Doppler Radar Profilers as Calibration Tools for Scanning Radars

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ABSTRACT

The National Oceanic and Atmospheric Administration's Aeronomy Laboratory has modified a standard 915-MHz profiler for use as a precipitation profiler in support of Tropical Rainfall Measuring Mission ground validation field campaigns. This profiler was modified to look vertically with a fixed dish antenna. It was operated during the Texas and Florida Underflights Experiment (TEFLUN) A in south Texas in April–May 1998 and during TEFLUN B in central Florida in August–September 1998. Collocated with the profiler was a Distromet, Inc., RD-69 Joss–Waldvogel disdrometer in Texas and Florida and a two-dimensional video disdrometer in Florida. The disdrometers are used to calibrate the profiler at the lowest range gates. At higher altitudes, the *calibrated* profiler reflectivities are compared with observations made by scanning radars such as the Weather Surveillance Radar-1988 Doppler in Dickinson, Texas, and Melbourne, Florida, and the S-band Doppler dual-polarization radar in Florida. The authors conclude that it is possible to use profilers as transfer standards to calibrate and to validate the reflectivities measured by the scanning radars.

1. Introduction

Precipitation is one of the most difficult parameters to simulate in numerical general circulation models. The Tropical Rainfall Measuring Mission (TRMM) is a joint National Aeronautics and Space Administration (NASA)–National Space Development Agency of Japan program aimed at improved measurement of precipitation from space to achieve a more precise estimate of the diabatic heating associated with tropical precipitating cloud systems. Although there are several missions on the TRMM satellite (Kummerow et al. 1998), we are primarily concerned in this paper with the validation of the TRMM precipitation radar (PR). The NASA TRMM ground validation program (Thiele 1992) is composed of ongoing precipitation measurements using scanning radars at primary sites in central Florida and south Texas; Kwajalein, Atoll, Republic of the Marshall-Islands; and Darwin, Australia, as well as sites in Brazil, Hawaii, Guam, Thailand, Taiwan, and Israel. In addition, intensive observations have been made in the Texas and Florida Underflights Experiment (TEFLUN) campaigns: TEFLUN A in south Texas during April–May 1998 and TEFLUN B in central Florida during August–September 1998; the TRMM Large-Scale Biosphere–Atmosphere Experiment in Brazil during January–February 1999; and the Kwajalein Experiment at Kwajalein, during August–September 1999. This paper presents observations obtained using a vertically directed 915-MHz Doppler

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radar profiler during TEFLUN A and B. In the following text we often refer to the 915-MHz (33-cm wavelength) profiler as an ultrahigh-frequency (UHF) profiler. The longer-wavelength very high frequency (VHF) profilers referred to below generally operate near 50 MHz (6-m wavelength).

Measuring precipitation with a vertically pointing scanning Doppler radar was reported by Atlas et al. (1973). The technique has not been routinely performed, because of the need to dedicate scanning Doppler radars to the observation of mesoscale systems over a large area. However, the operating modes of Doppler wind profilers are well suited to the routine observation of hydrometeors in the vertical profiler beam. Beginning in the 1980s, VHF profilers, which are more sensitive to ‘‘clear air’’ than UHF profilers are, have been used to retrieve vertical air motion patterns, partition precipitation, and infer diabatic heating rates in tropical convective systems (Wakasugi et al. 1986; Cifelli and Rutledge 1994, 1998; May and Rajopadhyaya 1996). More recently, UHF and VHF profilers have been used in combination to separate vertical air motions from hydrometeor fall velocities and to retrieve precipitation parameters (Currier et a1. 1992; Rajopadhyaya et a1. 1998; Cifelli et al. 2000). Recently, substantial progress has been made in the separation of returns from hydrometeors (Rayleigh scatter) and air motions (Bragg scatter) from UHF profiler observations as presented in Williams et al. (2000a). The dual-wavelength measurements employed by the Aeronomy Laboratory first in the Maritime Continent Thunderstorm Experiment and then in TRMM field campaigns enables the unambiguous separation of Rayleigh scatter and Bragg scatter in profiler observations (Gage et al. 1999b).

Because it is well known that rain fields tend to be inhomogeneous, especially in convective conditions, a dense network of rain gauges is usually employed for field campaigns that require a careful comparison of areal rain measurements with those provided by scanning radars, for example. Disdrometers, which measure the size distribution of drops, have come into widespread use in recent years (e.g., Sauvageot and Lacaux 1995; Tokay and Short 1996). When the drop size distribution is known, precipitation parameters such as equivalent reflectivity, hydrometeor fall velocities, rain rate, and so on can be calculated (Houze 1993). Although the disdrometers are of some use for direct calibration of scanning radars, they are somewhat limited in their usefulness because they necessarily provide information in a very small volume just above the surface. What is needed is a method to extend the disdrometer to larger spatial scales and to higher altitudes. A vertically directed profiler is capable of accomplishing this task, as described in this paper. Here we will consider the calibration of the profiler by a collocated disdrometer and the use of the profiler to provide independent calibration/validation for scanning radars. The use of the same profiler to provide drop size distributions will be discussed elsewhere (Williams et al. 2000b).

The conventional means for obtaining rain estimates from scanning radars is to employ a radar reflectivity–rainfall rate (*Z*–*R*) relationship (e.g., Houze 1993). However, recent studies (Atlas et al. 1999) have shown that *Z*–*R* relationships are highly variable in mesoscale convective storms and that the relationship may depend on the evolution of the storm. In this paper we avoid the direct comparison of the derived rain rates but compare instead the radar reflectivities of profilers with scanning radars and collocated disdrometers. In this way the profiler can act as a transfer standard between the disdrometer on the surface and the radars aloft.

The objective of this paper is to demonstrate the potential for Doppler radar profilers to serve as transfer standards to provide a means for calibration of scanning radars. This potential will be shown using observations taken in the TEFLUN-A campaign in south Texas and the TEFLUN-B campaign in central Florida. The profiler itself can be calibrated at low altitudes using a collocated disdrometer because the reflectivities are uniquely determined by the drop size distributions. However, disdrometers do not yield a perfect measure of drop size distributions, and their measurements must be used with some caution. Even disdrometers that do not measure the smallest drops accurately may still be useful for calibration purposes owing to the D^6 dependence (where D is drop diameter) of backscatter from hydrometeors in Rayleigh scatter. This paper is organized as follows. The 915-MHz profiler is described in section 2. Sample profiler observations from TEFLUN A and TEFLUN B are presented in section 3. Observed profiler reflectivities are compared with reflectivities calculated from disdrometer measurements in section 4 and with reflectivities observed by scanning radars in section 5. Section 6 contains a discussion of some issues that arise when using profilers as calibration tools. Concluding remarks are made in section 7.

2. Instrumentation

The National Oceanic and Atmospheric Administration’s (NOAA) Aeronomy Laboratory (AL) developed UHF wind profiler technology for tropical dynamics and climate research (Carter et al. 1995). The UHF profilers originally developed by AL for the measurement of lower-tropospheric winds in the Tropics have now been applied to precipitation research (Rogers et al. 1993a,b; Gage et al. 1994, 1996; Ecklund et al. 1995; Williams et al. 1995). The UHF profilers are sensitive to hydrometeors and provide a highly resolved time–height cross section of precipitating cloud systems. The observations yield the Doppler spectra of moving targets within the radar-observing volume. The Doppler spectra are processed to yield vertically resolved time histories of equivalent reflectivity, Doppler velocity, and spectral width over the profilers. During the past three years the

TABLE 1. Profiler parameters used in TEFLUN A.

