditions could be significantly different. Even though the rawinsonde has become the de facto standard for upper-air measurements, it too is subject to error (Hoehne 1980). Nevertheless, comparisons with sonde data are informative and likely to be important for the remote sensors to attain widespread scientific credibility.

Figures 6a and 6b show time series of simultaneous wind speed and virtual temperature data from profilers, RASS, and CLASS rawinsondes at Platteville for one of the ARM-91 IOPs. Data from the 404- and 50-MHz systems overlap at one of the selected heights; rawinsonde measurements from the nearest heights and times are shown by the circled crosses. There is good agreement between the measurements for this case of rapidly changing conditions associated with a cold front.

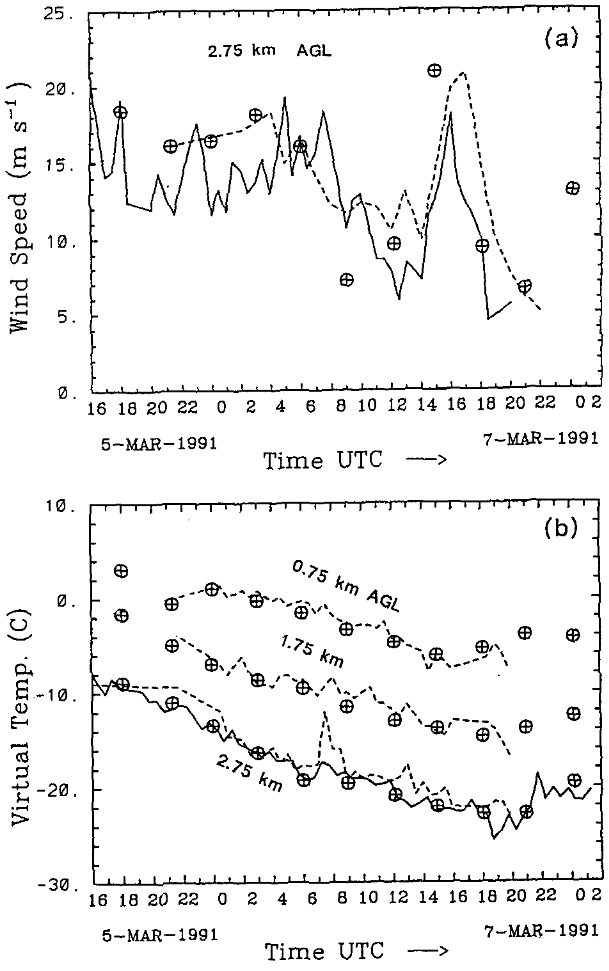
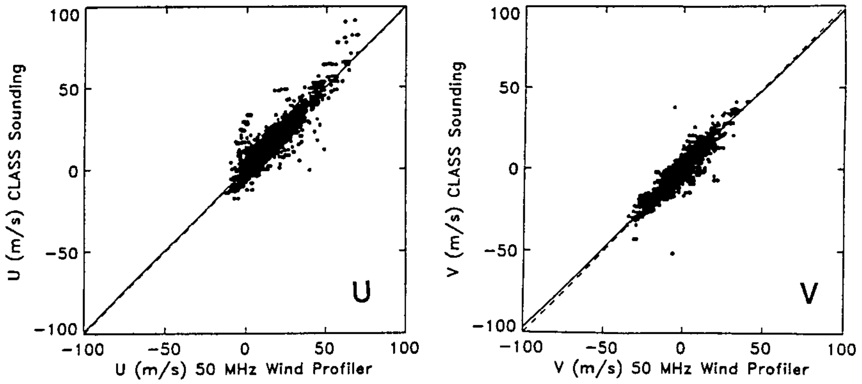


FIG. 6. Time series examples of (a) wind speed and (b) virtual temperature measurements at Platteville during an ARM-91 IOP. Solid lines are for the 50-MHz and dashed lines are for the 404-MHz wind profiler/RASS units, respectively. Circled crosses are data from CLASS rawinsondes.

