Wind profiler and radio acoustic sounding system at IMD, Pune: Some preliminary results

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A 404 MHz Wind Profiler/Radio Acoustic Sounding System fabricated by the Society for Applied Microwave Electronics Engineering and Research, Mumbai has been commissioned for utilization in the R&D mode at the India Meteorological Department, Pune. The system is capable of measuring all three components of vector wind, viz. zonal, meridional and vertical wind velocities. The system as configured has a typical height coverage of 6–10 km (depending on weather conditions) with a resolution of 300 m for wind and 2–3 km for temperature measurement. Regular observations with the system have commenced since June 2003. In this article we give a brief introduction to the system and present preliminary results for wind and temperature obtained during monsoon season 2003 and discuss the further application potential of the indigenously developed system.

The V/UHF radar systems capable of measuring all three components of neutral atmospheric wind, viz. meridional, zonal and vertical wind velocities, are generally termed as wind profiler. The return signals in these radar systems depend on the backscatter signals through Bragg scattering from turbulent fluctuations in radio refractive index in the neutral atmosphere which are caused by clear air density fluctuations and or also by Fresnel scatter²³. The mean wind at any given height carries these fluctuations/irregularities and thus the latter (and hence the backscatter signal) become a tracer of the mean wind velocity at that height. The backscatter signal naturally suffers a mean Doppler shift proportional to the average radial wind velocity. Measurement of this Doppler shift in three orthogonally placed radial beams leads to estimation of the mean vector wind. Wind profilers can be categorized based on the product of system’s average transmit power – aperture (size). VHF systems (operating around 50 MHz) and having average power aperture product in the range of or in excess of $10^5\ W\ m^2$ are capable of receiving detectable signals from all three regions of the neutral atmosphere, viz. mesosphere, stratosphere and the troposphere and are called ‘MST’ radar systems; there are a few MST radar systems the world over and India has one at Gadanki near Tirupathi in Andhra Pradesh. At NMRF, Gadanki a 1357.5 MHz boundary layer wind profiler has been commissioned under a Japanese collaboration programme. This system has a peak power aperture product of $1.2\times10^4\ W\ m^2$ and measures only winds from a few hundred meters to about 3 km.

A large number of profiler systems have been operational mainly in USA and Europe, which operate in the 400 MHz or 900 or 1200 MHz band of frequencies. The systems in the large network of 449 MHz profilers in USA have an average power aperture product value of around $3\times10^3\ W\ m^2$ and can obtain mean horizontal wind profiles, the height coverage of which varies from 6 to 16 km depending on the atmospheric conditions at the site². In India the only 400 MHz wind profiler system now available was developed by the Society for Applied Microwave Electronics Engineering and Research (SAMEER) in 2001 under the sponsorship of DST, New Delhi. The system has since been recommissioned on Pashan campus of India Meteorological Department at Pune and is being regularly operated as an R&D unit. The system has also an accessory acoustic attachment which enables the profiler to be operated in the Radio Acoustic Sounding System (RASS) mode, enabling measurement of atmospheric temperature profile to the heights of around 2 to 3 km.

Currently under a DST-sponsored project, the Indian Institute of Tropical Meteorology (IITM) located close to the system site is entrusted with the responsibilities of system operation and data archival in collaboration with the India Meteorological Department.

In this article we describe salient technical features of the system, signal processing procedures followed for quality control of the data products, and also present typical/representative data products such as typical power spectra leading to profiles of meridional, zonal and vertical winds and hourly averaged wind speed (ws) and wind direction (wd) profiles. A trend comparison has also been done between monthly average ws and wd values obtained from Radio sonde/Radio wind (RS/RW) (Mumbai), Pilot Balloon normals of Pune and that obtained by WP/RASS over the period of June–September 2003.

System description

The system consists of a dual polarized coaxial collinear antenna array made out of low loss dielectric RF coaxial
cable of 7/8" size. A parallel feed arrangement of two-way/five-way power dividers/combiners is made in slab line structures which feed the two polarization arrays. The two arrays are aligned along true N–S and E–W directions respectively. A set of high power coaxial configuration RF relays are used in conjunction with the five sets of four-way power dividers to suitably phase the arrays to produce three beams, two tilted beams; one along the east, the other along south and the third looking at zenith. A high power solid state diode duplexer is used to switch the antenna array to transmitter port during transmission and to receiver port during inter pulse period. A block schematic of the radar system is shown in Figure 1. The technical specifications of the system are given in the Table 1. More details of the hardware are described by Chande et al. We give below some important features of the receiver and signal processing system.

