COORDINATED IN-SITU AND REMOTE SENSING PRECIPITATION MEASUREMENTS AT THE KESSLER FARM FIELD LABORATORY IN CENTRAL OKLAHOMA

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Abstract

Understanding the microphysics of precipitation and the atmosphere in which it forms and evolves is important for scientists to accurately estimate rainfall rates and improve parameterizations in models that predict the weather. Therefore, the University of Oklahoma in collaboration with NOAAs National Severe Storms Laboratory is building up a suite of instrumentation to measure the properties of precipitation at the Kessler Farm Field Laboratory located in central Oklahoma. Measurements from this site build upon other precipitation studies being conducted within the Norman meteorological community. In particular, data collected at the field laboratory are being used in conjunction with the two S-band weather radars operated in Norman. One is a polarimetric radar system and the other is a phased array radar. These two radars are located only 30 km from the Kessler Farm Field Laboratory. Here we give an overview of this new facility, provide a description of the various instruments and their measuring capabilities, and show an example of recently collected data. In particular, we focus on how these complementary measurements are being used in order to study precipitation and precipitation microphysics.

1. INTRODUCTION

Despite years of continuing advancements in the area of quantitative precipitation estimation (QPE) there continues to be a significant need to extend our understanding of precipitation microphysics. For example, the often used relationships between the rainfall rate (R) and the radar reflectivity factor (Z) are know to be fraught with problems. These hinge on the fact that the so-called $Z-R$ relationships all assume a fixed form of the underlying drop-size distribution (DSD) of the hydrometeors responsible for the backscattered radar signal. However, DSDs can exhibit tremendous variability across rain events or even within a given storm system. In order to overcome the limitations of $Z-R$ relationships, one can use QPE algorithms developed especially for polarimetric weather radars. Through the addition of polarization diversity, it becomes possible to not only obtain better rainfall retrievals, but also to generate classifications of the types of precipitation being observed (rain, snow, graupel, hail, etc.).

The NOAA National Severe Storms Laboratory (NSSL) operates a polarimetric WSR-88D (KOUN), which is used to develop and test a suite of algorithms intended to improve upon current QPE methodologies. Using KOUN, the effectiveness of polarimetric weather radar observations has been successfully demonstrated (e.g., Ryzhkov et al., 2005). Indeed, the success of KOUN has been sufficient to convince NOAA officials to sanction the upgrade of the national network of WSR-88Ds within the U.S. to include polarization diversity (Saffle et al., 2007). NSSL in collaboration with the University of Oklahoma (OU) and several other agencies is also exploring the use of phased array technology for weather radars. This partnership has resulted in the development of the National Weather Radar Testbed (NWRT), through which an S-band phased array radar (PAR) is operated. PAR offers many opportunities such as decreasing scan times of weather systems, allowing for more flexible scanning strategies, and providing the ability to simultaneously monitor air traffic and weather phenomena (Forsyth et al., 2005). Both KOUN and PAR are located just north of OU at the NSSL radar testing facility.

Critical to the development of accurate remote sensing algorithms for both conventional weather radars and those capable of polarimetric operations is the availability of quality in-situ measurements. Therefore, OU and NSSL have begun building up a suite of instrumentation to measure the properties of precipitation at the Kessler

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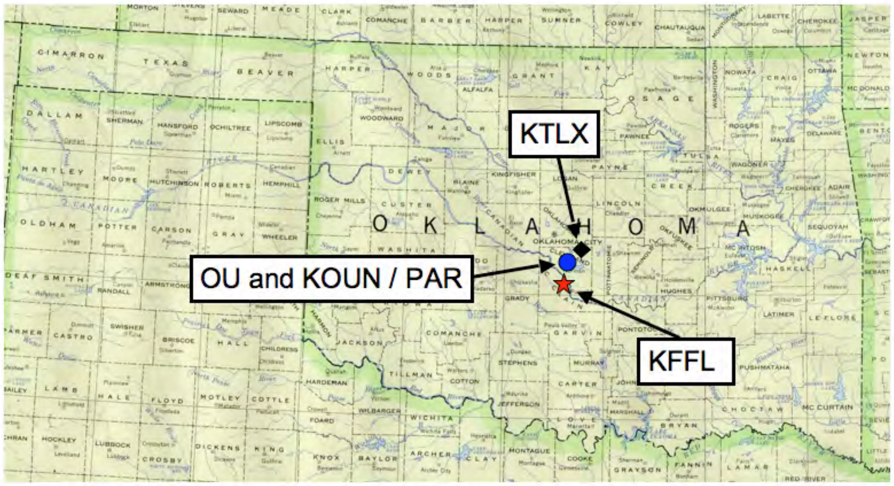

Figure 1: Map of Oklahoma showing the locations of the WSR-88D (KTLX), the University of Oklahoma (OU), the polarimetric WSR-88D (KOUN), the Phased Array Radar (PAR), and the Kessler Farm Field Laboratory (KFFL).

