

**Radar Wind Profiler and RASS (RWP50)  
Handbook**

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## **1. General Overview**

The 50-MHz Radar Wind Profiler/RASS (RWP50) measures wind profiles from (nominally) 2 to 12 km and virtual temperature profiles from 2 to 4 km. It operates by transmitting electromagnetic energy into the atmosphere and measuring the strength and frequency of backscattered energy. Virtual temperatures are recovered by transmitting an acoustic signal vertically and measuring the electromagnetic energy scattered from the acoustic wavefront. The propagation speed of the acoustic wave is proportional to the square root of the virtual temperature.

## **2. Contacts**

### **2.1 Mentor**

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### **2.2 Instrument Developer**

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## **3. Deployment Locations and History**

SGP Central Facility: Installed and operating since April 1994.

## **4. Near-Real-Time Data Plots**

See [General Quick Looks](#).

## **5. Data Description and Examples**

### **5.1 Data File Contents**

#### **5.1.1 Primary Variables and Expected Uncertainty**

The primary quantities measured with the system are the intensity and Doppler frequency of backscattered radiation. The wind speed is determined from the Doppler frequency of energy scattered from refractive index fluctuations (caused primarily by temperature fluctuations) embedded within the

atmosphere; the virtual temperature is determined from the Doppler frequency of microwave energy scattered from acoustic energy propagating through the atmosphere.

### **5.1.1.1 Definition of Uncertainty**

The primary observed quantities are Doppler frequency and signal Amplitude. Note that the observed quantities above are not the principal quantities of interest to most scientists. The derived quantities of most interest to scientists are the wind speed, wind direction, vertical wind speed, and virtual temperature as a function of height. The accuracies of these quantities, while dependent upon the accuracy of the frequency measurement, are also affected by atmospheric effects and vary considerably according to conditions. The wind speed is derived from measurements from the five beams. Since the individual components are not collocated in space, horizontal homogeneity is assumed in order to derive the wind vector as a function of height.

- Nominal accuracy for wind speed: 1.5 m/s
- Nominal accuracy for radial wind components along the pointing direction of the transmitter (e.g., vertical velocity): 0.75 m/s
- Nominal accuracy for wind dir: 3 degrees
- Nominal accuracy for virtual temp: 0.5.

### **5.1.2 Secondary/Underlying Variables**

This section is not applicable to this instrument.

### **5.1.3 Diagnostic Variables**

This section is not applicable to this instrument.

### **5.1.4 Data Quality Flags**

No flags are applied during data ingest of the consensus averaged winds and virtual temperatures. However, a parallel data stream with the “.b2” name field has data flags applied that look at relative values of temps or wind components. Neighboring values in space (height) and time (sequential profiles) are compared with predefined limits (given in the metadata of the NETCDF file). In addition to the unchanged wind component and temperature fields, a field of flags (on or off [1 or 0]) is supplied to “point” at suspect values.

Additional information may be found at [50 RWP Data Object Design Changes](#) for ARM netCDF file header descriptions.

### **5.1.5 Dimension Variables**

This section is not applicable to this instrument.

## 5.2 Annotated Examples

This section is not applicable to this instrument.

## 5.3 User Notes and Known Problems

This section is not applicable to this instrument.

## 5.4 Frequently Asked Questions

### Why don't the profiler values of winds and/or temperature agree with values from the radiosonde (BBSS)?

- The RWP provides values averaged over (nominally) 1 hour while the BBSS obtains only a grab sample at one instant in time at each height.
- The balloon from the BBSS travels with the mean wind; hence, it is not collocated with measurements from the RWP.
- The RWP values are volume averages over (nominally) 60-240 m in height by 9 degrees horizontally.
- The BBSS measures temperature, the RWP measures virtual temperature.
- The RWP may be detecting birds rather than the true wind.

### Why don't 50 MHz profilers have problems with birds similar to 915 MHz systems?

Because the wavelength of the 50 MHz systems is much larger than that of most birds; those birds capable of causing significant scattering for the 50 MHz system (e.g., Cranes, Pteradactyls) do not normally fly at the altitude normally used by the 50 MHz systems.