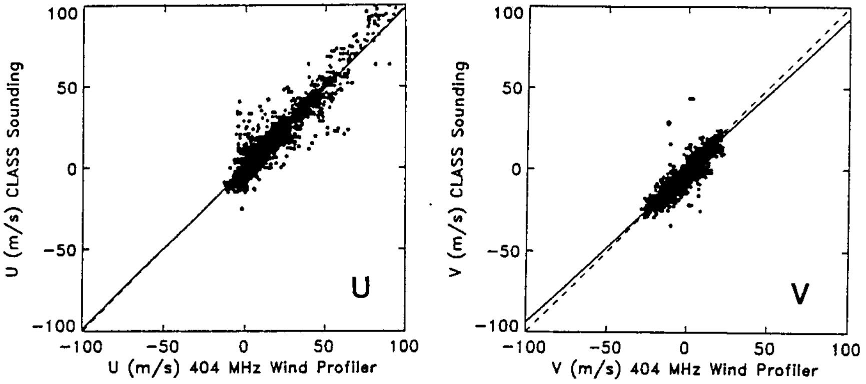
(a) PLATTEVILLE 50 MHz vs CLASS

npts = 4295 $\overline{|u|}_{sonde}$=11.7 m/s $\overline{|v|}_{sonde}$=7.7 m/s



(b) PLATTEVILLE 404 MHz vs CLASS

npts = 3448 $\overline{|u|}_{sonde}$=12.5 m/s $\overline{|v|}_{sonde}$=7.8 m/s



(c) DENVER 915 MHz vs NWS

npts = 3361 $\overline{|u|}_{sonde}$= 8.9 m/s $\overline{|v|}_{sonde}$=5.6 m/s

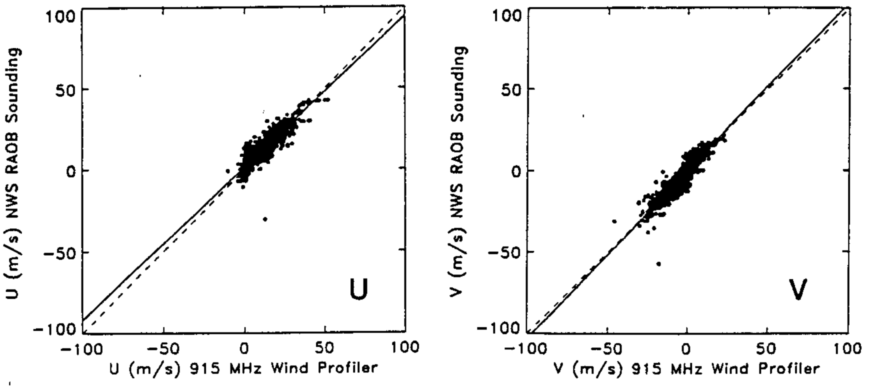


FIG. 7. Comparisons of wind measurements by collocated wind profilers and rawinsondes. Data are plotted for (a) low- + high-altitude modes of the 50-MHz profiler at Platteville, (b) low + high modes of 404-MHz WPDN profiler at Platteville, and (c) low mode of 915-MHz profiler at Denver. Dashed line denotes perfect agreement; solid line is least-squares fit to the data. The number of comparison points and mean magnitude of the sonde values are also shown.

Quantitative comparisons of the wind profiler/RASS data with sonde measurements were conducted by statistical analysis of all available data from the seven IOPs. The remote-sensor data used in the comparisons were those that had passed the hourly consensus test and the time–height continuity algorithm editing. No other screening for bad measurements or stratification for certain kinds of weather was done. Two CLASS soundings with obviously erroneous temperature measurements were excluded from the rawinsonde dataset. The sonde wind and temperature data received no editing beyond the routine NWS and NCAR processing. Comparisons were made for nearest points in height for all remote sensor data obtained within 0.5 h of a rawinsonde launch. Virtual temperature was measured directly by RASS and was computed from temperature and humidity measurements of the sondes.

1) WIND

Figures 7a–c show wind speed measurements from three different wind profiler frequencies compared with the data of collocated rawinsondes. Data from the 915-MHz profiler at Denver are compared with Denver NWS sondes and those from combined low- and high-altitude modes of the 404- and 50-MHz systems at Platteville are compared with the Platteville CLASS sonde. The *u* (east–west) and *v* (north–south) components of the horizontal wind vector are plotted separately in each comparison. Although several large discrepancies are noticeable,

TABLE 4. Wind profiler and RASS comparisons with rawinsondes during ARM-91 (mean differences are for sonde value–remote sensor value).

		Low alt. mode		High alt. mode	
System	T_v (°C)	u (m s^{-1})	v (m s^{-1})	u (m s^{-1})	v (m s^{-1})
915 MHz (Denver) vs NWS sonde					
No. of points	745	3361	3361	NA	NA
Correlation	0.99	0.92	0.93		
Mean difference	–0.07	0.99	0.21		
Std. deviation	0.96	3.04	3.02		
404 MHz (Platteville) vs CLASS sonde					
No. of points	800*	2197	2197	1251	1251
Correlation	0.97	0.93	0.91	0.93	0.90
Mean difference	–0.29	–0.10	–0.45	0.73	–0.80
Std. deviation	1.26	5.22	4.40	6.28	4.01
50 MHz (Platteville) vs CLASS sonde					
No. of points	2107	4158	4158	137#	137#
Correlation	1.00	0.93	0.94	0.82	0.93
Mean difference	0.08	0.92	0.46	–0.16	1.74
Std. deviation	1.02	4.71	3.61	6.74	5.61

NA = Not available; the high-altitude sampling mode of this profiler was not used during ARM-91.

*For heights below 2.5 km AGL only; see explanation in text.

#High-altitude sampling mode of this profiler was used on only one intensive operating period.

most of the thousands of comparison points are clustered close to the line of perfect agreement.

