Simplified Active Array L-Band Radar for Atmospheric Wind Profiling: Initial Results

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ABSTRACT

A simple approach is presented to implement an active aperture radar with a constrained beam-forming network that is adequate enough to generate multiple beams for atmospheric wind profiling. In this approach, elements of the antenna array are fed directly by dedicated transceiver modules, which are realized with commercially available communication components, making them low cost. A passive 2D beam-forming network distributes the exciter output signal and feeds the transceivers with appropriate phase distribution to generate different beams. This configuration, which is a simplified active array, eliminates the feed loss and achieves the best signal-to-noise ratio (SNR), thereby increases range coverage. Consequently, this scheme allows for a smaller antenna size when compared to a conventional passive array system, for the given range performance, and makes the wind profiler compact and transportable. A 1280-MHz, 64-element simplified active array radar has been developed, successfully validated, and is being operated at Gadanki, a tropical station in south India. Measured winds are in good agreement with those obtained with a collocated GPS sonde technique. This paper presents the configuration and sample results of the system.

1. Introduction

UHF wind profiling radar (WPR) is a potential tool for atmospheric research and operational meteorology. Two classes of radars, operating at 1 GHz and 400 MHz measuring winds in the lower-troposphere and troposphere regions, respectively, have evolved in the last 30 yr and have been deployed around the world extensively. Many UHF wind profilers have been developed in the recent past by research and commercial groups for applications ranging from air quality studies to climate monitoring (Balsley and Gage 1982; Gage and Balsley 1978; Gage et al. 1994; Rogers et al. 1993). Research applications include studies of low-level transport of water vapor (e.g., by trade winds), boundary layer convergence, frontal passages, low-altitude turbulence, global climate change, and vertical profiles of precipitation. Operational uses include air pollution prediction, wind shear monitoring, temperature profiling in the radio acoustic sounding system (RASS) mode, aviation operations, mesoscale meteorological forecasting, defense operations, forest fire management, weather modification, etc. Since these radars are very sensitive to rain and to some extent to clouds, they can be used for rain profiling, for instance, monitoring the height of the melting layer and the vertical extent of hydrometeors, deriving drop size distribution, classifying precipitating systems, etc. (Fabry and Zawadzki 1995; Williams et al. 1995; Rao et al. 2001, 2008, and references therein).

WPR derive information on the dynamical atmospheric phenomenon by making use of variations in amplitude and the frequency of radio waves, which are transmitted from the radar system, backscattered by the
minor irregularities in the refractive index of the atmosphere (and hydrometeors), and received by the radar system again. It is the sensitive coherent-pulse Doppler radar making use of either the Doppler beam-swinging (DBS) technique or spaced antenna (SA) technique for wind estimation. In the DBS technique, the narrow radar beam is switched into three or five noncoplanar directions in a fixed sequence. The mean Doppler obtained in different beam directions is used to compute the three components of the wind vector. The spaced antenna technique employs a single vertical beam but receives the echo with multiple receivers. Full correlation analysis between spaced receivers (Briggs 1984) is, then, performed to obtain wind.

The success of the Jicamarca Incoherent Scatter radar (Woodman and Guillen 1974) in obtaining strong continuous echoes between 10- and 35-km altitude inspired the use of other ionospheric radars to probe the troposphere and stratosphere. The real drive to make wind profiling radars practical for routine meteorological applications came from the Wave Propagation Laboratory (Carter et al. 1995) of the National Oceanic and Atmospheric Administration (NOAA) in the United States during the early 1980s. UHF wind profilers (Ecklund et al. 1988, 1990; Hashiguchi et al. 1995) are configured either with dish antenna or passive array for simplicity and commercial viability. However, WPR configuration has gone through transformation because of the advancements in radar technology. Solid-state power amplifiers (PAs) are replacing the tube-based counterparts, dish antennae are being replaced with an array of antennae, and analog receivers are getting replaced with digital processors. Mead et al. (1998) have demonstrated a 3D volume turbulent eddy profiler using an imaging receive array and an external wide beam transmit antenna. Each element of the receive array has its own dedicated data acquisition system. Height coverage of this system is limited because of wide spreading of the transmit power. May et al. (2002) used a simple dish antenna–based profiler with a state-of-the-art IF processor employing powerful clutter removal and data processing algorithms. Hashiguchi et al. (2004) used a semi-active array in which the array is active in one of the principal planes and passive in the other. Two sets of coaxial collinear arrays are used in orthogonal directions to steer the beam in cardinal planes. This system, employing relatively large antennae (4 m), is the most advanced in its class. Recently a wind profiler was developed with the Luneberg lens antenna (Imai et al. 2007) by Sumimoto Electric Industries Ltd. and RISH of Kyoto University jointly. It totally eliminates the need for any beam-forming–steering system.