## 6. Data Quality

### 6.1 Data Quality Health and Status

The following links go to current data quality health and status results:

- [DQ Hands](#) (Data Quality Health and Status)
- [NCVweb](#) for interactive data plotting using.

The tables and graphs shown contain the techniques used by ARM's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

### 6.2 Data Reviews by Instrument Mentor

- **QC frequency:** Daily
- **QC delay:** Instantaneous; daily
- **QC type:** Min/max flags, graphical plots, comparisons
- **Inputs:** Raw data

- **Outputs:** Summary reports
- **Reference:**

Data quality control procedures for this system are mature.

1. Data Flags:

A procedure has been in place and operating for several years that produces a parallel data stream to the “.a2” data, which consists of consensus averaged wind and temperature profiles produced by the wind profiler. These data are unchanged from the original data but have an additional data field consisting of flags referring to data that are questionable. The flags are determined based on differences between successive wind or temperature variables. Comparisons are made both in time and space and both forward and backward, i.e., comparisons with previous and successive values at a given height as well as comparisons with values above and below at a given time. If the values exceed defined limits they are flagged.

2. Comparison with radiosonde data:

Every routine launch of radiosondes by the BBSS is used to compare wind speed, wind direction, and virtual temperature between BBSS and the 50-MHz and 915-MHz profilers at the central facility. The approach taken is to compare all values of “good” profiler values with BBSS values averaged over nearly the same height interval. The differences are used to produce the mean, standard deviation, maximum, minimum, and number of values. These data are appended to a file that dates back to June 20, 1995. Summary plots of these data are inspected to determine degraded system performance (see Coulter and Lesht, [“Results of an Automated Comparison Between Winds and Virtual Temperatures from Radiosonde and Profilers”](#) (PDF Document) in *Proceedings of the Sixth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, CONF-9603149, San Antonio March 4-7, 1996, U.S. Department of Energy, pp. 59-60). The statistics of the differences are inspected daily.

3. Comparison between 915 MHz and 50 MHz profilers:

- a) A QME operates routinely to produce virtual a wind profile derived from both the 915 MHz and 50 MHz radar wind profilers.
- b) Portions of the wind profiles from the two instruments, using high power data from the 915-MHz profiler and low power data from the 50-MHz wind profiler, are compared in a manner similar to that used with BBSS and RWPs. Profiles of mean speed, direction, difference in u component, difference in v component and difference in w component are appended to a file dating to January 1997. In addition, a statistical analysis on the differences paralleling the differences used for the BBSS is done over comparable height intervals and appended to a file beginning January, 1996. These differences are primarily intended to look for the influence of birds on 915 MHz radar performance. The statistics of the differences are inspected daily.

4. 50-MHz beam strength comparison:

A comparison among output power for the three beams of the 50 MHz wind profiler is carried out daily by averaging the difference between returned signal strength in the lowest few acceptable range gates. Large differences appearing consistently are an indication of transmit problems. The differences are inspected daily.

5. Estimated maximum height of return:

The daily data from both 915-MHz and 50-MHz wind and temperature profilers are used to determine the maximum height attained in at least 25%, 50%, and 75% of the profiles during each 24 hour period. These data are appended to a file (for each site) beginning Jan. 25, 1993 (915 - CF), March 24, 1994 (50 - CF), and Jan. 1, 1997 (915 - Intermediate facilities). These data are plotted occasionally to determine trends that might indicate hardware problems.

6. Vertical time section perusal:

Approximately every 5 days, the wind and temperature fields over a 5-day period are plotted for both 50 MHz and 915 MHz profilers and visually inspected for consistency both within each system and in comparison between the two instruments. These plots are printed and stored in notebooks.

7. Daily inspection:

Vertical time sections of hourly averaged wind and temperature over a 24 hour period are inspected daily for system consistency and operation via data placed at a Web sites. (The displays for the 915-MHz system at intermediate facility #1 is available on the Web at <http://www.atmos.anl.gov/ABLE>).

### **6.3 Data Assessments by Site Scientist/Data Quality Office**

All DQ Office and most Site Scientist techniques for checking have been incorporated within [DQ HandS](#) and can be viewed there.

