The DeTect Inc. RAPTOR VAD-BL Radar Wind Profiler

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ABSTRACT

The DeTect Inc. RAPTOR velocity–azimuth display boundary layer (VAD-BL) radar wind profiler is a pulsed Doppler radar used to make automatic unattended measurements of wind profiles in the lower atmosphere. All data products are produced on site, in real time, and utilize quality control software to screen out interference. The nominal frequencies are 915 and 1290 MHz but other frequencies can be accommodated. While the architecture is similar to other boundary layer wind profilers, the RAPTOR VAD-BL is designed to provide consistently superior data quality due to its antenna design and signal processing capabilities. The antenna is a high-performance parabolic reflector with a feed that is designed in house for the operational frequency of the radar. The antenna is mounted on a robust military-grade azimuth-only positioner. The RAPTOR VAD-BL can collect data from several opposing beam positions with the goal of producing higher-quality wind data using the velocity–azimuth display (VAD) algorithm. The Advanced Signal Processing Engine (ASPEN) software used to calculate winds outperforms conventional consensus algorithms. The health and status of all critical subsystems is monitored via the profiler health monitor (PHM), a stand-alone monitor with its own microprocessor. Results from systems deployed for operational applications show the potential for the retrieval of high-quality data with excellent height coverage and a solid design that allows the antenna to perform under sustained high wind loading.

1. Introduction

Radar wind profilers (RWPs) with an operating frequency around 1 GHz are widely used to probe the boundary layer (BL). Although they do not offer the height coverage of radars that operate at very high frequency (VHF) and at the lower UHF range, their antennas are relatively smaller and can effectively measure winds in the BL. BL RWPs are routinely used in atmospheric research and operational applications. Examples of atmospheric research include determination of boundary layer height (Hashiguchi et al. 1995; Cohn and Angevine 2000), cold front characterization (Browning et al. 1998), heat and momentum fluxes (Angevine et al. 1993), classification of precipitating clouds (Williams et al. 1995), and rainfall drop size distributions (Schafer et al. 2002). Operational applications include weather forecasting, air quality forecasting for urban areas, and wind shear determination at airports.

Typical BL RWPs currently deployed utilize antenna arrays, either several fixed-beam microstrip antenna panels pointed in different directions or electronically steered phased array antennas (Carter et al. 1995). These antenna architectures can have certain limitations. For instance, electronically steered phased array antennas require a rather complicated feed network that involves the use of power dividers, phase shifters, and phase-matched feed lines. For passive phased array antennas, these feed networks incur insertion losses that effectively reduce the gain of the antenna and the detectability of the atmospheric signal. Active phased array antennas reduce the insertion losses at the expense of adding several transmit/receive modules, each feeding a section of the entire array. Typical antenna arrays normally point in a limited number of directions—for example, a vertical beam and two or four off-vertical beams at orthogonal azimuth angles. Although these configurations usually provide atmospheric data of good quality, there are some scenarios where degradation in quality could occur. For
instance, the clutter environment or radio frequency interference (RFI) could reduce the detectability of the atmospheric signal on one or more of the off-vertical beams. The Meteorological Systems Division at DeTect Inc. developed the RAPTOR velocity–azimuth display boundary layer (VAD-BL) RWP to overcome those limitations. The antenna is built from a commercial off-the-shelf (COTS) parabolic reflector. The prime-focus feed antenna is designed and built in house. This simple antenna architecture minimizes the feed losses and eliminates the complexity of the feed network associated with antenna arrays. Also, to increase the antenna aperture only, the parabolic reflector and the feed antenna need to be replaced. Because the RAPTOR VAD-BL antenna is mounted on a military-grade azimuth positioner at constant zenith angle, it can be pointed away from localized ground clutter and RFI sources. Additionally, there is no limitation in the number of azimuth directions to which it can point.

In the next section, the RAPTOR VAD-BL RWP specifications are presented. Section 3 describes the RWP subsystems. Section 4 shows data acquired with these systems and provides a brief discussion.

2. System specifications

The DeTect RAPTOR VAD-BL RWP was designed and built to measure winds in the BL with high performance, high reliability, and low maintenance. The RAPTOR VAD-BL uses an azimuth positioner specifically designed for this application that rotates a parabolic reflector at a constant zenith angle (McLaughlin et al. 2010). This feature allows for VAD processing of winds (Browning and Wexler 1968) measured in four, eight, or more discrete azimuth angles, or even in a continuous mode, thus getting more samples of the wind field than the two or four oblique beams that are typically used. Table 1 lists the specifications for the RAPTOR VAD-BL RWP.