Farm Field Laboratory (KFFL) located in central Oklahoma. Measurements from this site build upon other precipitation studies being conducted within the Norman meteorological community.

The Kessler Farm Field Laboratory is a 350-acre (140 ha) property, which is maintained and operated through OU. This faciltity, which is characterized as a mixed grass prairie, is used by a wide array of scientists and educators across OU. The principle OU units affiliated with KFFL are Architecture, Botany/Microbiology, Geography, Interdisciplinary Perspectives on the Environment, Meteorology, Oklahoma Climatological Survey, the Sam Noble Oklahoma Museum of Natural History (SNOMNH) and Zoology. As can be seen by the eclectic list of affiliate institutions and academic units, the KFFL user community embodies the spirt of interdisciplinary research. There are many exciting research and educational projects being conducted at KFFL, but here we focus on those pertaining to the atmospheric sciences.

2. KESSLER FARM FIELD LABORATORY

KFFL provides an ideal location for validation measurements of the weather radars KOUN and PAR. It is located approximately 30 km from these two radars, which is close enough to assure good resolution but far enough to be outside of the region of ground clutter. For example, for a 1° radar beamwidth and an elevation angle of 0.5°, the resulting angular resolution and height above ground level at 30 km are 500 m and 250 m, respectively. The relative locations of OU, KTLX (WSR-88D located near Oklahoma City), KOUN, PAR, and KFFL are shown in Figure 1. Furthermore, KFFL offers adequate infrastructure to support the validation instruments fielded there. This includes water, electricity, internet, and a secure and controlled environment. Finally, KFFL is already host to several other atmospheric measurement programs. That is, there are several readily available atmospheric measurements that can be used for targeted precipitation studies. Those relevant for this discussion are the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program, the Oklahoma Mesonet, and the NOAA Profiler Network (NPN). Each of these programs has instrumentation located directly on the KFFL property and the data are publicly available through the internet.

The DOE ARM Program operates the Southern Great Plains (SGP) site, which has field stations distributed across Oklahoma and Kansas (Stokes and Schwartz, 1994; Ackerman and Stokes, 2003). In particular, one of the SGP boundary facilities (BF-6) is located directly on the KFFL property. The ARM SGP is dedicated to the study of radiative interactions with the Earth and it's atmosphere and the role that these play on the climate. The BF-6 site (also called the Purcell site) is equipped with an Atmospheric Emitted Radiance Interferometer (AERI), balloon sounding system, microwave radiometer, Temperature, Humidity, Winds, and Pressure Sensors (THWAPS), and a Vaisala Ceilometer. The data are available from `http://www.arm.gov/sites/sgp.stm`. In addition to providing ancillary data when needed, the ARM SGP program is also a key player in hosting and providing support for several of the instruments to be described (see below).

KFFL is also host to one of the stations in the Oklahoma Mesonet. The Mesonet is a network of environmental monitoring stations operated by OU and Oklahoma State University (OSU) (Brock et al., 1995). There are over 110 stations. At each site, the environment is measured by a set of instruments located on or near a 10-meter-tall tower. Measured quantities include wind magnitude and direction, air temperature and humidity, pressure, soil temperature, soil moisture, incoming solar radiation, and the amount of precipitation. These data are available in real-time every 5 minutes (`http://www.mesonet.ou.edu/`). The Mesonet station located on KFFL is known as the Washington site.

One of the radars in the NOAA Profiler Network has been placed at KFFL. The NPN is dedicated to providing height profiles of the three-dimensional wind vector and the virtual temperature at several sites within the central U.S. (Benjamin et al., 2004). The profiler located at KFFL (Purcell site) operates at a frequency of 404 MHz and provides wind data in the height range from 0.5 to 16.25 km above ground level. Data from the radar are readily available in real time from one of the NOAA web sites with temporal resolutions of six minutes and one hour (`http://www.profiler.noaa.gov/`). The profiles of virtual temperature are provided by those sites equipped with Radio Acoustic Sounding System (RASS) functionality. Regrettably, the NPN UHF radars are not capable of providing Doppler spectra. As we discuss below, Doppler spectra from profiling radars provide a means of investigating the structure and evolution of precipitation as a function of time and height. Therefore, this radar is primarily used for wind comparisons.