Statistics from the comparisons are summarized in Table 4. Mean differences are generally less than 1 m s^{-1}, indicating very little bias of the profiler measurements relative to the sonde. For the low-altitude mode, difference standard deviations are about 3–4 m s^{-1}, and correlation values exceed 0.90. As expected, the agreement is not quite as good for the high-altitude mode, for which the horizontal separation between sonde and remote sensor data is usually large. The ARM-91 404- and 915-MHz statistics are quite similar to those found by Weber and Wuertz (1990) and Weber et al. (1990), respectively, for the same profilers. As Weber and Wuertz (1990) concluded, the data indicate good agreement between wind profiler and sonde measurements, and most of the variability is probably caused by real differences in the winds at the separated sampling locations aloft and by the differences in sample volume sizes.

2) VIRTUAL TEMPERATURE

May et al. (1989) compared virtual temperatures measured by WPL's 915- and 50-MHz RASS with those computed from nearby rawinsondes. About 50 soundings from a variety of meteorological conditions were examined. The rms differences were only about 1°C, even without adjusting the sound speed for vertical air speed. Data obtained when the measured vertical winds were negligible showed still smaller rms differences. The more extensive ARM-91 dataset has been examined in a similar manner. No correction for vertical velocity was attempted, but the vertical winds were likely to have been weak in the weather conditions of the ARM-91 IOPs.

Figures 8a–d display comparisons of WPL RASS data with those of collocated rawinsondes, and the comparison statistics are summarized in Table 4. Figure 8a shows the 915-MHz RASS and the NWS sonde data at Denver. The agreement is excellent: the mean RASS-sonde difference is 0.07°C, the standard