During the production and installation phases, the RAPTOR VAD-BL is calibrated for range and Doppler velocity. This is accomplished by superimposing a calibration signal of known delay and Doppler frequency to the normal receive signal. Timing parameters are adjusted until the calibration signal is detected at the correct range. It is also verified that the software can estimate the correct radial velocity corresponding to the Doppler frequency of the calibration signal. Additionally, the orientation of the parabolic reflector is set to accuracies better than 0.5° in elevation and 1° in azimuth.

3. Subsystems descriptions

A picture of the RAPTOR VAD-BL RWP installed in Samoa (13°48′54.8″S, 171°46′49.9″W) is shown in Fig. 1. For this system the radio acoustic sounding system (RASS) option was also installed to measure virtual temperature profiles.

The antenna is a COTS high-performance parabolic reflector. A COTS shield is mounted on top of the parabolic reflector to reduce clutter and RFI. The inside of the shield is covered with radio absorbent material to further reduce spillover and side lobes. A COTS radome covers the top of the antenna assembly. DeTect Inc. designs and builds the prime-focus feed antenna based on the frequency of the RWP and the dimensions of the
parabolic reflector. This antenna assembly is mounted on an azimuth positioner specifically designed for this application. The azimuth positioner points the parabolic reflector at a fixed zenith angle and can rotate at speeds up to $45^\circ \text{s}^{-1}$ in either direction.

A digital transceiver is built upon a COTS software-defined radio (SDR) card composed of a field-programmable gate array (FPGA), a 16-bit digital-to-analog converter (DAC) that generates the intermediate frequency (IF) waveform and timing signals, and a 16-bit analog-to-digital converter (ADC) that samples the radar return signal at IF. The conversion of the radar pulse from IF to radio frequency (RF) and vice versa is accomplished by a combination of IF conditioner (IFC) and up/down converter (UDC) units.

The high-power amplifier (HPA) is designed to house up to three solid-state power amplifier modules. The number of power amplifier modules is chosen to meet the specific needs of each installation. This design allows for increases in the output power if more modules can be added to the HPA (without external modifications to the HPA or the electronics rack) and soft-fail capability if the HPA contains more than one module.

For those installations where the RASS option is included, four parabolic dishes, each with a high-power transducer, are installed around the RF antenna. The transducers are powered with a high-power amplifier located inside a climate-controlled shelter. A range of acoustic frequencies with a wavelength near the half wavelength of the radar (condition for Bragg scatter) is sent in the RASS mode so that profiles of the virtual temperature can be calculated (Matuura et al. 1986; May et al. 1988).

The profiler data system (PDS) implements the antenna-pointing strategies and the radar modes. A typical installation uses two or three modes to measure winds from about 100 m to several kilometers in height. Only one mode is run at a time. Radar modes are designed to

![Fig. 2. Winds measured with the RAPTOR VAD-BL RWP installed in Samoa. Wind barbs as a function of height and time (UTC) are shown for 6 h on 24 Mar 2012.](image)
obtain the required sensitivity, range resolution, and velocity resolution for the sampled height range within reasonable unambiguous height and velocity limits. A high-resolution mode utilizes short noncoded pulses to sample the BL close to the ground with very fine-altitude resolution (~70 m). A low-resolution mode utilizes long pulses that increase the radiated power so that winds can be measured at higher altitudes at the expense of coarser-altitude resolution (~550 m). If finer-altitude resolution (~200 m) is needed at higher altitudes, then the longer pulses can be coded using complementary pulse coding (Schmidt et al. 1979). Other modes can be configured in similar ways so that their individual height coverages overlap (for height continuity purposes) and their overall coverage extends to the region of interest. Data processing in RWPs follows the basic steps described by Strauch et al. (1984). For the RAPTOR VAD-BL, the data processing is accomplished in two stages. Initially, the Basic Interface for Radar Control and Health (BIRCH) software takes the digital receiver data and calculates the spectra based on the fast Fourier transform (FFT) settings, and the coherent and incoherent number of averages for the radar mode. Additionally, BIRCH can enable several algorithms while calculating the spectra: clutter suppression [direct current (dc) bias removal and interpolation across dc spectral value], several window functions (e.g., Hanning, Hamming, Blackman, etc.), removal of RFI from the time series based on signal statistics, and Gabor filtering (Gabor frame decomposition of the data and filtering of signals with intermittent clutter signatures; a detailed explanation can be found in Lehmann 2012). The spectra are then saved to a database for additional data processing. The Advanced Signal Processing Engine (ASPEN) software collects the spectra from the database (for every mode, beam, and height), detects the significant peaks in the spectra (usually more than one in each spectrum), and calculates the noise level and moments: power, radial velocity, and spectral width (Strauch et al. 1984; Woodman 1985; Boyer et al. 2003). ASPEN then utilizes time–height continuity based on pattern recognition (Weber and Wuertz 1991; Weber et al. 1993) and homogeneity checks across all beams to identify the source of the spectral peaks as ground clutter, fliers (e.g., planes and birds), outliers, RFI, or atmospheric return. Finally, ASPEN calculates the horizontal and vertical winds using the radial velocities of atmospheric peaks identified previously, again checking for time–height continuity to assign a quality control value to the winds (Weber and Wuertz 1991; Weber et al. 1993). Typically, winds are reported in 6-min and 1-h intervals. In the 6-min case, the data collected in the last 60 min are retrieved and ASPEN runs quality control checks on the data, but only the last 30 min are used to calculate an average profile. For the wind profiles that are reported every hour, the typical quality control time is 4 h and the averaging time is 1 h. The long average time helps to satisfy the horizontal homogeneity assumption (Cheong et al. 2008). BIRCH is also used to control the radar and to monitor the status of the radar components through a graphical user interface (GUI). BIRCH and ASPEN run on the wind profiler computer (WPC), which also houses the SDR card.
The profiler health monitor (PHM) constantly checks the status and health of most of the RWP components and passes that information to the WPC. The PHM runs independently of the WPC and can shut down the radar when major alarms are detected even in the event of a loss of communication with the WPC or WPC malfunction.