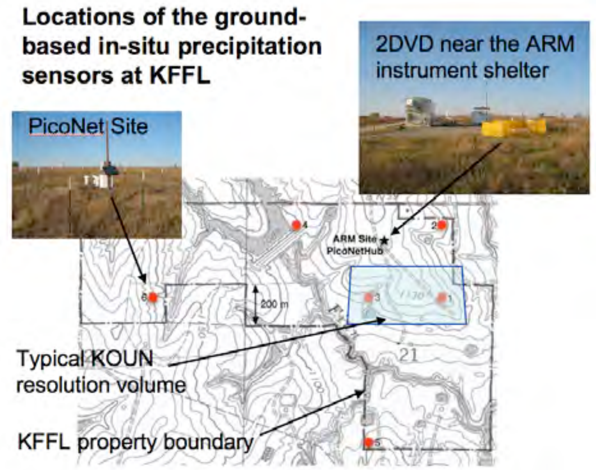

Figure 2: Relative locations of several of the ground-based in-situ sensors at KFFL dedicated for the monitoring of precipitation. The red dots indicate the positions of the six nodes in the PicoNet.

Since one of the most important parameters associated with the retrieval of precipitation properties is the distribution of drop or particles sizes, a two-dimensional video disdrometer (2DVD) has recently purchased and placed at KFFL. The 2DVD is capable of measuring the size, fall speed, shape, and orientation of individual hydrometeors, which pass through a 10x10 cm^2 sampling area (Kruger and Krajewski, 2002). Such measurements are particularly valuable for comparison with polarimetric weather radar data, which are capable of directly estimating the oblateness of raindrops based on differential reflectivity observations. The sampling area of the 2DVD is transected by two perpendicular light sheets, which are slightly offset in height. The shadows of any hydrometeors passing through the light sheets are detected using line-scan cameras. In essence, images of each particle are recorded and the fallspeed is deduced by the length of time required for the falling particle to cover the distance separating the two light sheets. Particle sizes are sorted into 41 bins with a spacing of 0.2 mm within the range of 0.1 to 8.1 mm. Data are provided at one minute intervals. Infrastructure support for the deployment of the 2DVD is partially provided by the ARM program and the instrument itself is located near the ARM building at KFFL.

Complementary to the 2DVD, a network of tipping-bucket rain gauges has also been recently installed at KFFL. This network is formed in a six-node array and is collectively known as the KFFL PicoNet. Each node consists of three collocated rain gauges, a data logger, and a radio link used to form a wireless network. It was decided to place three gauges at each node in order to improve data quality. On one hand, averaging the collocated rainfall measurements reduces local random errors that are high in tipping-bucket gauges at short timescales (Ciach, 2003). On the other hand, comparing the differences between the three gauges with these natural local random errors allows quick and effective detection of possible instrumental failures (Ciach and Krajewski, 2006). In addition, the triple-gauge setups provide enough redundancy to assure the continuity of accurate rainfall measurements at each node of the KFFL PicoNet. The time of tip from each gauge is measured with an accuracy of one second and data are recorded every minute. All of the data loggers are automatically synchronized to the internet time through the wireless network. Results from the data loggers are transmitted to a central receiving station, which is housed at the ARM site. From here, the data are communicated via the internet back to OU for processing. The placement of the PicoNet nodes has been chosen in order to form a non-redundant array (Golay, 1971). The minimum spacing between the nodes is only 350 m, which allows for the study of spatial variability of rainfall over small scales. Locations of the PicoNet nodes together with other ground-based in-situ instrumentation for the study of precipitation are shown in Figure 2. Note the spacing of the PicoNet nodes with respect to sampling volume of KOUN when overlooking KFFL.