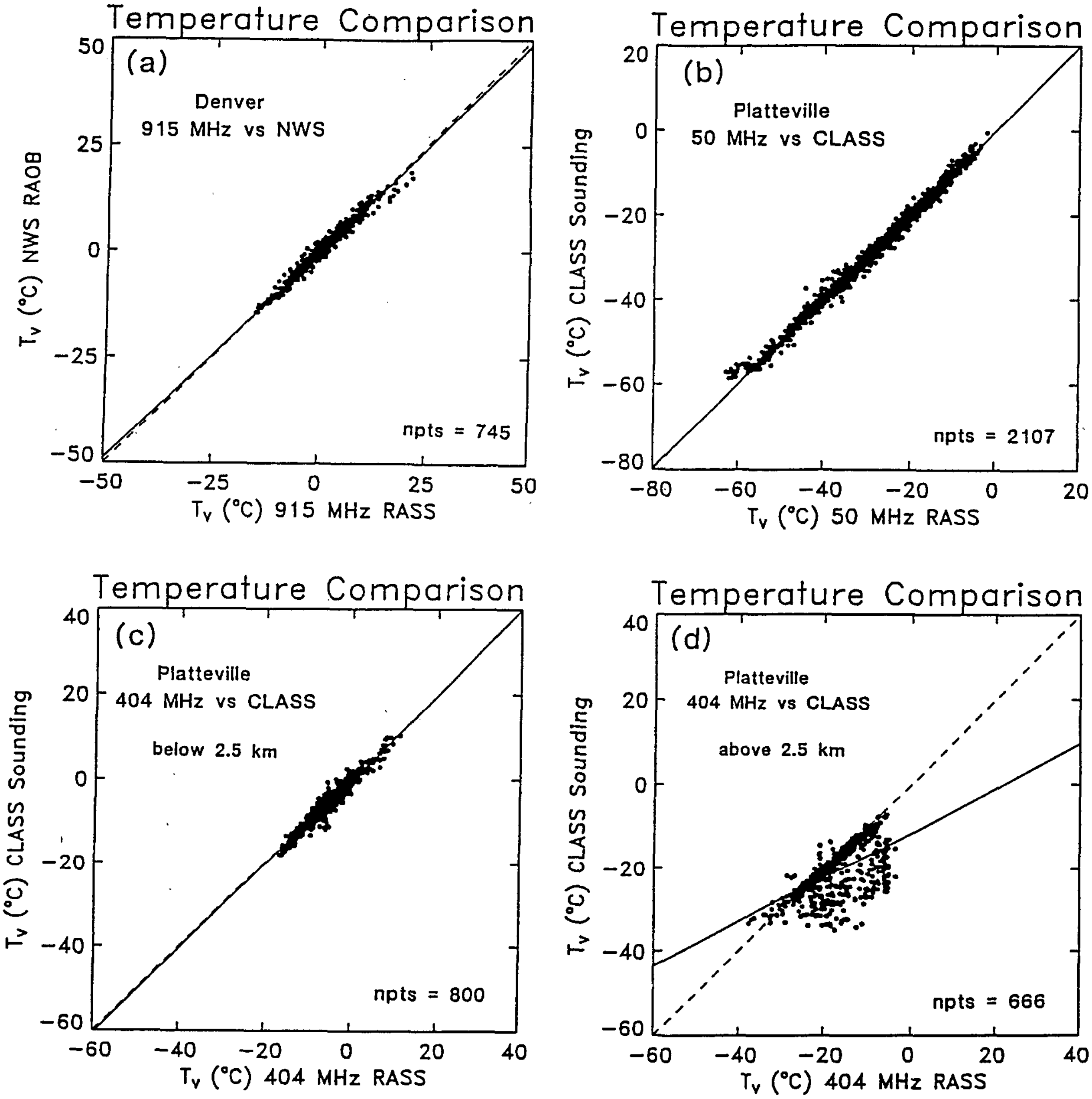


FIG. 8. Comparison of virtual temperatures measured by RASS and rawinsondes for ARM-91 IOPs for (a) the WPL 915-MHz system at Denver, (b) the WPL 50-MHz system at Platteville, (c) the WPDN 404-MHz system at Platteville for data below 2.5 km AGL, and (d) above 2.5 km. The dashed line denotes perfect agreement, the solid line is a least-squares fit to the data. The number of comparison points is also shown.

deviation of the differences is 0.96°C, and the correlation value is 0.99. Data for the 50-MHz RASS at Platteville are plotted against CLASS sonde data in Fig. 8b. Again, the agreement is excellent (Table 4), with the exception of a slight offset at the very lowest temperatures.

The lower-altitude comparisons of RASS data from the 404-MHz WPDN unit at Platteville also show excellent agreement with the CLASS sonde data in Fig. 8c. Figure 8d, however, reveals serious discrepancies above 2.5 km where the RASS virtual temperatures were frequently much higher than those of the sondes. Almost all the discrepancy points were from the uppermost heights, where the signal-to-noise ratio is weakest.

The 404-MHz data above 2.5 km were examined in detail and three probable sources of RASS error were identified. First, the RASS echoes were sometimes masked by internally generated interference, causing all weak signals to have the same measured sound velocity and, thus, virtual temperature. If this temperature was similar to valid nearby measurements at lower altitudes, the time–height pattern continuity editor (Wuertz and Weber 1989) was unable to reject the data as it would have if the numbers were significantly different from those of neighboring points. Second, operational mission constraints of this network profiler permitted temperature profiling only twice an hour during ARM-91. Thus, unlike the other RASS units, these virtual temperature data did not undergo consensus test averaging, and the continuity editor operated on the noisier "raw" data of individual profiles. As a result, at low signal-to-noise ratio (when the processor output is a random value), the editing algorithm accepted points that were consistent with the closest valid data. Since the closest valid data were at lower heights, the erroneous RASS temperatures were generally too high. Finally, the operational mission of the WPDN constrained the RASS processing such that it was not always possible to achieve sufficient isolation between the sound-speed signal and the vertical airspeed signal. WPL's processor on this unit could misconstrue the near-zero air speed and the weak acoustic pulse–speed signals at high altitudes. For a speed of 0 m s^{-1}, the result is an erroneous virtual temperature value of -5.5°C. A vertical cluster of points at about this temperature is apparent in Fig. 8d.

These problems were primarily the result of the ad hoc manner in which RASS capability was, by necessity, added to this operational wind profiler for the ARM-91 project. Engineering solutions to the problems are straightforward and future RASS additions to WPDN profilers should not suffer from these errors. With this exception, the overall agreement between RASS and sondes was extremely good, as the statistics of Table 4 verify.

The virtual temperature profile in Fig. 9 illustrates one source of differences between the remote and in situ measurements. In this example the rawinsonde data reveal a shallow elevated inversion layer that is missed by the coarser vertical resolution of the RASS. The vertical resolution of the wind profilers and RASS varies with the unit and with the selected height range (Table 1). However, the resolution is generally poorer than that available from sondes. Knowledge of shallow layers of abrupt wind and temperature changes may be important for forecasting purposes. The limited capability of wind profilers and RASS units for detecting these situations is a shortcoming of the current systems. This limitation may be eased by combining the finer-scale measurements of a 915-MHz system in the boundary layer with coarser 404- or 50-MHz measurements at higher levels. The fact that profilers and RASS can detect features of modest to large vertical extent, such as fronts, and follow them with temporal resolution that is far superior to the routine twice-daily rawinsonde data has been demonstrated by Nieman et al. (1991).

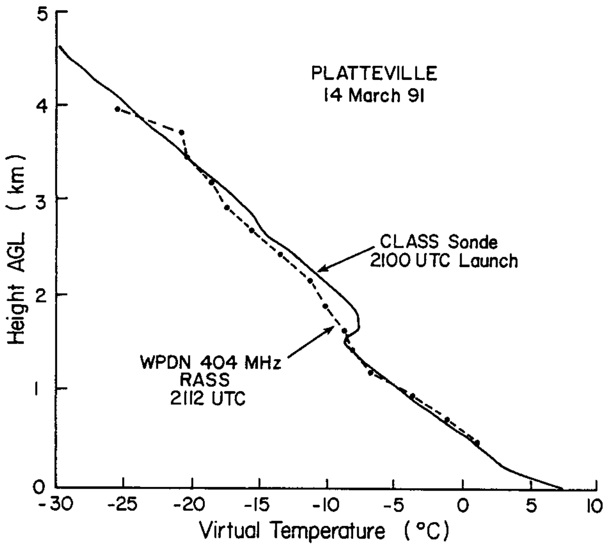


FIG. 9. Profiles of virtual temperature measured by the 404-MHz RASS and computed from data of the CLASS rawinsonde at Platteville.