Frequency	915 MHz
Wavelength	32.8 cm
Peak power	500 W
Antenna	3-m shrouded dish
Beamwidth	5°
Height resolution	105 m
Max height sampled	18.0 km
Max radial velocity	±20 m s^{-1}
Spectral points	256
Dwell time	30 s
Recording	Full spectra

TABLE 2. Profiler parameters used in TEFLUN B.

Frequency	915 MHz
Wavelength	32.8 cm
Peak power	500 W
Antenna	3-m shrouded dish
Beamwidth	5°
Height resolution	138 and 330 m
Max height sampled	18.0 km
Max radial velocity	± 20 m s^{-1}
Spectral points	256
Dwell time	30 s
Recording	Full spectra

NOAA AL developed and deployed a pair of vertically directed precipitation profilers that operate at 915 and 2835 MHz (S band) for the TRMM field campaigns (Gage et al. 1999a).

For TRMM ground validation field campaigns, the two profilers have been collocated with disdrometers and rain gauges to provide calibration for scanning radars that, in turn, are used to calibrate the TRMM PR measurements. For these field campaigns, a Distromet, Inc., RD-69 disdrometer also known as a Joss–Waldvogel disdrometer (JWD) was utilized to provide a calibration for the profiler reflectivity. For the TEFLUN campaigns, we integrated the data stream from the JWD into the AL profiler data stream to guarantee that the timing of the profiler and disdrometer measurements were coincident.

The 915-MHz profiler used here is similar to the 915-MHz profilers described in Carter et al. 1995. Tables 1 and 2 contain the operating parameters for the 915-MHz profiler used in TRMM field campaigns. The profilers are shown in Fig. 1 as they were deployed in TEFLUN B. In TEFLUN B, a two-dimensional video disdrometer (2DVD) was operated by The University of Iowa in close proximity to the profilers and the JWD. Both disdrometers can be seen in the foreground of Fig. 1. The rectangular box contains the 2DVD, and the JWD is mounted on the tripod closer to the container in the background. The ‘‘doghouse’’ next to the 2DVD contains an air-conditioned computer that controls the 2DVD. The shrouds for the two profiler antennas can be seen to the right of the container. The larger shroud surrounds the 915-MHz profiler antenna, and the smaller shroud surrounds the 2835-MHz antenna. Just to the right of the antenna shrouds is the portable generator used to power the instruments.

In Texas, the profilers were in south Houston at the Sims South Water Treatment Plant operated by the City of Houston Public Works Department. This site is 33 km WNW of the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar in Dickinson, Texas, as is shown on the map in Fig. 2a. In Teflun B, the profilers were located as shown in Fig. 2b east of Holipaw, Florida, on the south side of U.S. Route 192 at the Triple N Ranch managed by the Florida Game and Fresh Water Fish Commission (now the Florida Fish and Wildlife Conservation Commission). This site is 35 km west of the Melbourne WSR-88D and 38 km northwest of the National Center for Atmospheric Research (NCAR) S-band Doppler dual-polarization (S-pol) radar.

In both of the TEFLUN field campaigns, the profilers were surrounded by rain gauges and disdrometers to provide an opportunity for intercomparisons and cross-checks between the various instruments. Because a two-dimensional video disdrometer was used in TEFLUN B but not in TEFLUN A, it was only possible to check the performance of the JWD against the 2DVD in Florida. Intercomparisons between the two types of disdrometers in Florida reveal an offset or bias between reflectivities calculated from the two instruments. Although the JWD has some problems measuring small drops in heavy rain (Williams et al. 2000b), it is a very reliable instrument capable of providing reasonably good inferred reflectivities for calibration purposes.

3. Sample profiler observations

TEFLUN A took place in south Texas in April and May 1998. Just prior to the beginning of TEFLUN A, Texas had experienced a wet and mild winter, as would be expected during the winter months of an El Niño year. During March, a remarkable transition occurred over the Gulf states, including Texas and Florida. The abnormally wet winter was replaced by a very dry spring and summer. In Houston there is normally about 215 mm of rain during April and May, but in 1998 there was a total of only 32 mm in April and May. Most of this rain fell on 18 April.

A time–height cross section of reflectivity, Doppler velocity, and spectral width as seen by the 915-MHz profiler on 18 April is shown in Fig. 3. Note that the blue background at the lowest heights in Fig. 3 is primarily caused by Bragg scattering from refractivity turbulence. A SW–NE band of stratiform and convective rain associated with a cold front developed north of Houston early on 18 April and passed over the profilers during the afternoon of 18 April. Precipitating clouds are evident beginning about 0100 UTC and continued off and on until just after 2000 UTC. As seen by the profilers, most of the precipitating cloud structure was probably stratiform in nature, although embedded con-

FIG. 1. Picture of the AL profilers in central Florida during TEFLUN B.

vection was present at times. Note the bright band in the reflectivity plot (top) just above 3.0 km. This bright band is especially well developed during the rainiest period between 1500 and 1800 UTC. The presence of the melting layer near 3 km is confirmed by the rapid increase in hydrometeor fall velocities seen in the Doppler velocity plot (middle). The spectral width plot (bottom) shows relatively large values of spectral width above the melting level during much of the day consistent with the presence of vertical air motions, turbulence, and spectral broadening from strong horizontal winds. This picture is in marked contrast to the small values of spectral width often observed in tropical convection in mature stratiform rain (Williams et al. 1995; Gage et al. 1996; Tokay et al. 1999).

During the early summer of 1998, drought conditions prevailed over much of central Florida. However, seasonal rains began to fall in July, and many good rain events were experienced during the TEFLUN-B campaign. A sample rain event observed by the 915-MHz profiler on 17 September is shown in Fig. 4. During this period, synoptic conditions over central Florida favored southerly flow with high pressure over the Atlantic to the east and low pressure to the west over the Gulf of Mexico. The Geostationary Operational Environmental Satellite (*GOES-8*) imagery (not shown) shows bands of convective showers extending across Florida. Profiler observations from 1800 UTC 17 September to 0000 UTC 18 September are shown in Fig. 4. The reflectivity plot (top) shows deep convection above the melting level commencing after 1800 UTC in several episodes until about 2100 UTC. Up until 2100 UTC there is a mixture of deep convection and some stratiform rain, evidenced, for example, by the bright band around 2000 UTC. After 2100 UTC, mature stratiform conditions prevailed. Note the dramatic increase in fall velocities of hydrometeors below the melting level (middle plot) and the small spectral widths (bottom) above the melting level in mature stratiform rain after 2100 UTC.