### **6.4 Value-Added Procedures and Quality Measurement Experiments**

Many of the scientific needs of the ARM Program are met through the analysis and processing of existing data products into “value-added” products or VAPs. Despite extensive instrumentation deployed at the ARM CART sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the program. Conversely, ARM produces some VAPs not in order to fill unmet measurement needs, but instead to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces “best estimate” VAPs. A special class of VAP called a Quality Measurement Experiment (QME) does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks,

comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth. For more information see:

- [VAPs and QMEs](#)
- Combined 915-50 MHz temperature profile
- Combined 915, 50 MHz profiler, MWR, other sources temp profile
- Site-wide advective tendencies
- Site-wide divergence calculation.

## **7. Instrument Details**

### **7.1 Detailed Description**

#### **7.1.1 List of Components**

The 50-MHz radar wind profiler is manufactured by Radian Corp. It consists of a large antenna field of elements created essentially by coaxial cable suspended roughly 1.5 m above a ground plane. The approximately 70-m square antenna is oriented in a horizontal plane so the “in-phase” beam travels vertically.

Other components in the system include three large acoustic sources (located at the southwest and southeast corners and the center of the north edge of the antenna array), a receiver, an interface module, and a computer for data analysis and processing.

#### **7.1.2 System Configuration and Measurement Methods**

The radar wind profilers operate by transmitting in two different vertical planes and receiving backscattered energy from refractive index fluctuations that are moving with the mean wind. By sampling in the vertical direction and in two tilted planes, the three components of motion can be determined.

The system consists of a single phased array antenna that transmits alternately along three pointing directions: one vertical, one tilted about 15 degrees to the south in the north-south vertical plane, and one tilted about 14 degrees to the west of vertical in the east-west vertical plane.

Radial components of motion along each pointing direction are determined sequentially. It takes, nominally, 30 to 45 seconds (dwell time) to determine the radial components from a single pointing direction. Thus, at the Southern Great Plains (SGP) site the system cycles through three beams (East, North, and vertical) at low power, and then cycles the three beams again at a high power (longer pulse length) setting. The whole process is repeated. About five minutes elapse before the system returns to the beginning of its sequence. Within an averaging interval, the estimates from each beam-power combination are saved (11 to 12 in a 1-hour period) and these values are examined and compared at the end of the period to determine the consensus-averaged radial components of motion.

Briefly, consensus averaging consists of determining if a certain percentage (e.g., 50%) of the values fall within a certain range of each other (e.g., 2 m/s). If they do, those values are averaged to produce the radial wind estimate. The radial values are then combined to produce the wind profile. The results of this



averaging process are what are reported in the “.a2” data files produced by the ARM data system. Included in these files are: height, speed, direction, radial components, # values in consensus, and signal-to-noise ratio (SNR).

During one time period when the system operates in a single pointing direction (dwell time), data are created in the “.a1” and “.a0” files. The system transmits pulses at about a 1- to 10-kHz rate into the atmosphere. The backscatter from each transmit pulse is sampled at, for example, a 250-kHz rate. This results in one sample every 600 m in range. The samples at each range gate are averaged together (time domain integration) over some number (e.g., 100) of pulses to produce a phase value for input into a FFT. After (e.g., 64) values are produced, the FFT is performed (one for each range gate). This process takes on the order of 1 sec. A number (about 30) of these spectra are then averaged together during the dwell time. At the end of the dwell time we have produced a single averaged spectrum from each range gate along the designated pointing direction. The spectra themselves are placed in the “.a0” data files.

The spectra are analyzed by the system before moving to the next pointing direction. This analysis produces estimates of the SNR, the noise, the mean velocity (proportional to frequency), and the first moment (spectral width) at each range gate. This is the information that is stored in the “.a1” data files. Thus, both the “.a1” and “.a0” data files have information about (dwell time) intervals; however, the data sequences pointing directions and output powers.

A note of warning about the mean values in the “.a1” files. The values are 1% of full scale times 100, where full scale is the nyquist velocity of the spectrum. Thus, velocity estimates are determined by multiplying the “mdf” column times the “oband” or “vband” values (described in the metadata) and dividing by 10,000.