Advancement in the area of solid-state technology made it possible to build active array radars, which are the most advanced systems. In these systems, which are employed in the military domain, each element of the array is fed by a dedicated transmit–receive (TR) module, consisting of a power amplifier and low-noise amplifier (LNA) with common digital phase shifter and attenuator. These systems have two distinct advantages: (i) elimination of antenna feeder loss, which results in enhanced signal-to-noise ratio (SNR) or better range coverage, and (ii) beam agility, where the radar beam can be switched into unlimited directions. However, these systems are technologically complex and prohibitively expensive.

The beam-agility feature, which makes the active array system very complex and expensive, is overkill for the wind profiling application, which needs only three or five beams. In this paper we present a simplified active array radar configuration in which the beam-agility feature is replaced with a constrained beam-forming network, which is adequate enough to generate multiple beams for the wind profiling application. This system is simple in architecture (like a passive array) and highly sensitive (similar to an active array). Configuration of a simplified active array wind profiler is presented in section 2. A description of the simplified active array wind profiling radar built and being operated at the National Atmospheric Research Laboratory (NARL), is presented in section 3. Initial results and wind validation are presented in section 4. Conclusions are given in section 5.
2. System configuration

Configuration of the simplified active array wind profiling radar is illustrated in Fig. 1. Elements of the antenna array are fed directly by dedicated low-power transceivers, each consisting of a power amplifier and LNA connected to the common antenna port through a circulator. A transmit–receive switch switches the input port between the PA and LNA. The digital phase shifter and attenuator, which appear at the input section of the TR module in a full-fledged active array, are removed. These two components, costly and associated with high-level control complexity, are the key elements of the active array radar system, facilitating the beam-agility feature. To simplify the beam formation, a low-power, passive, 2D beam-forming network is kept at the input of the transceivers. This network distributes the radar exciter output signal and feeds the transceivers with appropriate amplitude and phase distribution. In the receive mode, the outputs from the transceivers are appropriately weighted, phase shifted, and combined in the beam-forming network before feeding the down converter.

A major challenge in realizing this configuration is the development of transceivers. In addition to being low cost, they need to have uniform gain and phase characteristics in both the transmit and receive paths. Both these problems can be addressed by realizing the transceivers with commercially available communication components, which are inexpensive because of their bulk production. By virtue of mass production, the electrical (gain and phase) characteristics of the commercial components are identical. The low-power, passive, beam-forming network is to be realized with \( M \) input ports (each corresponding to a beam direction) and \( N \) output ports (connected to transceivers). A signal fed to an input port is distributed among the output ports with a specific phase gradient generating radar beam in a particular direction. A low-power, high-speed, solid-state, single-pole-multi-through (SPMT) switch is used at the input of the beam-forming network to select the desired input port (or beam). The main advantage of the...
passive beam-forming network is that it avoids the need for periodic phase calibration.

In this scheme, all the transmitted power is delivered to the antenna as there is no feed loss involved and the receiver system noise floor is at a minimum since the LNA is kept near the antenna. As a result, the SNR of the received echoes is significantly enhanced. If the cosmic noise is ignored, for the given set of experimental parameters, the SNR can be empirically expressed as

\[ \text{SNR} \propto \frac{PA}{2L^2 - L}, \]

where \( P \) is the transmit power, \( A \) is the antenna aperture, and \( L \) is the attenuation (loss) factor. This configuration allows significantly smaller antennae when compared to a conventional passive array system for the given SNR (or performance) and makes the wind profiler compact and transportable. However, this statement is valid only if the background cosmic noise temperature is smaller than the receiver noise temperature of the radar, which is true in the case of radars operating in the UHF band. Another advantage of this scheme is the simple nature of beam forming. In essence, the simplified active aperture system achieves the best SNR (and thereby range coverage) as an active aperture radar and offers a very simple beam-steering scheme of a passive array. This configuration ideally suits the wind profiling application, where only three or five beams are needed.