In addition to the ground-based in-situ measurements being conducted at KFFL, a UHF wind profiling radar has also been installed at the facility. It is a 915-MHz boundary layer radar (BLR), which is maintained and operated through OU's Atmospheric Radar Research Center (ARRC). The beamwidth of the BLR is 9° and the beam can be directed vertically or electronically steered along 4 oblique directions having zenith angles of 22° (Carter et al., 1995). The minimum range resolution for the radar is 60 m, but a more typical mode of operation uses a range resolution of 100 to 200 m. A picture of the profiler is provided in Figure 3. As is true for the 2DVD and the KFFL PicoNet, operations of the 915-MHz wind profiler are partially supported by the ARM program.

One of the driving motivations for locating the BLR at KFFL is to investigate the time and height evolution of precipitation and compare these measurements with those from KOUN, KTLX, and PAR. This is achieved by examining the measured Doppler spectra while the radar is operated in a vertically pointing mode. If the radar signal received by the BLR is primarily from the backscatter from hydrometeors and if these hydrometeors are falling through stagnant air, then the calculated Doppler spectrum for a given range gate will reflect the fallspeeds of the particles within the sampling volume. Furthermore, if an analytic relationship between the terminal fallspeed of the particles as a function of effective diameter is assumed, then the underlying DSD can be retrieved from the Doppler spectra (Doviak and Zrnić, 1993). That is, the Doppler spectra are mapped from velocity space into diameter space while taking the backscattering contributions from the different particle sizes into account. For observations made at 915 MHz (wavelength of 33 cm) it is safe to assume the Rayleigh approximation for raindrops.

Used collectively, the suite of instrumentation available for conducting precipitation measurements over KFFL provide a powerful research platform. For a given precipitation event, mesoscale surface observations are available from the Oklahoma Mesonet. The three-dimensional structure of the precipitation can be monitored using KTLX. When available, data from KOUN and PAR can also be used. By having access to multiple weather radars, it is possible, for example, to perform dedicated range height indicator (RHI) scans with KOUN or PAR while still monitoring the overall features of the precipitating system with KTLX. Since wind data are available from the NPN radar, the BLR can be configured in such a way as to optimally monitor the precipitation aloft: emphasis on vertical beam measurements, dwell times on the order of 30 seconds, good Doppler velocity resolution, and so forth. The estimated DSD from the lowest sampling height of the BLR (typically 200 m above the ground) can be compared with the DSDs recorded at the surface using the 2DVD. Furthermore, if spatial variability is observed in the rainfall rate data from the PicoNet, these variations may be detected in the gate-to-gate differences as seen by the weather radars. The resulting data sets are being used in the development of QPE algorithms.

Figure 3: Picture of the UHF boundary layer radar with the ARM site shown in the background.

3. PRECIPITATION MEASUREMENTS

In this section we provide a brief example of observations conducted at KFFL in conjunction with one particular storm event as it moved across central Oklahoma. Since the main focus of this paper is to outline the facilities available for investigating precipitation over KFFL, we will not discuss these data in detail. Furthermore, emphasis will be placed on measurements made with the 915-MHz profiling radar. For an example of recent findings involving the 2DVD the reader should refer to Cao et al. (2007).

On June 17, 2006 a mesoscale convective system (MCS) developed and passed directly over KFFL. The MCS produced 23.1 mm of rain at KFFL over a 2.7 hour

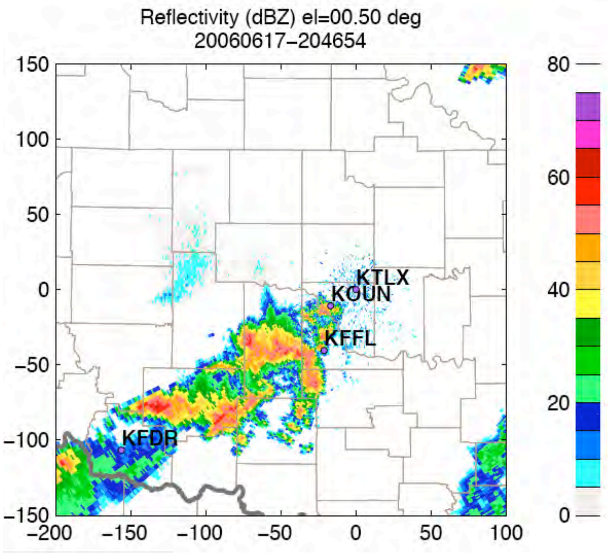

Figure 4: PPI plot of the radar reflectivity corresponding to to a 0.5° elevation scan using KTLX. Data are for the June 17, 2006 MCS event. The axes on the plot indicate the distance in kilometers from KTLX.

period, with the majority of rain occurring during the first 15 minutes. A plot showing the radar reflectivity of the MCS as observed with KTLX is shown in Figure 4. These data were collected at 20:47 Z (15:47 CST), just as the storm was reaching KFFL. On this day, the BLR was operating in a vertical beam only mode with a height resolution was 100 m. Spectral and moment data were processed and recorded every 20 seconds. Therefore, the BLR observations provide good spatial and temporal resolution.