The time–height cross sections of reflectivity, Doppler velocity, and spectral width have become standard profiler products for precipitation research. They are very useful for diagnosing the convective systems and for viewing the vertical structure and evolution of the precipitating clouds (Gage et al. 1994; Williams et al. 1995). As of the time of writing, these products can be

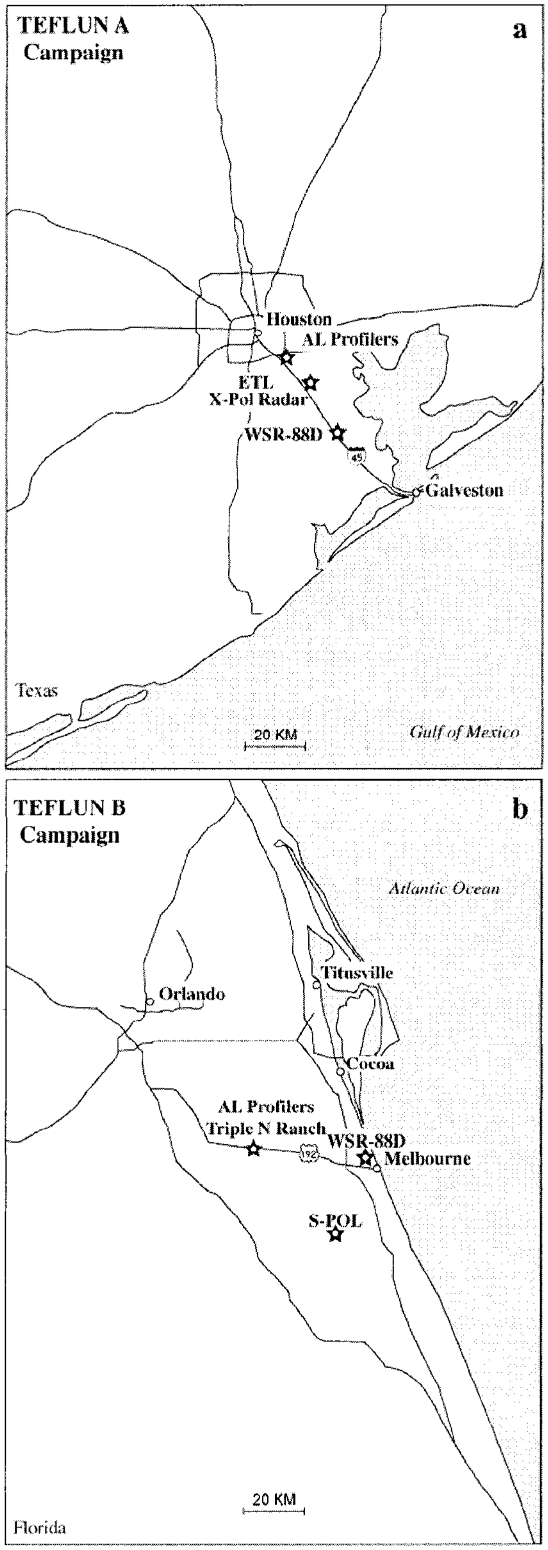

FIG. 2. Maps of instrument locations in (a) Houston and (b) central Florida.

viewed at the AL Web site (www.al.noaa.gov) for several field campaigns, including all of the TRMM field campaigns.

4. Calibration of profiler reflectivities using disdrometers

When the drop size distribution is known, radar reflectivity can be calculated using the equation:

$$Z = \int N(D) D^6 \, dD. \qquad (1)$$

In Eq. (1), $N(D)$ is the drop size distribution. Other precipitation parameters can also be calculated from the drop size distribution but are not considered here. Disdrometers are therefore useful tools for calibration and validation of radar observations, although they only provide information for a very small volume just above the surface. The JWD is an impact disdrometer that produces a voltage when a drop strikes the surface of its 50-cm^2 styrofoam cone. The voltage output is calibrated to provide a measurement of the momentum transfer of drops, which is related to their size. The JWD has a dead time immediately following the impact of a drop, and in heavy rain this dead time can lead to undercounting of raindrops (Williams et al. 2000b). The 2DVD is an optical device that has two orthogonal beams of light in horizontal planes displaced about 6 mm in the vertical. To be counted, a drop must pass through both beams of light. The 2DVD gives an estimate of the size of the drop and its shape as well as its fall velocity.

In their analysis of observations from the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment Tokay et al. (1999) intercompared observations from a 915-MHz profiler at Kapingamarangi Atoll, Federated States of Micronesia, and a collocated JWD to study the classification of tropical precipitation (Williams et al. 1995). At Kapingamarangi the profiler and disdrometer were operated independently; for the TEFLUN field campaigns a special effort was made to integrate the JWD data into the profiler data stream.

The 915-MHz profiler maintains its calibration very well within a few decibels as evidenced by nearly a decade of experience in numerous field campaigns. Nevertheless, absolute calibration of these profilers remains uncertain. For the purposes of TRMM, we calculate reflectivity from the disdrometer drop sizes and use the calculated reflectivity as a reference for the profiler reflectivity. Distromet provides standard software for calculating reflectivities from the number of drops in 20 size bins. The JWD disdrometer, however is capable of binning drop sizes in 127 bins, and this capability was used in Florida with new software that calculates reflectivity from the number of drops in the 127 bins.