3. 64-element simplified active array WPR

A 1280-MHz simplified active array wind profiling radar (Srinivasulu et al. 2006) was developed and is being operated at NARL. The antenna array consists of 64 microstrip patch antenna elements arranged in an \( 8 \times 8 \) matrix over an area of \( 1.4 \text{ m} \times 1.4 \text{ m} \). Interelement spacing is chosen as \( 0.73\lambda \) (where \( \lambda \) is the radar wavelength) to achieve an optimal compromise between the beamwidth and grating-free maximum steer angle. Each element of the planar array is fed by a dedicated 18-W
solid-state transceiver, which is realized in a compact package with commercially available components. The passive beam-forming network is realized with a 2D modified Butler matrix as illustrated in Detrick and Rosenberg (1990). Figure 2 shows the modified linear Butler matrix, which is the basic building block for realizing the 2D matrix. In this scheme the traditional Butler matrix is modified to generate a zenith (broadside) beam at the expense of one of the outermost beams. A zenith beam is very useful for the wind profiling radar in obtaining the vertical wind component and studying precipitation. The phase distribution, at the output ports of the 2D Butler matrix, is given by the following equation:

\[ \varphi_{m,n} = m \left( \frac{\pi}{4} \right) + n \left( \frac{\pi}{4} \right), \]  

where \( m (1, 2, \ldots, 8) \) and \( n (1, 2, \ldots, 8) \) are the output ports along the orthogonal directions and \( i (-2, -1, 0, 1, 2) \) and \( j (-2, -1, 0, 1, 2) \) are the input ports. This network generates 25 usable beams in the 2D angular space, as shown in Fig. 3, for the chosen interelement spacing. Negatively numbered input ports are designated as \( L \) ports and positively numbered input ports are designated as \( R \) ports. The input port with \( i = 0 \) and \( j = 0 \) is referred to as the zenith port. An SP5T switch is kept at the input of the Butler matrix to select five beams \((L_1L_1, R_1R_1, ZZ, L_1R_1, \) and \( R_1L_1)\) for DBS operation. The remaining input ports are terminated with characteristic impedances. The zenith angle of the oblique beams is 14° down toward the northeast, southwest, northwest, and southeast directions. Taylor weightings are incorporated at the output ports of the beam-forming network to realize a sidelobe level of −17 dB. The two-way beamwidth of the antenna radiation pattern is 6.5°. The transmitter total peak power is about 800 W and a maximum duty ratio of 10% is provided. The entire wind profiler system is kept in an air-conditioned shelter of 1.5 m × 1.9 m × 1.8 m size. Figure 4 shows the picture of the wind profiler. The ground plane of the planar microstrip patch array acts as a roof to the shelter and the transceivers and beam formers are suspended below the antenna array. A slanted aluminum fence is kept around the antenna array to suppress the ground clutter signal due to the surrounding trees and hills. The instrumentation rack, kept inside the shelter at ground level, contains the radar exciter, down converter, IF amplifier chain, direct IF digital receiver, and PC-based radar controller.

Experimental, control, and processing parameters are set in the radar controller PC through a graphical user interface (GUI) developed using VC software on a Windows platform. Sample GUIs are shown in Fig. 5. The timing and control signal generator (TCSG), which is controlled by a radar controller PC, generates the timing and control signals for various subsystems. RF pulse generated by the exciter is distributed to transceivers and antennae via the beam-forming network. In the receive mode, the echoes received by the antenna array are passed through transceivers and combined in the beam-forming network before feeding the down converter. An additional \( T/R \) switch, located in the