Usually only the antenna assembly is installed outside a climate-controlled shelter. All the electronics [those described above and others, such as a keyboard–video–mouse (KVM) console, an electronics power supply (EPS), etc.] are mounted on a rack inside the shelter.

4. Data results and discussion

Figure 2 shows winds measured with the RAPTOR VAD-BL RWP installed in Samoa. This radar operates at 1290 MHz with a peak output power of 2 kW. The diameter of the parabolic reflector is 3 m. The winds are calculated every 6 min and 6 hours’ worth of winds are displayed by ASPEN for 24 March 2012. The radar was configured to collect data from about 100 m above ground level (AGL) to 13 km AGL. Wind profiles collected during the installation of the radar in Samoa frequently reached 8 km in clear air (see Fig. 4 below) and up to about 13 km when raining (Fig. 2). Data from these heights are not normally expected from a UHF BL RWP, but this is attributed to the high-gain antenna, high-power amplifier and, of course, tropical atmospheric conditions.

Figure 3 shows winds measured with the RAPTOR VAD-BL RWP installed at Horn Point (Cambridge, Maryland) during Hurricane Sandy on 29–30 October 2012. This radar operates at 915 MHz with a peak output power of 800 W. The diameter of the parabolic reflector is 3 m. During the main part of the hurricane, there were winds in excess of 40 m s$^{-1}$ (equivalent to 90 miles per hour, or 145 kilometers per hour, or 78 kt, where 1 kt = 0.51 m s$^{-1}$) and high winds were measured from the surface to 4 km.

Although the RAPTOR VAD-BL RWP does not point vertically, ASPEN can still calculate the vertical
motion from opposing coplanar beams. Angevine et al. (1993) provide the equation based on the zenith angle and the measured radial velocities. Figure 4 shows a screen capture from ASPEN that includes the calculated vertical velocity profile from the RAPTOR VAD-BL in Samoa. Taking data at several azimuth angles, as the VAD technique requires, can also provide additional information, such as convergence/divergence, translation, or deformation characteristics of the horizontal wind field (Browning and Wexler 1968).

RWPs calculate the winds under the assumption of a horizontally homogeneous wind field. To check if the measured winds comply with this requirement, two estimates of the vertical wind are calculated using data from two sets of opposing beams (e.g., north and south beams, and east and west beams). If these two vertical winds are close to each other, then it is assumed that the wind field was horizontally homogeneous for that particular height, and the horizontal wind is calculated; otherwise, the wind at this altitude is discarded from the profile. Figure 2 shows winds that passed this homogeneity check and all other quality control checks (Weber and Wuertz 1991; Weber et al. 1993).

When the RASS option is installed with the RAPTOR VAD-BL, virtual-temperature profiles are also calculated. Height coverage is comparable to other typical installations with an operating frequency around 1 GHz (e.g., May et al. 1988). Figure 5 shows profiles collected over Horn Point in Cambridge, Maryland. The profiles show a dynamic temporal evolution of the temperature in the lower atmosphere with a descending layer of temperature inversion. Outliers above 1400 m are also present likely because of low sensitivity at those times and heights.

In summary the RAPTOR VAD-BL RWP has shown the potential for measuring high-quality winds with excellent height coverage. Comparisons with other instruments of known precision and long-term data analysis were outside the scope of this paper, but they will be pursued in the future to further validate the performance of the system. The antenna design, which minimizes feed losses and increases the gain, has also proven to be capable of withstanding sustained high winds.
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REFERENCES