Examples of profiler reflectivities in comparison with

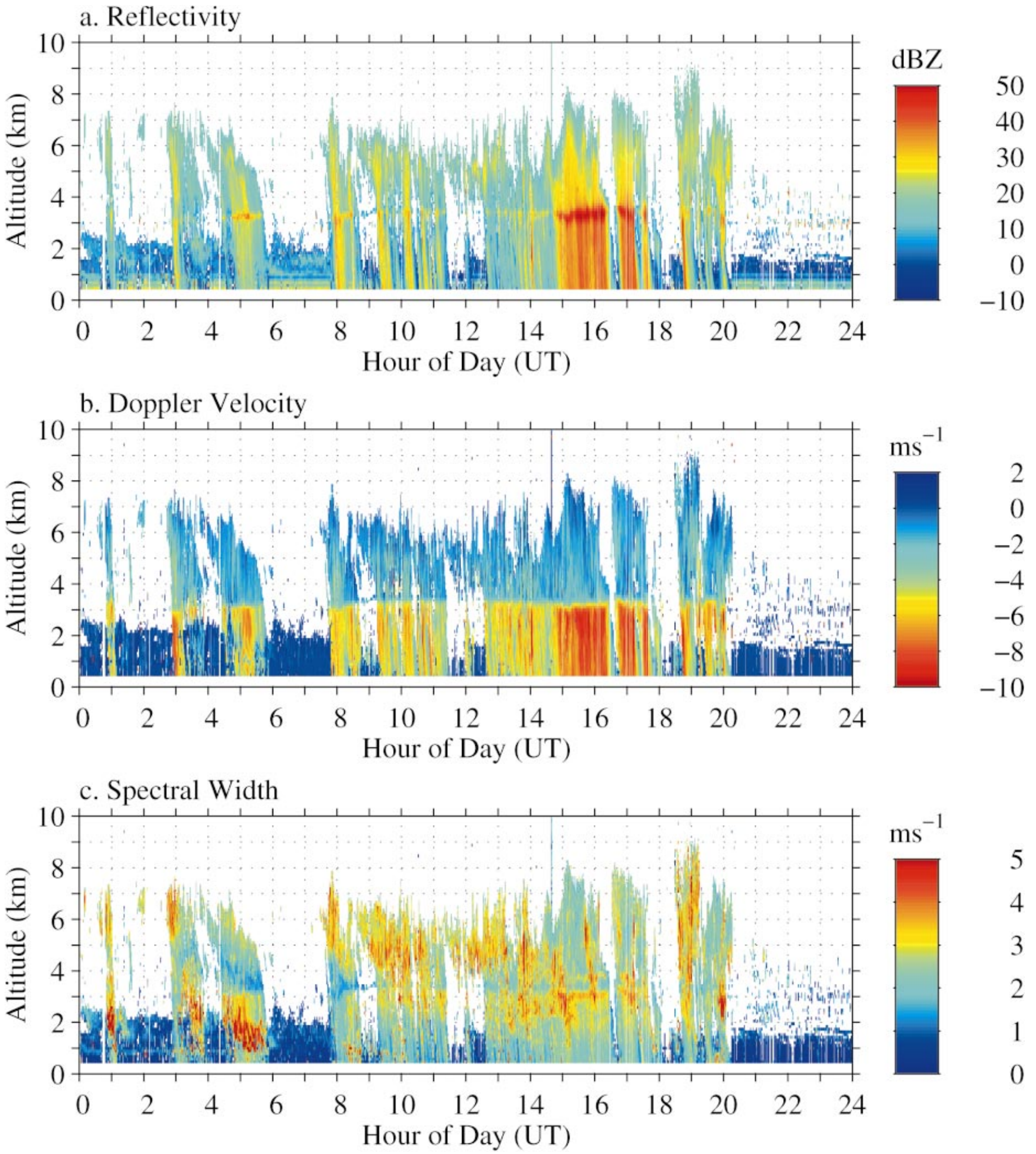

FIG. 3. Profiler observations from Houston, TX, on 18 Apr 1998 during TEFLUN A. (top) A time–height cross section of the equivalent reflectivities recorded by the 915-MHz profiler. (middle) The time–height cross section of Doppler velocity. (bottom) The time–height cross section of spectral width.

disdrometer-inferred reflectivities are shown in Figs. 5–8. The first and only opportunity to utilize the disdrometer to calibrate the profiler observations during TEFLUN A occurred on 18 April in Houston. Figure 5 contains a comparison of time series of *uncalibrated* 915-MHz profiler reflectivities observed at 422 m between 1400 and 1800 UTC on 18 April 1998 with the time series of reflectivities calculated from the JWD. As can be seen in Fig. 3, the bright band associated with stratiform rain is clearly visible just above 3 km for most of this period. Temporal variations in reflectivities observed at 422 m by the 915-MHz profiler show

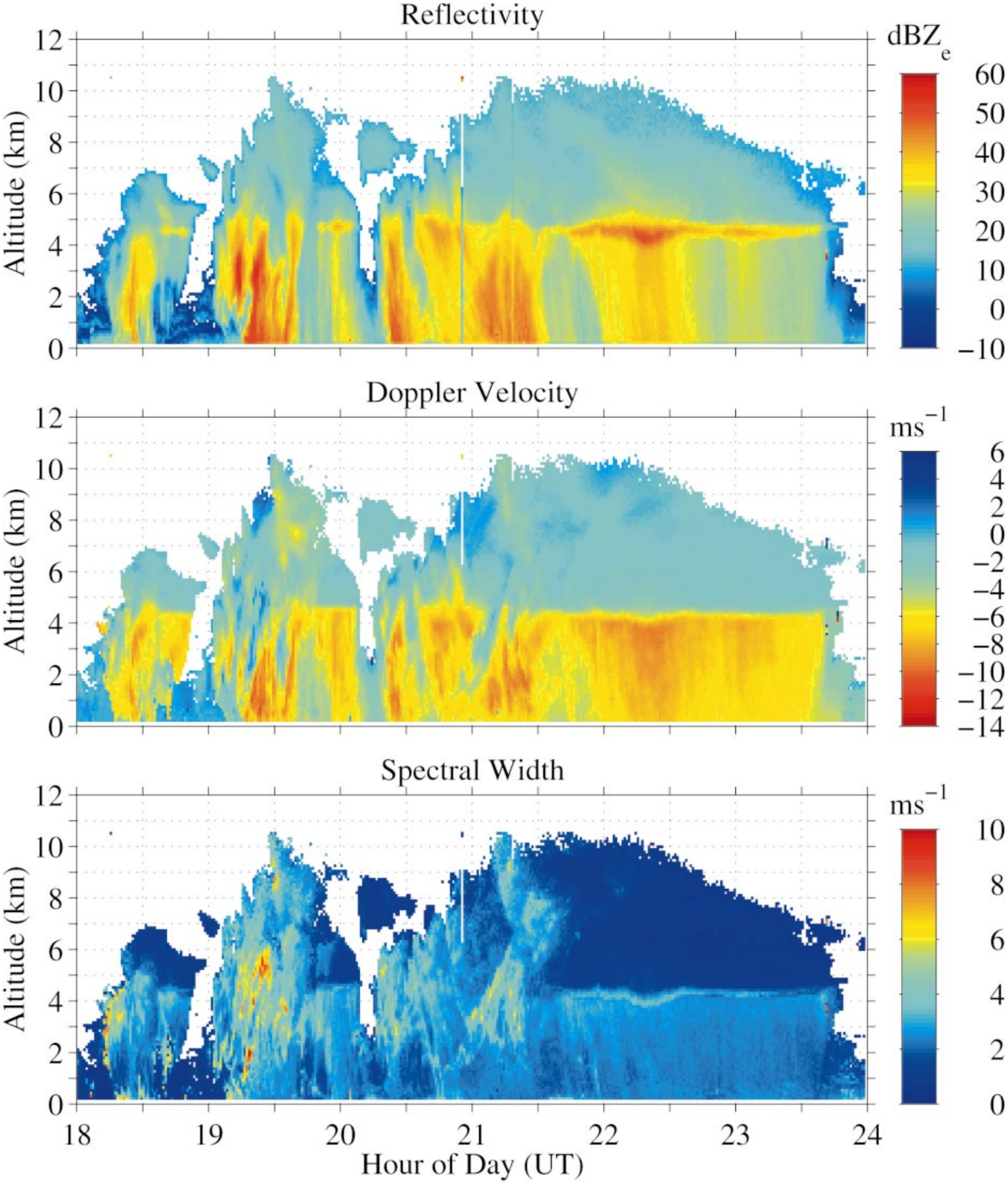

FIG. 4. Profiler observations from Triple N Ranch in central Florida on 17 Sep 1998 during TEFLUN B. (top) A time–height cross section of the equivalent reflectivities recorded by the 915-MHz profiler. (middle) The time–height cross section of Doppler velocity. (bottom) The time–height cross section of spectral width.

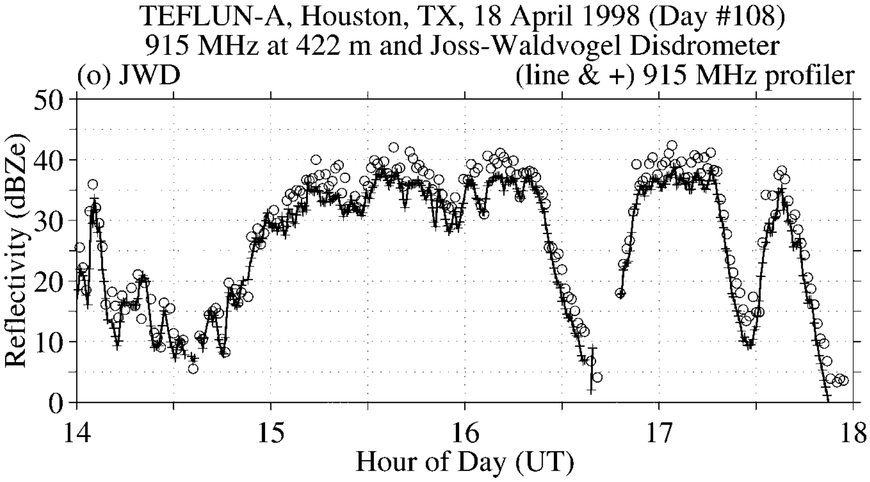

FIG. 5. Comparison of time series of reflectivities between 915-MHz profiler and calculated values from the Joss–Waldvogel disdrometer (JWD) on 18 Apr 1998 during TEFLUN A.

excellent correlation with the temporal variations of reflectivities calculated from the disdrometer. A detailed comparison of the 915-MHz reflectivities and JWD-inferred reflectivities has been carried out quantitatively for this day and is presented next.