5. Microwave radiometer performance

Climatologically based statistical retrievals can produce crude profiles of water vapor from the radiometer's path-integrated measurement. However, assimilation of the integrated value (precipitable water vapor) alone has been shown to be almost as useful in improving numerical weather forecasts as assimilation of complete vapor profiles (Kuo et al. 1993). Figure 10 shows time series plots of precipitable water vapor measured by WPL's microwave radiometers and annotated for comparison with collocated measurements by NWS and CLASS rawinsonde data for one of the ARM-91 IOPs. The agreement is excellent and the figure illustrates the vastly superior temporal resolution (2 min) of the radiometer measurements.

Frequent ARM-91 and WISP rawinsonde launches allowed many opportunities to compare radiometer and sonde measurements of precipitable water vapor. Unfortunately, the CLASS measurements of surface humidity sometimes appeared to be erroneous relative to their in-flight measurements just above the surface. For these comparisons, measurements made by dewpoint hygrometers at the WPL radiometer sites were substituted for the CLASS surface humidity data.

Figure 11 compares precipitable water vapor values measured by the radiometer with those computed from the humidity profile data for 121 CLASS sound-

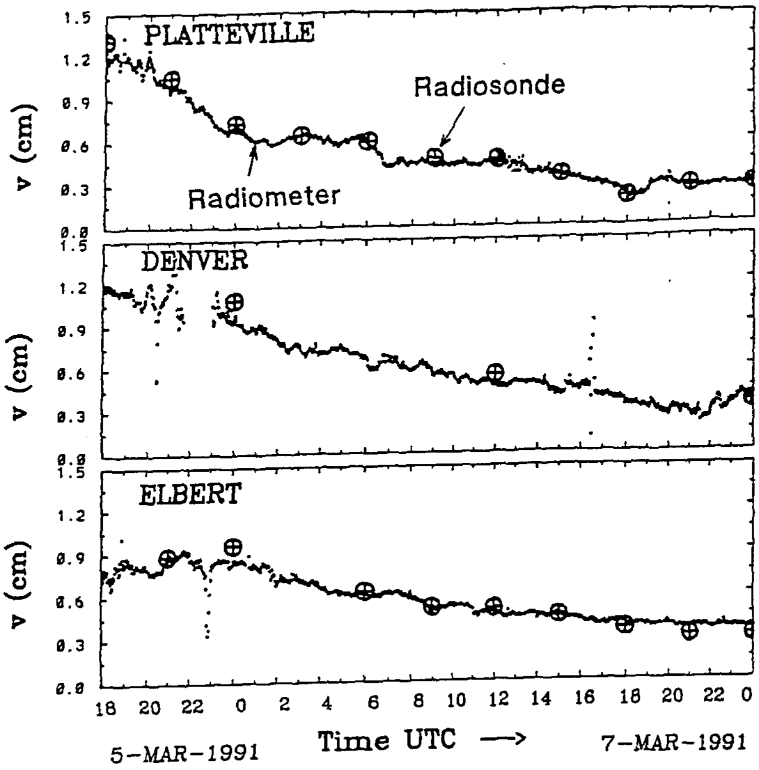


FIG. 10. Time series examples of precipitable water vapor measured by microwave radiometers and radiosondes at three locations during an ARM-91 IOP.

ings at Platteville from mid-January to the end of March. The agreement is very good for these comparisons, which include clear and cloudy conditions. The rms difference was 1.1 mm for these relatively dry conditions in which the PWV values ranged from 1 to 13 mm. The limited span of vapor values does not allow an evaluation of the errors for humid conditions that are common in other geographic areas. However, in an earlier study that included more humid conditions (PWV = 1–29 mm) at Denver, Hogg et. al. (1983) found an rms difference of 1.7 mm for six months of comparisons with NWS radiosondes. The limited sensitivity of NWS sondes to low humidities (Wade 1991) and the poorer vertical resolution of the sonde data used in the earlier study may account for some of the improvement in ARM-91. In addition, advances have been made since the earlier study in the accuracy of absorption coefficient values used in the radiometric retrievals (Westwater et al. 1990) and in automated screening of the radiometer data for spurious features such as those caused by wet antennas. The liquid content of the ARM-91 clouds was low; thus, potential adverse effects of very high liquid contents on the vapor retrievals (Hogg et al. 1983) were not encountered.

Similar comparisons of integrated liquid water content of clouds are not possible because the NWS and CLASS sondes are not equipped with a liquid water sensor. Comparisons of radiometer measurements of liquid with in situ measurements by research aircraft have shown fairly good agreement (Hill 1992). Stankov and Bedard (1993) demonstrate the use of radiometer liquid measurements, in conjunction with other remotely sensed parameters, for monitoring aircraft icing hazards. The radiometer accuracy, sensitivity, and sonde comparison data are summarized in Table 5.