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<th>TABLE 1. Specifications of the WPR.</th>
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<td>Frequency</td>
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<td>Technique</td>
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<td>Antenna type</td>
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<td>Array size</td>
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<td>Two-way beamwidth</td>
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<td>Transmit/receive type</td>
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<td>Peak power</td>
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<td>Duty ratio</td>
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<td>PW</td>
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<td>Coherent integrations (NCI)</td>
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<td>Time series points (NFFT)</td>
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<td>Range bins</td>
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<td>Receiver</td>
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<th>TABLE 2. Experimental parameters for different observations.</th>
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<td><strong>Parameter</strong></td>
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<td>PW (µs)</td>
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<td>Coded/uncoded</td>
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<td>IPP (µs)</td>
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<td>Coherent integrations</td>
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instrumentation rack (as shown in Fig. 1), is used to switch the active antenna array between the exciter and down converter. The 70-MHz receive IF signal is appropriately amplified and band limited before feeding the direct IF digital receiver, which performs analog-to-digital conversion, down conversion to baseband, decoding (pulse compression), coherent integration, dc and clutter removal, spectral computation, incoherent integration, and data transfer to a PC. Further data processing is carried out in the PC to estimate the moments and computation of the wind vector. Clutter removal is carried out by detrending the time series data as described by May and Strauch (1998). In this method, the data are segmented and a linear fit line is estimated for each segment and then the line is subtracted. This process eliminates the clutter effectively. The mean noise level is computed in the spectral domain as illustrated by Hildebrand and Sekhon (1974). Spectral moments (power, mean Doppler frequency, and Doppler width) are computed based on Woodman (1985) and Barth et al. (1994). Three components of wind are estimated using the method described by Sato (1989). Consensus averaging is performed to obtain wind. The radar control PC displays data in different formats as chosen through GUI. Specifications of the profiler are shown in Table 1.

4. Observations

The wind profiler was operated intensively during May 2010. Pulse width (PW) of the system is varied from 0.25 to 8.0 μs in binary steps. Both uncoded and coded transmission is possible. For the case of coded transmission the baud length can be selected from 0.25 to 4.0 μs in binary steps and the code length can be selected from 2 to 32 in binary steps. The interpulse period (IPP) used for the case of clear-air observation is about 40–60 μs for wind profiling. Coded pulse transmission is used for observing the upper height range. The typical time duration for collecting data for one time series frame of 1024 points is about 1–2 s. Spectral averaging is done for 20–60-s (typical) periods for each beam.
direction. Radar beam is switched in five directions in sequence for deriving the wind vector. During precipitation, only the zenith beam is operated and the IPP is increased to 100 $\mu$s to cover the range up to 15 km. Table 2 shows the experimental parameters used for different modes of observations.

a. Observations in clear-air condition

Figures 6a–c show typical range–Doppler spectra for low mode and higher modes in the 14°NW direction, obtained during fair weather. Figure 6d shows the range Doppler spectra obtained in the five beams used for the DBS mode of operation to derive the 3D wind vector. The height coverage performance in a clear-air case for the month of May 2010 is shown in Fig. 7. From the figure, it may be noticed that the typical height coverage of the profiler for the case of 1-$\mu$s uncoded pulse and 50-$\mu$s IPP operation (dashed line) is 2.5–5 km. In the case of 4-$\mu$s coded pulse with 1-$\mu$s baud and 50-$\mu$s IPP operation, the height coverage is improved by $\sim$(1.0–1.5) km and is about 3.5–6.5 km as indicated by the solid line. NARL (Jayaraman et al. 2010) has operated a 1357.5-MHz wind profiler (Krishna Reddy et al. 2001) during the period 1998–2000 with a $24 \times 24$ passive array and peak power of 1 kW. Though the antenna size of the old profiler is 9 times larger than the new system, it has a larger feeder loss factor of 3.16 (5 dB). Height coverage of the old profiler with 1-$\mu$s uncoded pulse and 50-$\mu$s IPP operation is shown as a dotted line (for the month of May 1999) for reference. It may be noticed that despite using a smaller array, height coverage of the new wind profiler is comparable with the old profiler, as per Eq. (1).