A lag correlation was performed, and it was determined that the best correlation occurred with a 1-min lag (1 min was also the time resolution of the time series) of the disdrometer values in comparison with the profiler observations. This lag is consistent with an average fall velocity of 7 m s^{-1} for hydrometeors falling from 422 m to the surface. A fall velocity of 7 m s^{-1} is consistent with the terminal velocity of a drop in the size range of 2–2.5 mm and agrees with observations for stratiform rain reported in Cifelli et al. (2000).

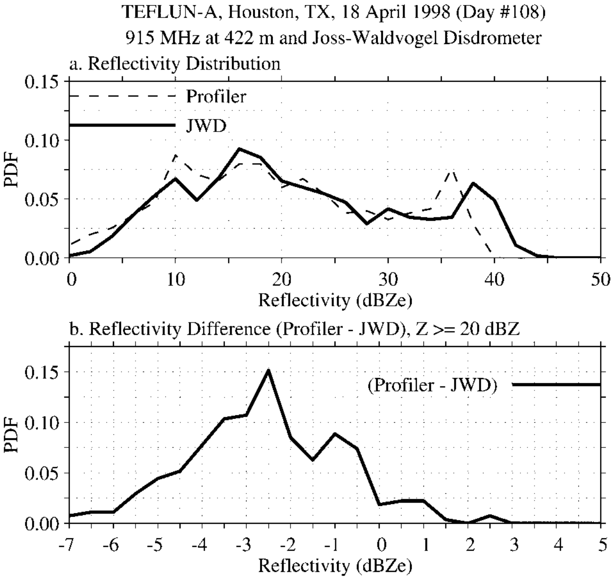

FIG. 6. Histograms of profiler and inferred disdrometer reflectivities for 18 Apr in Houston. (a) Histogram of original equivalent reflectivity observed by the 915-MHz profiler and inferred from the disdrometer for the same period as for the time series in Fig. 5. (b) Histogram of the reflectivity differences in Fig. 6a.

Figure 6a shows a histogram of the reflectivities comparing the uncalibrated 915-MHz profiler measured reflectivities at the third range gate located at 422 m and the JWD inferred values. In Fig. 6b, the histogram of the differences between the 915-MHz profiler-measured reflectivities and the JWD-inferred reflectivities after applying the 1-min lag are plotted. Values of the JWD-inferred reflectivities are very noisy below about 20 dB*Z* and are not included in Fig. 6b. Considering only the values with JWD-inferred reflectivities greater than 20 dB*Z* and less than 40 dB*Z* yields a mean difference of close to 2.5 dB*Z*. This value has been used to adjust the radar constants and to provide the desired calibration of the profiler.

Figure 7 contains observations for 17 September 1998 from Triple N Ranch in central Florida during TEFLUN B. In this case, the observations contain both convective and stratiform precipitation and cover a 6-h period from 1800 UTC 17 September to 0000 UTC on 18 September (cf. Fig. 4). Stratiform precipitation is most evident by the bright band (seen in Fig. 4) above 4 km after 2130 UTC. In this example the uncalibrated 915-MHz reflectivity at 275 m is compared with the calculated reflectivity from both the JWD and the 2DVD. The calculations shown for TEFLUN B were made using the full resolution of the disdrometer with special software developed by AL. The time series of reflectivities observed by the profiler track the reflectivities calculated from the disdrometers very well, although there is an offset between the two disdrometers that is discussed below.

Figure 8a shows a histogram of the reflectivities, comparing the uncalibrated 915-MHz profiler-measured reflectivities at the third range gate located at 327 m and

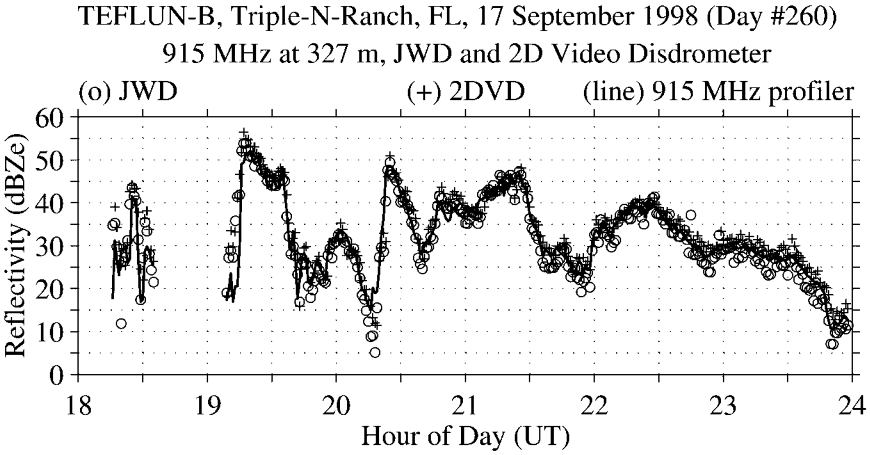

FIG. 7. Comparison of time series of reflectivities between 915-MHz profiler, JWD, and 2DVD on 17 Sep 1998 during TEFLUN B.

the JWD- and 2DVD-calculated values. The plotted values are from five rain events for which both JWD and 2DVD measurements are available. In Fig. 8b, the histogram of the differences between the 915-MHz profiler-measured reflectivities and the JWD-calculated reflectivities are plotted. For the reflectivity difference we have only used reflectivities greater than 20 dBZ. This threshold eliminates the values under very light rain. The distribution of reflectivity differences implies that the profiler reflectivities need to be *decreased* by 0.16 dB to account for the offset with respect to the JWD-calculated reflectivities. The JWD values have been used to adjust the radar constants and to provide the desired calibration of the profiler. Also shown in Fig. 8b is the distribution of differences in calculated reflectivities for the two disdrometers. Note that there is an offset of about 1.8 dB between the calculated reflectivities determined from these two instruments.

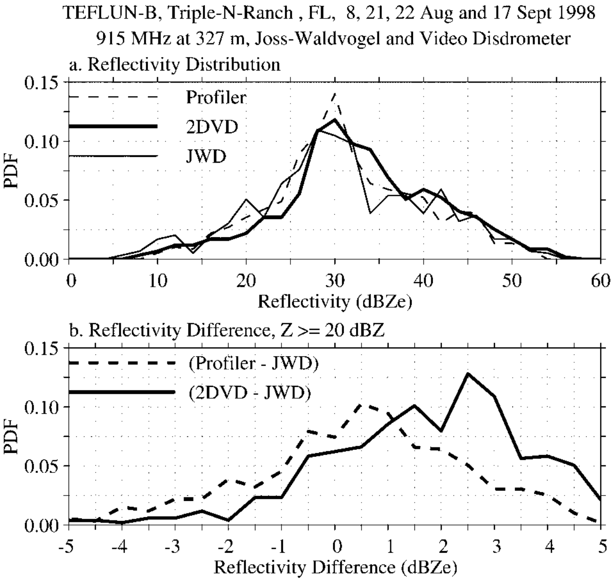

FIG. 8. Histograms of profiler and inferred disdrometer reflectivities for five rain events including 17 Sep 1998 at Triple N Ranch in central Florida during TEFLUN B. (a) Histogram of original equivalent reflectivity observed by the 915-MHz profiler and inferred from the disdrometer for the same period as for the time series in Fig. 7. (b) Histogram of the reflectivity, differences in Fig. 8a restricted the range of 20–40 dBZ.