The vapor and liquid contents are derived by retrievals from the radiometer's fundamental measurement of brightness temperature for the detected frequencies. Keihm (1991) shows that brightness temperatures measured by the WPL and JPL radiometers at Platteville agreed within 0.1 K for clear sky conditions for both 20.6 and 31.65 GHz. Although this point of excellent agreement does not constitute a measure of absolute or overall accuracy, it is an encouraging note for these independently designed and calibrated radiometers. Meaningful comparisons in cloudy conditions are greatly complicated by the different beamwidths of the two systems.

6. Summary and conclusions

The wintertime ARM-91 project in Colorado used

TABLE 5. Summary of WPL dual-channel radiometer measurement statistics.

	Precipitable water vapor (mm)	Path-integrated cloud liquid water content (mm)
Theoretical absolute accuracy	0.70	0.030
Sensitivity (2-min integration time)	0.07	0.005
Comparisons with rawinsondes, difference:		
• from CLASS at Platteville in ARM-91	1.1	—
• from NWS at Denver (Hogg et al. 1983)	1.7	—

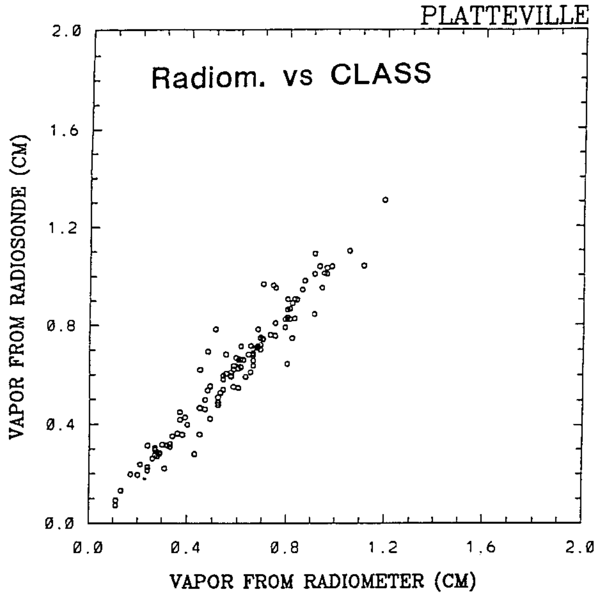


FIG. 11. Comparison of precipitable water vapor measured by the microwave radiometer and the CLASS rawinsonde at Platteville for 121 wintertime soundings.

ground-based remote sensors to continuously measure the kinematic and thermodynamic structure of the atmosphere. Three microwave radiometers and five different wind profiler/RASS units were operated simultaneously to obtain measurements of precipitable water vapor and profiles of wind and virtual temperature. The profilers at Platteville included the three most common frequencies used by researchers to date: 50, 404, and 915 MHz. The remote-sensor measurements were augmented by and compared with data from frequent rawinsonde launches during intensive operating periods.

Analyses of the wind profiler and RASS data show a wide range of height coverage capability for the different systems. Wind measurements were obtained 90% of the time to heights of 10 km AGL for the WPL 50-MHz system, 13 km for the WPDN 404-MHz system, 1.4 km for the WPL high-power 915-MHz system, and 0.6 km for the AL boundary-layer 915-MHz profiler. The height coverage of virtual temperature measurements by RASS was limited to lower regions of the atmosphere for each system. Virtual temperature profiles were obtained 90% of the time to heights of about 4.4 km for the WPL 50-MHz unit, 2.7 km for the WPDN 404-MHz system, 1.3 km for the WPL 404-MHz system, 0.95 km for the WPL high-power 915-MHz system, and 0.4 km for the AL boundary-layer 915-MHz RASS. As expected, the height coverage of RASS decreased significantly with increasing frequency because of more severe acoustic attenuation at higher frequencies. Several other factors also influence RASS height coverage. Data from warmer, more humid conditions show improved height coverage for the boundary-layer profiler and RASS. By combining measurements from all three frequencies, wind and virtual temperature profiles extending above the middle of the troposphere can be obtained most of the time.

Extensive comparisons of the remote-sensor data with those of collocated rawinsondes indicate very good to excellent agreement between the remote and in situ measurements. Mean differences between sonde and remote sensor were less than 1 m s^{-1} for horizontal wind components and less than 0.3°C for virtual temperature for most systems. Standard deviations of the sonde–remote sensor differences were about 3–4 m s^{-1} for wind speed components and about 1°C for virtual temperature. Microwave radiometer measurements of precipitable water vapor had an rms difference of about 1 mm from the sonde data.

The ARM-91 height coverage results clarify performance differences between a variety of profiler and RASS designs. The comparisons of profiler, RASS, and radiometer data with rawinsonde measurements . . . are very encouraging.