RASS operation is essentially the same, except the averaging time is about 10 minutes and only a single pointing direction (vertical) is used. Also, the atmosphere is “seeded” with a sound wave; the index of refraction changes created by the sound wave are the signal source. In order to sample the sound wave (speed about 340 m/s) and the atmosphere (to remove air velocity from temperature estimates), a larger FFT is required (2048 points). This requires a smaller number of points for each time domain integration and increases the processor time required to calculate the FFT. The “.a0” files again are spectra; however, only a portion of the spectra are reported, namely a region near 0 Doppler shift to account for atmospheric motions and a region around the expected speed of sound. The “.a1” files now consist of moments and widths from both the atmospheric portion of the spectrum and from the acoustic portion (the main contributor to the temperature calculation). The “.a2” files consist of profiles of temperature and number of consensus values.

In normal operation, temperature profiles are determined during the first 10 minutes of every hour and the wind profile is averaged over the remaining 50 minutes.

### 7.1.3 Specifications

- **Frequency:** 50 MHz
- **Maximum Range:** 16 km 10 km
- **Range Gate:** 0.3-1 km
- **Pulse Length:** 250, 500, 750, 1000 m

- # Spectra/Ave Spectrum: 1-100
- # Pulse/Time Domain Integration: 1-1000.

## **7.2 Theory of Operation**

This section is not applicable to this instrument.

## **7.3 Calibration**

### **7.3.1 Theory**

This section is not applicable to this instrument.

### **7.3.2 Procedures**

This section is not applicable to this instrument.

### **7.3.3 History**

This section is not applicable to this instrument.

## **7.4 Operation and Maintenance**

### **7.4.1 User Manual**

This section is not applicable to this instrument.

### **7.4.2 Routine and Corrective Maintenance Documentation**

This section is not applicable to this instrument.

### **7.4.3 Software Documentation**

ARM netCDF file header descriptions may be found at [50 RWP Data Object Design Changes](#).

### **7.4.4 Additional Documentation**

See the [Preventative Maintenance Procedure Summaries for the RWP50](#) at the Southern Great Plains (SGP) site.

## **A. Calibrations and Related Performance Checks**

### **1. What are factory recommended calibration procedures? (Identify NIST traceability.)**

The only true calibration procedures are carried out during the Acceptance Test Plan (ATP) that is performed immediately before the instruments are put into service. These procedures are/were

carried out by Radian personnel and the instrument mentor and include the following:

- Output Power: Measured at the output of the final amplifier/preamplifier, including both forward and reflected power measurements (3990 W y).
- Center Frequency: Transmit frequency (49.8 MHz) is measured using a signal generator input to the receiver.
- Doppler Direction: Using a special control parameter file, small signal frequency differences are analyzed to determine the appropriate sign of the analyzed frequency difference.
- Dynamic Range: A signal generator with variable attenuator is used as input to the system to establish a dynamic range of at least 55 dB.
- System Sensitivity: Signal generator is used to establish a minimum detectable level of at least -127 dBm.
- Range verification: A delay line is used to establish range accuracy of +/- 50 m.

All the above procedures are detailed in the ATP, Chapter 3, pages 3-9 through 3-26.

## **2. What are the factory recommended performance checks?**

As detailed in the ATP (Chapter 4), these include visual inspection, system power, timing, data transfer, antenna integrity, and RASS operation verification. The following additional performance checks are detailed on page 100 of the system manual supplied by Radian:

- Control lights
- Date and time accuracy
- Data display operating
- Final amplifier current stationary
- Appropriate antenna rotation
- Data appearance
- SNR levels unchanged.

## **3. What are the mentor calibration procedures?**

There are no “mentor calibration procedures” other than comparison of data with other available sources of data. This, however is more of a quality control check.

## **4. What are the mentor performance checks?**

The mentor performance checks include the following:

- Regular noise level checks (done by Site Ops)
- Regular final amplifier current checks (done by Site Ops)
- Daily data existence (done by mentor)
- Vertical time sections of winds and temperatures (done by mentor)
- Continuous (daily) maximum height attained monitoring (done by mentor).

**5. How are calibration and related performance checks documented?**

- a. Where are procedures documented?  
ATP, system operator's manual supplied by Radian Corporation and an Operators manual specific to the SGP supplied by the instrument mentor.
- b. Have major changes to calibration procedures occurred? NO  
If so, for which components and when?
- c. Are major changes to calibration procedures expected to occur? NO  
If so, for which components and when?