5. Calibration of scanning radars using Doppler radar profilers

Disdrometers have been used by some researchers as a calibration tool for scanning radars (e.g., Joss et al. 1968; Goddard and Cherry 1984; Short et al. 1997). However, the difficulty of comparing the observations in the very small volume represented by the disdrometer with the much larger radar-observing volume is greatly compounded for a scanning radar as opposed to the profiler. In other words, it is much easier to relate the time series of observations made by a vertically directed profiler at low altitudes to the time series of disdrometer-inferred reflectivities than it is to relate a times series of scanning radar reflectivities to a time series of disdrometer-inferred reflectivities. This fact is because the scanning radar does not typically dwell over a given location as well as because of the fact that the pulse volume of the scanning radar is typically many times larger than the corresponding profiler pulse volume (Cifelli et al. 1996).

Intercomparison of scanning radar reflectivities with profiler reflectivities raises its own problems because of the fact that the pulse volumes are not perfectly matched, but the procedure is not as difficult as relating disdrometer-inferred reflectivities with scanning radar reflectivities. In this section, we make intercomparisons of 915-MHz profiler reflectivity measurements with scanning radar reflectivity measurements to demonstrate the feasibility of using the profiler observations to calibrate the scanning radar.

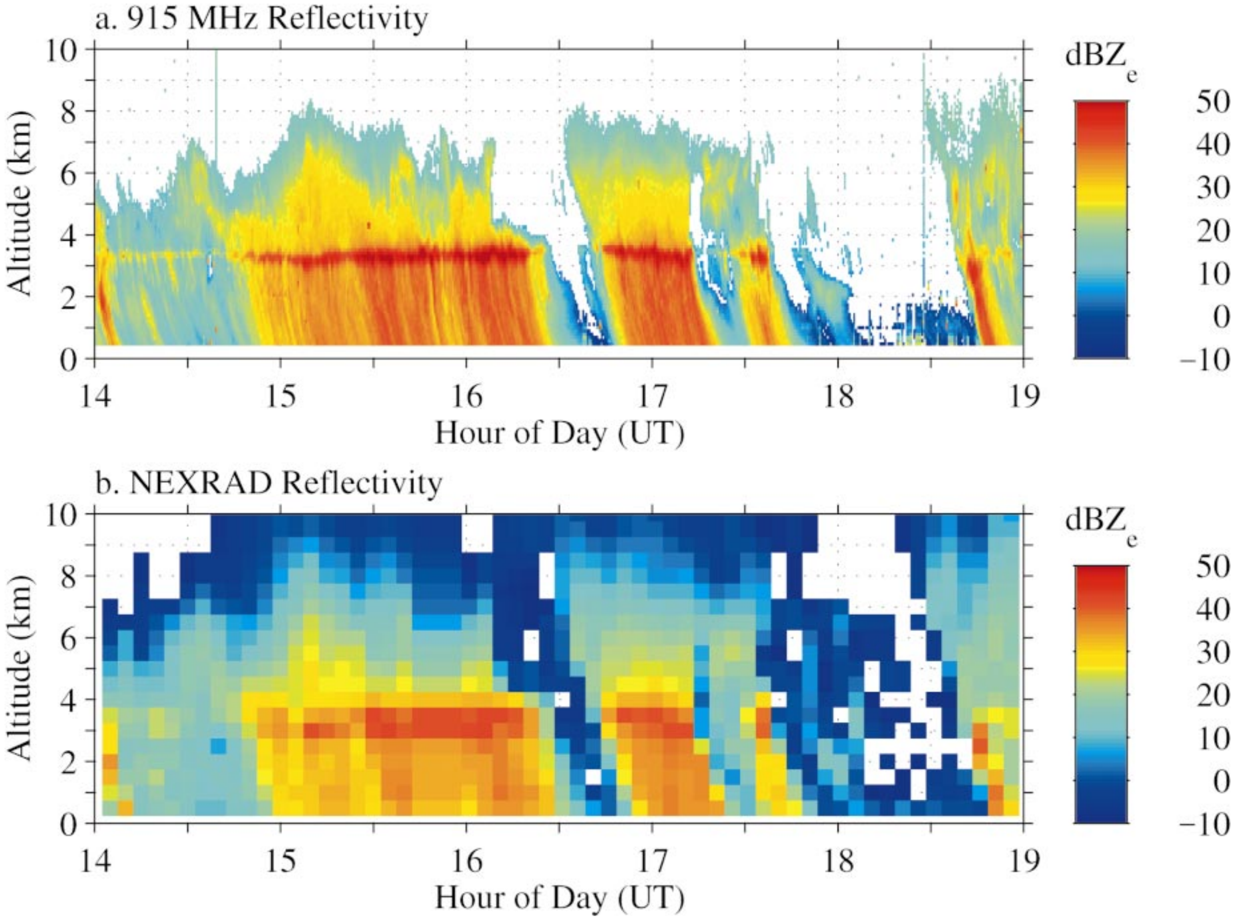

FIG. 9. Comparison of time–height sections of WSR-88D reflectivities over the profiler site and profiler reflectivities (18 Apr; 1400–1800 UTC).

Figure 9 shows a comparison of a time–height cross section of Dickinson, Texas, WSR-88D reflectivities on 18 April during TEFLUN A over the location of the profiler with the 915-MHz profiler reflectivities. Note that the scanning radar reflectivities have been interpolated to a Cartesian grid prior to plotting. The time–height cross section of WSR-88D reflectivities shows the much coarser resolution of the scanning radar as compared with the profiler attributable to a combination of the Cartesian gridding and the larger pulse volume of the scanning radar. The WSR-88D is horizontally polarized. In Texas at a range of 33 km, the pulse volume of the Dickinson WSR-88D over the profiler was 0.3 km^3, which can be compared with the profiler pulse volume of 0.0019 km^3 for the 105-m mode at 2 km. Although the bright band is not well resolved in the WSR-88D reflectivities, the two sets of reflectivities show the same overall vertical structure and evolution of the precipitating clouds over the profiler. The vertical resolution of the scanning radar is dependent upon range. At a range of 20–40 km the beam-spreading effect from the scanning radar is minimal so that the vertical resolution over the profiler is relatively good. Moreover, the separation distance is large enough to allow the scanning radar to sample over the profiler through a substantial fraction of the troposphere.

Figure 10a shows a comparison of time series of *calibrated* 915-MHz profiler reflectivities at 2.0 km in Houston, Texas, on 18 April during TEFLUN A with the WSR-88D reflectivities observed over the profiler location at 2.0 km. From this comparison, it does appear that the WSR-88D reflectivities are lower than the profiler reflectivities by several decibels. This impression is supported in Fig. 10b, in which we show the histograms of reflectivities and reflectivity differences from the calibrated profiler and WSR-88D.