The ARM-91 height coverage results clarify performance differences between a variety of profiler and RASS designs. The comparisons of profiler, RASS, and radiometer data with rawinsonde measurements, although not true tests of accuracy, are very encouraging. Increased confidence in and future use of the ground-based remote sensing technologies for research and operations are supported by these findings. Continuous observations by remote sensing augmented by occasional rawinsonde data provide a potent combination that maximizes the temporal and vertical resolution of upper-air measurements.

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WPDN wind profiler data were obtained from NOAA/FSL; Daniel Law provided engineering data on the profiler. Meteorologists from FSL provided daily weather briefings for WISP, which also aided the ARM field operations.

References

Angevine, W. M., D. A. Carter, W. L. Ecklund, and K. S. Gage, 1991: A new technique for temperature profiling using RASS. Preprints, *25th Intl. Conf. on Radar Meterology,* Paris, Amer. Meteor. Soc., 241–244.

Balsey, B. B., and K. S. Gage, 1982: On the use of radars for operational wind profiling. *Bull. Amer. Meteor. Soc.,* **63,** 1009–1018.

Bedard, A. J., Jr., 1990: The measurement of sonic boom waveforms and propagation characteristics: Techniques and challenges. Preprints, *AIAA 13th Aeroacoustics Conf.,* Tallahassee, FL, Amer. Inst. Aeronautics & Astronautics, 9 pp.

Brewster, K. A., and T. W. Schlatter, 1988: Recent progress in automated quality control of wind profiler data. Preprints, *8th Conf. on Numerical Weather Prediction,* Baltimore, Amer. Meteor. Soc., 331–338.

Chadwick, R. B., and N. Hassel, 1987: Profiler: The next generation atmospheric sounding system. Preprints, *3rd Intl. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanpgraphy and Hydrology,* New Orleans, Amer. Meteor. Soc., 15–21.

Dabberdt, W. F., H. L. Cole, P. Hildebrand, T. Horst, Y. H. Kuo, C. Martin, K. S. Gage, W. Ecklund, R. Strauch, E. R. Westwater, and W. L. Smith, 1991: The integrated sounding system—A new observing system for mesoscale research. Preprints, *7th Symp. on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., J128–133.

DOE, 1990: Atmospheric Radiation Measurement program plan. DOE/ER-0441, U. S. Dept. of Energy Rep., 116 pp. [Available from the National Technical Information Service, U. S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.]

Ecklund, W. L., D. A. Carter, and B. B. Balsey, 1988: A UHF wind profiler for the boundary layer: Brief description and initial results. *J. Atmos. Oceanic. Technol.,* **5,** 432–441.

Frisch, A. S., B. L. Weber, R. G. Strauch, D. A. Merritt, and K. P. Moran, 1986: The altitude coverage of the Colorado wind profilers at 50, 405, and 915 MHz. *J. Atmos. Oceanic Technol.,* **3,** 680–692.

——, ——, D. B. Wuertz, R. G. Strauch, and D. A. Merritt, 1990: The variations of C_n^2 between 4 and 16 km above sea level as measured over 5 years. *J. Appl. Meteor.,* **29,** 645–651.

Fukao, S., N. Yamasaki, R. M. Harper, and S. Kato, 1982: Winds measured by UHF Doppler radar and rawinsondes—Comparisons made on 26 days. *J. Appl. Meteor.,* **21,** 1357–1363.

Harris, C. M., 1966: Absorption of sound in air versus humidity and temperature. *J. Acoustic Soc. Amer.,* **40,** 148–159.

Hill, G. E., 1992: Further comparisons of simultaneous airborne and radiometric measurements of supercooled liquid water. *J. Appl. Meteor.,* **31,** 397–401.

Hoehne, W. E., 1980: Precision of National Weather Service upper air measurements. NOAA Tech. Memo., NWS T&ED-16, 23 pp. [Available from the National Technical Information Service, U. S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.]

Hogg, D. C., F. O. Guiraud, J. B. Snider, M. T. Decker, and E. R. Westwater, 1983: A steerable dual-channel microwave radiometer for measurement of water vapor and liquid water in the troposphere. *J. Climate Appl. Meteor.,* **22,** 789–806.

Keihm, S. J., 1991: Water vapor radiometer intercomparison experiment, Platteville, Colorado. Final Rep., Jet Propulsion Laboratory, 38 pp. [Available from JPL, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109.]

Kuo, Y., Y. Guo, and E. R. Westwater, 1993: Assimilation of precipitable water measurements into a mesoscale numerical model. *Mon. Wea. Rev.,* **121,** 1215–1238.

Lataitis, R. J., 1992: Signal power for radio acoustic sounding of temperature: The effects of horizontal wind, turbulence, and vertical temperature gradients. *Radio Sci.,* **27,** 369–385.

Lauristen, D. K., 1991: A review of the CLASS sounding system and an overview of its successor: NEXUS. Preprints, *7th Symposium on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., 265–269.

——, Z. Malekmadani, C. Morel, and R. McBeth, 1987: The Cross-chain Loran Atmospheric Sounding System (CLASS). Preprints, *6th Symposium on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., 340–343.