Signal-to-noise ratio (SNR) and Doppler velocity data from the BLR for June 17 are presented in a range time intensity format in Figure 5. The leading convective edge of the MCS began moving over the profiler at around 15:30 CST. This can be noted in Figure 5 by the presence of large SNR values above 4000 m AGL, as liquid water is carried upwards by the strong updrafts. The presence of large upward velocities are also apparent in the Doppler velocity data shown in the lower panel. Around 16:00 CST, aliasing in the velocity data is clearly visible. The convective portion of the MCS is followed by a short transition phase at approximately 16:15 CST and then stratiform precipitation for the remainder of the event. A bright band can easily be seen between 3000 and 4000 m AGL. Furthermore, the change in phase of the precipitation particles from ice to liquid is noted by the transition in the Doppler velocity data from values near 1-2 m s^{-1} to those near 8-10 m s^{-1}. We are using the convention that positive velocities indicate motion towards the radar for this presentation. All of the noted features in Figure 5 can be expected during MCS events.

A sample plot of normalized stacked Doppler spectra during the stratiform portion of the MCS are shown in Figure 6 along with their corresponding SNR values. As was mentioned earlier, under the right conditions, Doppler spectra from a vertically pointing UHF radar can be used to study precipitation microphysics in time and height. Here it becomes apparent that a great deal of structure is present in the Doppler spectra. The transition across the melting layer (characterized by the bright band) is again easily seen. Even below the bright band and after the precipitation has completely changed to raindrops, there is still notable variability in the Doppler velocity values. It is not known, however, if the shifts in the bulk fallspeeds are due to fluctuations in the vertical velocity of the ambient air or on account of physical mechanisms affecting the DSD. To address this question, additional data are needed. One can either directly measure the air velocity (for example using a VHF wind profiler) or obtain independent height profiles of the DSD. The later approach is being investigated using data from KOUN and the 915-MHz wind profiler Teshiba et al. (2007).

4. CONCLUSION

Here we have provided a brief overview of the facilities available at KFFL, which are primarily being used by OU and NSSL in a collaborative program designed to monitor and study precipitation events in central Oklahoma. Some of the instrumentation at KFFL has only recently been installed: a UHF BLR, a 2DVD, and a network of tipping-bucket rain gauges (PicoNet). Other instruments, which were already located at KFFL, provide additional measurements that can and will be used in support of this effort. These are maintained and operated by the Oklahoma Mesonet, the DOE ARM program, and the NOAA profiler network. The collection of instruments now in place at KFFL provide many opportunities for both ground-based in-situ and remote sensing observations of precipitation. These data are being used in conjunction with complementary observations from the weather radars KTLX, KOUN, and PAR.

This ensemble of instruments comprise a unique testbed for precipitation studies and remote sensing algorithm development. The resulting measurements are being used to classify precipitation types (rain, snow, sleet, graupel, hail, etc.) detected above KFFL, to characterize the dynamic state of the atmosphere through