Figure 11 contains comparisons of profiler reflectivities with the reflectivities observed over the profiler by the NCAR S-pol and Melbourne WSR-88D scanning radars on 17 September 1998 during TEFLUN B. Figure 11a shows a comparison of time series of calibrated 915-MHz profiler reflectivities at a height of 327 m with the S-pol reflectivities observed over the profiler location at a height of 321 m. We calculate that the S-pol pulse volume was 0.05 km^3 over the profiler site. Figure 11b shows a comparison of time series of calibrated

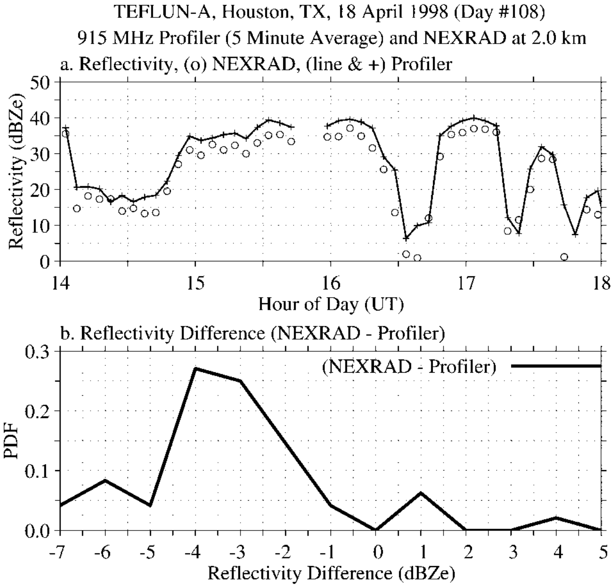

FIG. 10. Comparison of reflectivities at 2.0 km over the profiler site on 18 Apr 1998 as seen by the 915-MHz profiler and the Dickinson, TX, WSR-88D. (a) Comparison of time series of reflectivities. (b) Histogram of WSR-88D minus 915-MHz profiler reflectivity differences.

915-MHz profiler reflectivities at a height of 2.1 km with the Melbourne, Florida, WSR-88D reflectivities observed over the profiler at a height of 2.1 km. In both Figs. 11a and 11b, the scanning radar reflectivity data are in polar coordinates; the data have not been interpolated to a Cartesian grid. Because of the large gate spacing (1.0 km) used by the WSR-88D radar, the profiler data in Fig. 11b were averaged (in Z) in time (3 min) and height (seven range gates) to approximate the pulse volume of the Melbourne radar over the profiler site, which is about 0.34 km^3. Histograms of reflectivity differences between the S-pol and the profiler and the WSR-88D and the profiler are shown in Fig. 11c.

The profiler reflectivities are, on average, about 0.3 dB higher than WSR-88D reflectivities and about 0.8 dB higher than the S-pol reflectivities. We calculate that the S-pol pulse volume was 0.05 km^3 and that the Melbourne WSR-88D pulse volume was 0.34 km^3 over the profiler site. Both sets of scanning radar reflectivity time series are well correlated with the profiler reflectivities. Note, however, that in Fig. 11a there are times of substantial disagreement between the profiler and S-pol reflectivities centered around 1930 UTC, just before 2030 UTC, and again just before 2130 UTC. Reference to Fig. 4 shows that these are times of heavy convective precipitation. At such times, the spatial gradients of reflectivity are likely to be very large, contributing to space–time ambiguities between the two platforms. During this period, the S-pol radar was performing rapid update sector scans at a fixed elevation angle (0.5°) over the profiler while the WSR-88D was performing a full volume scan and as a consequence was sampling the atmospheric column over the profiler much less frequently than was the S-pol radar. Although we might for this reason expect the S-pol reflectivities to agree better with the profiler reflectivities than the WSR-88D reflectivities do, this agreement is not obviously the case for the example in Fig. 11. More cases and additional analysis will be required to quantify the bias among the scanning radar and profiler platforms.

6. Discussion

In this paper we have intercompared profiler reflectivities with reflectivities inferred from JWD and 2DVD and reflectivities observed by several scanning radars. Overall, the time series of reflectivities track each other very well, reinforcing the idea that the disdrometers can be used as a tool for calibrating profiler observations and that the profiler can be used to calibrate a scanning radar. There are several issues that arise in making these intercomparisons that we address below.

a. Profiler–disdrometer intercomparisons

In section 4 intercomparisons of disdrometer-inferred reflectivities with profiler-determined reflectivities were made for TEFLUN A (Figs. 5 and 6) and TEFLUN B (Figs. 7 and 8). The comparisons made in Texas on 18 April during TEFLUN A yielded the result that the disdrometer reflectivities exceeded the profiler reflectivities by about 2.5 dBZ, and the comparisons made in Florida during TEFLUN B showed that the profiler reflectivity exceeded the disdrometer reflectivity by close to 0.2 dBZ. In both campaigns the same instruments were utilized, but there were some important changes made to the instruments that can explain these differences.

Between TEFLUN A and TEFLUN B both the JWD and 915-MHz profiler were modified to improve performance. Briefly the JWD was modified as follows. The standard program provided by Distromet to determine the drop size distribution contains 20 drop sizes or bins. We wrote a new program that retains all 127 bins for drop sizes so that calculations of reflectivity could use the more complete distribution of drop sizes. This new program also provides a 10-s time series of data from the JWD that allows much better correlation with the profiler in comparison with the 60-s values from the Distromet software. We analyzed Florida data obtained with the JWD using the new approach and the standard method. The differences between the two were found to be small. In Texas the JWD was set up with the sensor flush with the surface; in Florida the disdrometer sensor was elevated on a tripod as shown in Fig. 1. Furthermore, in Texas we noted that the JWD computer clock would drift somewhat. In Florida we synchronized the JWD computer to the profiler by resetting the JWD computer clock every 5 min.

For TEFLUN B, the 915-MHz profiler was modified by replacing the 8-bit analog-to-digital (A/D) converter