NARL launches GPS sonde balloons regularly—on a daily basis at 1730 local time (LT). Winds derived from the GPS sonde technique are used to validate the radar-measured winds. Figure 8 shows the typical comparison of zonal ($u$) and meridional ($v$) winds measured by WPR and GPS sonde. It may be noticed from the figure that the agreement is good even at upper heights (4–6 km) where the SNR is relatively poor. The scatterplot that

![Fig. 7. Height coverage of 64-element active array radar and 576-element passive array radar for the month of May.](image)

![Fig. 8. Comparison of winds observed by the WPR and GPS RS winds at 1715 LT 4 May 2010.](image)
compares the zonal \((u)\) and meridional \((v)\) winds measured by WPR and GPS radiosonde for about 27 flights is shown in Fig. 9. The correlation coefficients are found to be excellent (i.e., 0.94 and 0.92, respectively, for \(u\) and \(v\)), validating the radar observations. A small intercept and a slope close to 1 of the linear regression line indicate that radar-measured winds are accurate. The figure also shows no apparent bias in radar winds. Despite the fact that wind variability is at a maximum at the balloon flight time (evening hours), the intercomparison of winds measured by radar and GPS sonde is found to be very good (correlation coefficient of 0.92–0.94).

Figure 10 shows the time–height cross section of hourly horizontal winds obtained by the profiler between 0000 and 2400 LT 14 May, depicting a diurnal variation of winds. It is clearly apparent from the figure that the wind variability is quite large not only with time, but also with height. Both direction and magnitude are varying considerably. It is also evident from the figure that this profiler is capable of providing wind measurement up to a height of 4–5 km.

Figure 11 shows the diurnal variation of radar reflectivity (in terms of SNR) in zenith direction on 14 May along with the surface temperature measured by a collocated 50-m instrumented tower. The boundary layer

\[ y = 0.96x - 0.396 \text{ (m/s)} \]
\[ R = 0.921 \]
\[ y = 0.953x - 0.15 \text{ (m/s)} \]
\[ R = 0.936 \]
top can be seen in the figure as a layer of high reflectivity (Angevine et al. 1994). The figure clearly depicts the evolution of the atmospheric boundary layer. The variation of radar reflectivity follows that of the surface temperature, which starts rising from 0700 to 1400 LT and then collapses in the late evening. Krishna Reddy et al. (2002) and Kumar and Jain (2006) reported similar observations for Gadanki (a tropical station in south India) using the old wind profiler.

b. Observations during precipitation

UHF wind profilers can provide valuable information about precipitating cloud systems (Gossard 1988; Gage et al. 1996; Ecklund et al. 1995; Williams et al. 1995; Ralph 1995; Rao et al. 2001, 2008). Given the strong dependence of Rayleigh scattering on the wavelength of the probing radar ($\eta_R \propto \lambda^{-4}$, where $\eta_R$ and $\lambda$ are volume reflectivity and wavelength of the radar, respectively), the height coverage of the profilers increases dramatically during precipitation. Figure 12 shows the typical range–Doppler spectra obtained during stratiform precipitation on 19 May 2010. The figure clearly shows a steep gradient in Doppler velocity and also spectral width in the height region of 5.35–4.2 km (roughly the height of the $0^\circ$C isotherm). It may be noticed from the figure that the Doppler velocity of the raindrops is about 7–8 m s$^{-1}$ below the melting layer (bright band). Figure 13 shows the observations made by the profiler during different precipitation events; an isolated thunderstorm, cyclone, and a heavy rain event. All three cases depict the variability of rain and show different stages of the event (i.e., the convective, stratiform, and transition stages; Rao et al. 2008). Range-corrected SNR (reflectivity), Doppler velocity, and spectral width measured by the radar and surface rainfall rate measured by a collocated impact-type disdrometer (Rao et al. 2001) are shown for all three cases. Figure 13(left) shows the observation during an isolated thunderstorm event on 31 March 2010 when the radar was running on a trial basis. The convection, observed in the initial stages of the event, was observed up to a height of $\sim$11 km, but was short-lived (about 30 min, between 1550 and 1620 LT). Following convection, both transition (an intermediate stage between convection and stratiform rain; Rao et al. 2001) and stratiform rain is observed. The radar bright band, an indicator of stratiform rain (Williams et al. 1995; Rao et al. 2008), is also observed in spells at around 4.35-km height. The Doppler velocity of the rain is found to be $\sim$11 and $\sim$6 m s$^{-1}$ during and after the convection, respectively. It may be noticed that the convective stage is associated with large Doppler spreads, indicating high levels of turbulence and the presence of a wide range of raindrops. It is interesting to see the radar-detected GPS sonde flight track, seen as a slant straight line in Fig. 13 during 1750–1800 LT. The corresponding surface rainfall shows large values ($\sim$45 mm h$^{-1}$) during rain from convective clouds and light rain from stratiform clouds.