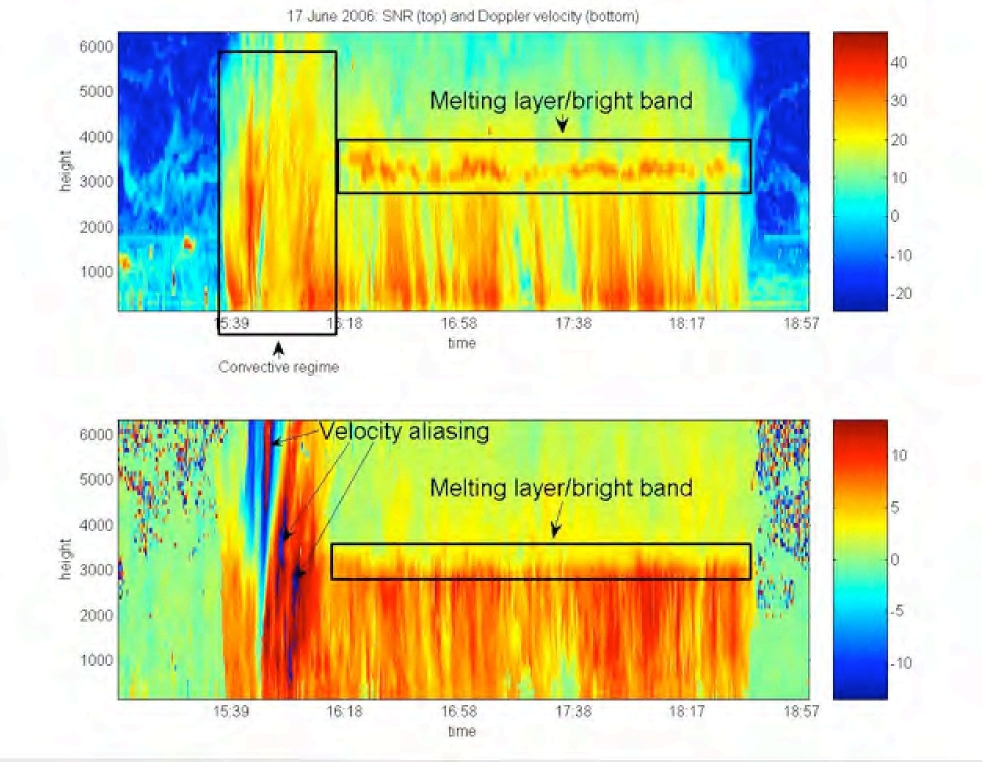

Figure 5: Range time intensity plots of the SNR (upper panel) and the Doppler velocity (lower panel) corresponding to data for an MCS collected with the 915-MHz wind profiler. The SNR are plotted on a logarithmic scale. The values of the Doppler velocities are given in m s^{-1}.

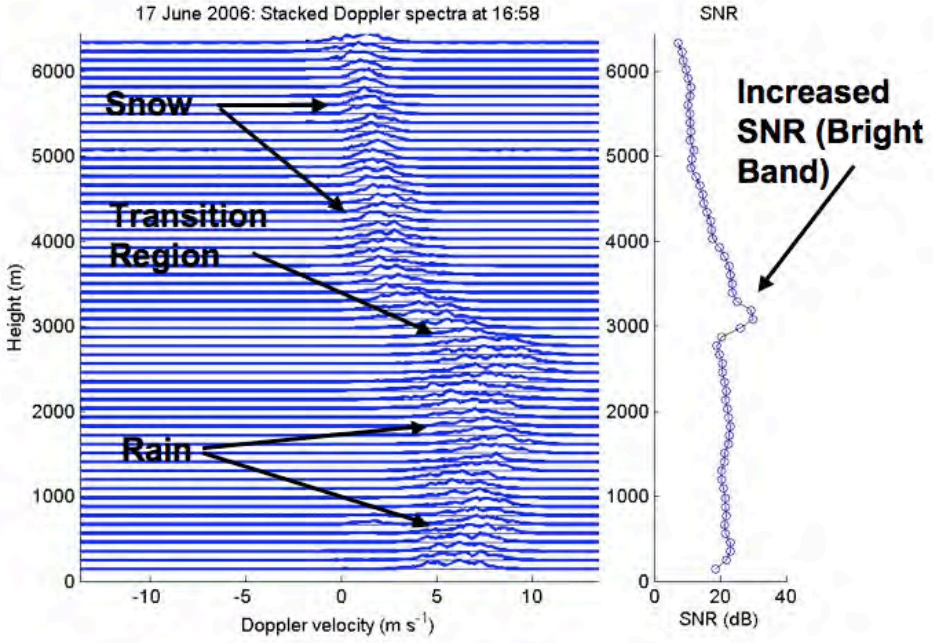

Figure 6: Normalized stacked spectra for observations made with the 915-MHz wind profiler while operated in a vertical-beam mode. Also shown is a profile of the corresponding SNR.

which the precipitation is falling, and to study the development and evolution of the precipitation particles with height. Once the precipitation reaches the surface, characteristics (size distribution, particle shape, fall speed) and spatial distribution of the precipitation are retrieved. Some of the currently active programs of investigation include studies of the development of rainfall retrieval algorithms based on polarimetry, storm initiation processes, and precipitation microphysics in and around the melting level.

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