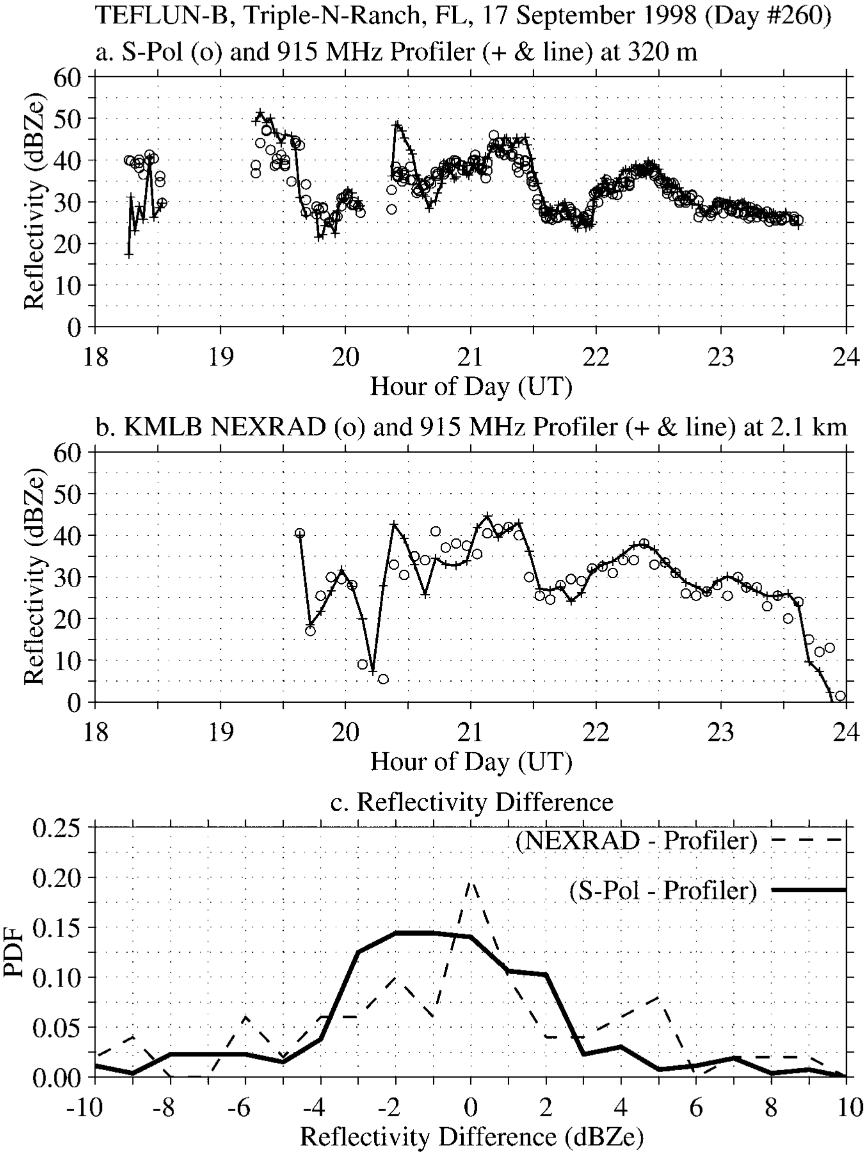

FIG. 11. Comparisons of reflectivities over the profiler site as seen by the 915-MHz profiler, The Melbourne WSR-88D, and the S-pol radar. (a) Comparison of time series of S-pol reflectivities at 321 m over the profiler site in central Florida on 17 Sep 1998 with 915-MHz profiler reflectivities at 327 m. (b) Comparison of time series of WSR-88D reflectivities at 2.0 km over the profiler site in central Florida on 17 Sep 1998 with 915-MHz profiler reflectivities at 2.1 km. (c) Histogram of WSR-88D minus 915-MHz profiler reflectivity differences and S-pol minus 915-MHz profiler reflectivity differences.

with a 12-bit A/D converter. This change provided a much improved dynamic range for the profiler and lessened the possibility of the profiler receiver becoming saturated. However, it was discovered upon completion of the Florida campaign that the pulse length of the profiler-transmitted pulse had been inadvertently lengthened to 138 m from the 105-m pulse length used in Texas. This change would tend to increase the observed reflectivities and is responsible for about a 3 dB *increase* in the *uncalibrated* profiler reflectivity between Texas and Florida when the pulse length change is not accounted for in the radar equation.

In making comparisons between profiler reflectivities and reflectivities calculated using disdrometers, there are obviously many issues that arise, not the least of which is the time–space ambiguities that result from comparing a ‘‘point’’ measurement at the surface with a volume measurement at several hundred meters above the surface. Actually, the collecting area of the JWD is about 50 cm^2, and the collecting area for the 2DVD is about 100 cm^2. The observing volume of the disdrometers is determined by the fall velocity of raindrops and, for drops falling at 7 m s^{-1}, would be close to 1 m^3 for a 30-s sample; the volume observed by the 2DVD is about 2.1 m^3. The volume observed by the profiler with a nominal 100-m pulse length is about 7.8×10^4 m^3 at 300 m and 8.6×10^5 m^3 at 1 km. Thus there are roughly 5–6 orders of magnitude difference in the observing volume for the disdrometers and profilers. Under these circumstances, especially under convective conditions, it is remarkable that the reflectivities calculated from the drop size distributions of the disdrometers agree as well as they do with the profilers. Furthermore, the quality of the agreement of the disdrometer and profilers depends on the height separation of the two instruments. Profiler comparisons with disdrometers are best made at the lowest profiler heights that are fully recovered. Below several hundred meters, echoes from ground clutter and so on can saturate the receiver. It takes several hundred meters for the signals to become small enough to fall within the dynamic range of the receiver. This point is usually the second or third range gate in the vicinity of 327 and 432 m, respectively. Note, however, that velocity information can be valid even at the lowest range gates for which the receiver is not fully recovered. Further complications arise from the quality of the drop size distribution measured by the disdrometers.

The presence in Florida of the collocated 2DVD helps place the profiler–JWD comparisons in some perspective. As can be seen in Fig. 8a, there are systematic differences between the reflectivities calculated using the JWD and 2DVD. In fact, the 2DVD has a bias of close to 2 dB relative to the JWD. The nature of the reflectivity biases will need to be examined further and understood before we can have complete confidence in the use of a disdrometer to calibrate the profiler. The presence of a collocated 2DVD disdrometer in Florida helped us to put the JWD results in perspective, as discussed next.

The JWD that we have used is the RD-69 disdrometer manufactured by Distromet, Inc. (Joss and Waldvogel 1967; Sauvageot and Lacaux 1995). This JWD has been used routinely for about 30 yr and has proved to be reliable for field use with a minimum of maintenance. The JWD is an impact device that measures the momentum imparted by a drop on the sensor surface, which is about 8 cm in diameter. There is a finite recovery time that can make it difficult to record the impact of a small drop hitting the disdrometer surface following the impact of a large drop. Consequently, the JWD does not count the small drop sizes very well during heavy rain. Williams et al. (2000b) have recently shown that the JWD misses a large number of small drops during heavy rain. However, missing small drops has a small effect on the calculated reflectivities owing to the D^6 dependence of Rayleigh backscatter from hydrometeors.

As noted above, the JWD is a very robust instrument that requires little attention in the field. The 2DVD, on the other hand, requires considerable attention to achieve reliable operation. It will be important in future research to understand and to correct for any biases in calculated reflectivities from these two instruments.

b. *Scanning radar versus profiler intercomparisons*

In section 5 we made comparisons between the 915-MHz profiler and several scanning radars. The scanning radars typically scan in azimuth at a fixed elevation angle. When operating in a volume-scan mode, the WSR-88D scans in azimuth over a range of elevation angles to sweep out a volume of the atmosphere. It takes typically 5 min for the WSR-88D to return to the same volume of the atmosphere. Thus a given volume of the atmosphere, which is well sampled every 30 s by the profiler with its fixed vertically directed beam, is sampled very infrequently by a scanning radar in a volume-scanning mode. Furthermore, the beamwidth of the scanning radar is large enough that the height resolution of the scanning radar is coarse, depending on range. For example a WSR-88D scanning radar with 1° beamwidth will have a vertical resolution at 10 km of about 175 m and a vertical resolution at 30 km greater than 500 m. Thus, for good profiler–scanning radar intercomparisons at low altitudes, the distance between the scanning radar and the profiler should be less than about 30 km. Moreover, the comparisons should be done in stratiform rain.

7. Concluding remarks

Profiler observations of hydrometeors in precipitating cloud systems have been taken during several TRMM ground validation field campaigns. Measurements with a collocated JWD show that reflectivities observed at the lowest reliable heights of the profiler track the calculated reflectivities deduced from the JWD. Although there are reasons to expect differences between the two sets of observations because the disdrometer samples a much smaller volume close to the surface and the profiler observes a much larger volume above the surface, the agreement appears to be good enough, at least during stratiform rain, to use the disdrometer to calibrate the profiler observations.

Intercomparisons between profiler reflectivities and scanning radar reflectivities over the profiler also track each other very well, although more analysis is needed to quantify biases in measurements. A well-calibrated profiler can then be used to calibrate or validate a scanning radar. To perform the calibration under optimal conditions there should be continuous, preferably stratiform, rain and the scanning radar should, if possible, be directed over the profiler to maximize sampling of the same volume observed by the profiler.

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