**6. Who implements (mentor) calibration and performance checks?**

- Mentor: Site Ops for system hardware Mentor for data integrity
- Factory: Factory, Site Ops, mentor
- Site Ops: Site Ops
- Other \_\_\_\_\_:

**7. What is standard schedule of calibrations and checks?**

Factory calibrations are done at time of installation and are recommended by the mentor for every year.

Other checks are recommended for Site Ops to perform in the Operator's Manual (p. 7):

- Every 3 mo. operating level comparison
- Every 2 yr antenna analysis (factory procedure)
- Monthly: RASS sources level, acoustic sources operating
- Daily: Operation, data existence
- Weekly: Data integrity.

**8. How are the calibration and check procedures initiated (queued)?**

- Scheduled Calendar Event: Monthly change of temperature range appropriate and expected to maximize accuracy and reliability of virtual temperature profiles.
- Work Order: When data existence fails, or other problem is identified by the mentor.
- Data Inspection: Daily (data existence, maximum height, and comparison with BBSS) and weekly (vertical time sections of wind vectors and virtual temperature contours).
- Instrument Failure: Site Ops checks daily for operation, monthly for physical level and pointing direction, output levels.
- Other \_\_\_\_\_:

**9. How long does it take to perform calibration and performance check procedures?**

- Basic factory calibration: 1-2 days
- System operating: 30 min/day
- Data existence and daily checks: 30 min/day

- Data quality: 2 hr/5 days.

**10. Are any data affected or lost during calibration or performance check procedures?**

- Basic factory calibration: All data lost
- System operating: None
- Data existence and daily checks: None
- Data quality: None.

**11. What are corrective procedures when calibrations and or performance checks fall behind schedule?**

None.

**B. Calibration Data**

**1. Where are calibration data documented? (List for each procedure.)**

- \_ Site Data System:
- \_ Site Ops Data base - Hard Copy: ATP
- \_ Site Ops Data base - Electronic Copy: Site Ops log
- \_ Instrument Mentor - Hard Copy: ATP
- \_ Instrument Mentor - Electronic Copy:
- \_ Data Logger:
- \_ netCDF file:
- \_ Special Archive Database:
- \_ Special Databases accessible via the WWW:
- \_ Other: Mentor log book; profiler log book (at profiler).

**2. Where are calibration coefficients and algorithms applied to convert data to geophysical units?**

In System operating program (POP3), applied to a1 and a2 data.

**C. Maintenance Procedures**

**1. What are the factory recommended maintenance procedures: (preventive and corrective)?**

- In System Manual (p. 97):
- Clean air filters
- Remove dust
- Check cables
- Inspect antenna, fences, exterior cables, guys, anchors.

**2. What are the mentor preventative and corrective maintenance procedures?**

In Operator's Manual (p. 7). These procedures include the following:

- Regular noise level checks (done by Site Ops)
- Regular final amplifier current checks (done by Site Ops)
- Daily data existence (done by mentor)
- Vertical time sections of winds and temperatures (done by mentor)
- Continuous (daily) maximum height attained monitoring (done by mentor).

**3. How are maintenance procedures documented?**

- a. Where are procedures documented?
  - i. In system operators manual (p. 97-100)
  - ii. In operators manual (p. 7)
  - iii. In Site Ops log at SDS.
- b. Have major changes to maintenance procedures occurred? NO  
If so, for which components and when?
- c. Are major changes to maintenance procedures expected to occur? NO  
If so, for which components and when?

**4. What is the procedure schedule?**

- Daily: Check operation, verify data existence
- Weekly: Check data quality
- Monthly: Check system alignment, cables, output levels, antenna switching
- Yearly: Repeat ATP.

**5. How are the procedures initiated (queued)?**

- Scheduled Calendar Event: Automatic change of parameter files for temps
- Work Order: Data nonexistence or apparent malfunction determined by mentor
- Data Inspection: Regular and automatic procedure of mentor
- Instrument Failure:
- Other \_\_\_\_\_: Site Ops standing operation: daily check of operation, monthly checks of hardware.

**6. How long does it take to perform maintenance procedure?**

- System operating: 30 min/day
- Data existence and daily checks: 30 min/day
- Data quality: 2 hr/5 days.