Martin, C. L., 1991: Summary of observations made during the WISP/ARM 1991 field program in support of the integrated data assimilation and sounding system development. *Proc. Lower Tropospheric Profiling: Needs and Technology,* Boulder, CO, Amer. Meteor. Soc., 139–140.

May, P. T., K. P. Moran, and R. G. Strauch, 1988: The altitude coverage of temperature measurements using RASS with wind profiler radars. *Geophys. Res. Lett.,* **15,** 1381–1384.

——, ——, and ——, 1989: The accuracy of RASS temperature soundings. *J. Appl. Meteor.,* **28,** 1329–1335.

——, R. G. Strauch, K. P. Moran, and W. L. Ecklund, 1990: Temperature soundings by RASS with wind profiler radars. *IEEE Trans. Geosci. Remote Sens.,* **28,** 19–28.

Moran, K. P., D. B. Wuertz, R. G. Strauch, N. L. Abshire, and D. C. Law, 1991: Temperature sounding with wind profilers. *J. Atmos. Oceanic Technol.,* **8,** 606–608.

Neff, W., J. Jordan, J. Gaynor, D. Wolfe, W. Ecklund, D. Carter, and K. Gage, 1991: The use of 915-MHz wind profilers in complex terrain and region air quality studies. Preprints, *7th Symposium on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., J230–233.

Nieman, P. J., P. T. May, B. B. Stankov, and M. A. Shapiro, 1991: Radio acoustic sounding system observations of an arctic cold front. *J. Appl. Meteor.,* **30,** 881–892.

Passi, R. M., and C. Morel, 1987: Wind errors using the worldwide Loran network. *J. Atmos. Oceanic Technol.,* **4,** 690–700.

Peters, G., H. Timmerman, and H. Hinzpeter, 1983: Temperature sounding in the planetary boundary layer by RASS—System analysis and results. *Int. J. Remote Sens.,* **4,** 49–63.

Rasmussen, R. M., M. K. Politovich, J. Marwitz, W. Sand, J. McGinley, J. Smart, R. Pielke, S. Rutledge, D. Wesley, G. Stossmeister, B. Bernstein, K. Elmore, N. Powell, E. Westwater, B. Stankov, and D. Burrows, 1992: Winter Icing and Storms Project. *Bull. Amer. Meteor. Soc.,* **73,** 951–974.

Reinking, R. F., Ed., 1991: Lake Ontario Winter Storms project final technical report. Kaman Sciences Corp., 213 pp. [Available from Kaman Sciences, 1500 Garden of the Gods Rd., Colorado Springs, CO 80907.]

Russell, C. A., and J. R. Jordan, 1991: Portable clutter fence for UHF wind profiling radar. Preprints, *7th Symposium on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., J152–156.

Smith, W., H. Revercomb, H. Howell, H. Woolf, R. Knuteson, R. Decker, M. Lynch, E. Westwater, R. Strauch, K. Moran, B. Stankov, M. Falls, J. Jordan, M. Jacobsen, W. Dabberdt, R. McBeth, G. Albright, C. Paneitz, G. Wright, P. May, and M. Decker, 1990: GAPEX: A ground-based atmospheric profiling experiment. *Bull. Amer. Meteor. Soc.,* **71,** 310–318.

Stankov, B. B., and A. J. Bedard, Jr., 1993: Remote sensing observations of winter aircraft icing conditions: A case study. *J. Aircraft*, **30**, in press.

Strauch, R. G., B. L. Weber, A. S. Frisch, C. G. Little, D. A. Merritt, K. P. Moran, and D. C. Welsh, 1987: The precision and relative accuracy of profiler wind measurements. *J. Atmos. Oceanic Technol.*, **4**, 563–571.

Wade, C. G., 1991: Improved low humidity measurements using the radiosonde hygristor. Preprints, *7th Symposium on Meteorological Observations and Instrumentation,* New Orleans, Amer. Meteor. Soc., 285–290.

Weber, B. L., and D. B. Wuertz, 1990: Comparison of rawinsonde and wind profiler radar measurements. *J. Atmos. Oceanic Technol.*, **7**, 157–174.

——, ——, R. G. Strauch, D. A. Merritt, and K. P. Moran, D. C. Law, D. van de Kamp, R. B. Chadwick, M. H. Ackley, M. F. Barth, N. L. Abshire, P. A. Miller, and T. W. Schlatter, 1990: Preliminary evaluation of the first NOAA Demonstration Network wind profiler. *J. Atmos. Oceanic Technol.*, **7**, 909–918.

Westwater, E. R., J. B. Snider, and M. J. Falls, 1990: Ground-based radiometric observations of atmospheric emission and attenuation at 20.6, 31.65, and 90.0 GHz: A comparison of measurements and theory. *IEEE Trans. Antennas Propag.*, **38**, 1569–1580.

Wuertz, D. B., and B. L. Weber, 1989: Editing wind profiler measurements. NOAA Tech. Rep., ERL 438- WP 62, 78 pp. [Available from the National Technical Information Service, U. S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.]

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