Figure 13(middle) shows the observations made by the profiler when this region is under the influence of Cyclone Laila. Though the cyclone path is about 100 km from the radar location (in the Bay of Bengal), the rainbands of the cyclone passed over the radar site on 19 May producing a good amount of rainfall. Steady rain spells were observed during this period. The bright band can be seen throughout the event at 4.5-km height. The Doppler velocity of the rain is found to be $\sim$11 and $\sim$6 m s$^{-1}$ during and after the convection, respectively. It may be noticed that the convective stage is associated with large Doppler spreads, indicating high levels of turbulence and the presence of a wide range of raindrops. It is interesting to see the radar-detected GPS sonde flight track, seen as a slant straight line in Fig. 13 during 1750–1800 LT. The corresponding surface rainfall shows large values ($\sim$45 mm h$^{-1}$) during rain from convective clouds and light rain from stratiform clouds.

Figure 13(right) shows the observations made by the profiler during a severe thunderstorm (producing heavy rainfall) that occurred on 5 July 2010 are shown in Fig. 13(right). In this particular case, severe convection for a long duration is observed,
followed by stratiform precipitation. Heavy rainfall is recorded at the surface during the convection. Both updrafts and downdrafts can be observed in this case. The positive Doppler velocity indicates the presence of strong updrafts, which are so strong that they carry hydrometeors upward. The bright band can be seen clearly at about 4.5-km height during the stratiform precipitation (1630–1830 LT). These results are found to have similar characteristics to those presented earlier by Krishna Reddy et al. (2002) using the old wind profiler at Gadanki.

5. Conclusions

A 1280-MHz wind profiling radar is successfully designed and developed with simplified active array configuration and a passive beam-forming network. Observations are made with very good temporal and spatial resolutions. The profiler is validated by comparing the measured winds with those obtained by a collocated GPS sonde. The cost of the active array is minimized by using transceivers with commercially available communication components. The nature of an active array significantly enhances the SNR (or range coverage) and allows for a reduction of antenna size when compared to a passive array for the same performance. This aspect has been demonstrated by comparing results obtained by the 64-element active array wind profiler with those of a 576-element passive array profiler. A passive 2D modified Butler matrix is employed to generate beams in the 2D angular space. The beam-switching mechanism is carried out simply by controlling a low-power, high-speed, solid-state, single-pole-multi-through switch appropriately. The performance of this WPR is superior, as it employs fully active aperture antennae. Because of the passive beam-forming network, no maintenance or calibration is needed for the radar beam pointing. This WPR has been deployed at three locations in last 12 months, without any downtime. Further, as each antenna has its own transceiver, the failure of a few transceivers...
will not affect the performance of the system because of graceful degradation. In essence, the simple active array configuration leads to compact (transportability), low-cost (multiple production), calibration-free (simple), and high-performance (superior spatial and temporal resolutions and height coverage) wind profilers. However, the radar beam is broader because of the smaller array size and leads to spectral broadening though it may not affect the mean Doppler (or wind) measurement.

The development of a larger 1280-MHz simple active array wind profiler with a 256-element (16 × 16) array is at an advanced stage at NARL. This system, built as a follow-up to the 8 × 8 array radar, is undergoing trial runs. Both radars are identical except for the size of the array and beam formers. A detailed technical presentation of the 256-element array profiler along with the initial results will be presented in a separate paper. A simple active array configuration can also be adopted for building a 400-MHz class of wind profilers, which are potential candidates for an operational network because of their height coverage. Research is in progress to adapt the transceivers and beam formers for a 430-MHz wind profiler.

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