**7. Are any data affected or lost during maintenance procedure?**

No

**8. How are potential affects to data documented?**

Data Quality Reports

**9. What are corrective procedures when maintenance falls behind schedule?**

None

**10. Where is actual maintenance work documented?**

- Site Ops log
- Instrument mentor's personal log.

**D. Data Integrity and Quality Inspections**

**1. What nodes or activities along the data pipeline affect (or can potentially affect) the data stream?**

- Controller Boxes
- Microprocessors
- Data Logger
- Communication Lines/Links
- Calibration Data Files
- Ingest Modules
- Others? (List).

**2. What are current difficulties?**

- Implementation of QA procedures by SDS
- Ability of SDS to handle vertical-only mode of operation for data ingest.

**3. List and describe any standard or non-standard data inspections (active or planned) under each of the following categories:**

- Data Existence check: Daily ingest of "raw" consensus files (active)
- Mentor QC checks (during ingest): Quality Control delta checks (planned)
- Mentor QC checks (outside of ingest):
  - Vertical time section of vector and contour plots (active)
  - Maximum height of wind and temperature profiles/day (active)
  - Comparison with BBSS (active).

- \_ Within Platform Check:
- \_ Multiple Platform Check: Comparison with BBSS
- \_ QMEs/VAPs:
  - Combine 915, 50 virtual temperature profiles (planned)
  - Establish flags for questionable data (planned)
  - Compare temps and winds with BBSS (planned).
  
- \_ Other automated netCDF file checks
- \_ Other analytic tools or algorithms.

**4. Does storage media exist on the instrument system to back up data and store it for delayed data ingest? Please identify media and the maximum period of time that the data can be backed up on the media.**

Yes: The hard disk can hold spectra and consensus files for approximately 12 days. It can hold consensus only files for 1 year. An optical disk can hold spectral data for 1 to 2 months.

## 7.5 Glossary

See the [ARM Glossary](#).

## 7.6 Acronyms

See the [ARM Acronyms and Abbreviations](#).

## 7.7 Citable References

There are numerous references to radar wind profiling, too many to list. A good collection can be found in the proceedings from:

- Lower Tropospheric Profiling: Needs and Technologies. American Meteorol. Soc. and German Meteorolog. Soc. Boulder, Colorado, September 10-13, 1991.
- Third International Symposium on Tropospheric Profiling: Needs and Technologies, Max-Planck-Gesellschaft zur Forderung der Wissenschaften, NCAR, NOAA. Hamburg, Germany, August 30 - September 2, 1994.

A few recent papers:

- Angevine, W. M., and J. I. MacPherson. 1995. Comparison of Wind Profiler and Aircraft Wind Measurements at Chebogue Point, Nova Scotia. *J. Atmos. and Oceanic Tech.* 12, pp. 421-426.
- Merritt, D.A. 1995. Statistical Averaging Method for Wind Profiler Doppler Spectra. *J. Atmos. and Oceanic Tech.* 12, pp. 985-995.



- Nastrom, G.D., and F.D. Eaton. 1995. Variations of Winds and Turbulence seen by the 50-MHz Radar at White Sands Missile Range, New Mexico. *Journ. Appl. Meteorol.* 10, pp. 2135-2148.
- Wilczak, J. M., and collaborators. 1995. Contamination of Wind Profiler Data by Migrating Birds: Characteristics of Corrupted Data and Potential Solutions. *J. Atmos. and Oceanic Tech.* 12, pp. 449-467.
- Williams, C.R., W.L. Ecklund, and K.L. Gage. 1995. Classification of Precipitating Clouds in the Tropics Using 915-MHz Wind Profilers. *J. Atmos. and Oceanic Tech.* 12, pp. 996-1012.

A few early classic papers:

- Ecklund, W.L., D.A. Carter, and B.B. Balsley. 1988. A UHF Wind Profiler for the Boundary Layer: Brief Description and Initial Results. *J. Atmos. Oceanic Technol.* 5, pp. 432-441.
- Ecklund, W.L., D.A. Carter, B.B. Balsley, P.E. Currier, J.L. Green, B.L. Weber, and K.S. Gage. 1990. Field Tests of a Lower Tropospheric Wind Profiler. *Radio Sci.* 25, pp. 899-906.