Coherent and incoherent integration

The Bragg scattering coefficient/cross section is normally defined in terms of volume reflectivity ($m^2/m^3$)$^{5,6}$. For a typical Bragg scatter this ranges from values of $10^{-13}$ to $10^{-17}$ $m^2/m^3$ in the troposphere$^6$. The return radar signal for a single pulse return is therefore very weak, and can be typically several decibels below the system noise floor. However, the atmospheric return signal has relatively long coherence time$^6$ and hence the signal-to-noise ratio can be improved considerably by (coherently) integrating certain number of range-gated returns. A time series of certain number of such coherently integrated samples/signals for every range gate is then used to compute the signal spectrum. Even the spectra obtained in this fashion can be quite noisy and hence in practice several such spectra are (incoherently) averaged before they are used for computation of moments (0th, 1st and 2nd) which respectively give us estimation of signal power (volume reflectivity), the (radial) wind velocity and the velocity spread (measure of turbulence).

Use of coding/pulse compression technique

Since the radar backscattered power depends directly on the pulse width of the radar pulse, one may think, therefore, that the radar range could be increased by increasing the pulse width of the transmit signal. However, the range resolution of the radar is better if the radar transmits a narrow (width) pulse. The other way is, of course, increasing the transmit power of the radar and transmitting a narrow pulse to maintain a fine range resolution. However this latter option is rather costly and much more technically involved. The way out of the situation, that of maintaining a high average transmit power and yet obtaining fine enough range resolution is to use the technique of a pulse compression$^6$. In time domain pulse compression can be easily implemented by way of phase coding, especially binary phase coding, which lends itself conveniently for digital processing of the signal.

In phase coded waveforms a long pulse is divided into $M$ number of short bauds (subpulses) of equal duration. The phase of each baud (subpulse) is selected in accordance with a suitable phase code. In binary phase coding one uses phases of 0° or 180° for the subpulses depending on the baud code elements represented by either +1 or –1 respectively. If the target remains phase coherent for sufficiently long time, the radar return can be processed or decoded in such a way that it is equivalent to a return received from a pulse of one baud width but almost $M$ times the actual transmitted peak power. The received signal in that case is decoded by cross correlating the signal with a replica of the transmitted pulse. In the profiler system being reported upon an 8 bit coded signal with 2 µs baud length is used.

Out of numerous binary phase codes, the complementary codes$^7$ have been found quite suitable for use in profiler

![Figure 1. A block schematic of the radar system.](image)

**Table 1. System specifications**

| Operating frequency/bandwidth       | 404.37 MHz/± 0.250 MHz |
| Pulse repetition period            | 60 µs /160 µs         |
| Pulse width                        | 2 µs (uncoded); 16 µs (8 bit coded) |
| Peak transmit power                | 16 kW                 |
| Duty ratio                         | 10% Maximum           |
| Unambiguous radial/velocity resolution | 15.7 mps/0.2 mps     |
| Number of coherent integration     | 76                    |
| Number of incoherent integration   | 10                    |
| Number of FFT points               | 256/512 (selectable)  |
| Acoustic output power for RASS mode| 100 W (nominal)       |
Signal processing and system RF/video gain

The RF/IF/video system gain in profiler radar could be as much as 100 dB or more. The decoding and signal processing in a modern receiver are invariably performed by digital techniques. The time domain video signal after quadrature detection is therefore passed onto a suitable A/D converter. The RF/IF video gain is to be so designed that the lowest expected atmospheric signal gets amplified to a level of at least one or two lowest bits of the A/D converter at its inputs without saturation of any RF/IF video stages and the A/D converter by the system noise. When and only when, this condition is satisfied the digital processing gain (through decoding, coherent integration and spectral processing) can be realized leading to improvement in signal detectability.

Coherent integration and unambiguous spectrum measurement angle

We have already indicated that single pulse returned from clear air is very weak and hence certain numbers of range gated returns are integrated to improve the S/N ratio before computation of spectra and detection. Although atmospheric clear air signal has relatively long coherence time and such integration is feasible, one must realize that higher coherent integration time automatically narrows the unambiguous measurement range of the Doppler shift frequency which in turn limits the unambiguous measurement range of the radial velocity. If $\tau$ is the inter-pulse period, the effective integration time is $n_c \tau_i = T$ for $n_c$ number of pulses coherently integrated. Thus the sampling period of the time series used for evaluation of the spectrum is $T$. This means, by the sampling theory, Nyquist frequency or the unambiguous frequency would be $(1/2T)$ and measurement could be done unambiguously up to Doppler frequency of $(1/2T)$ in the spectrum. Thus,

$$f_{\text{max(ambiguous)}} = \frac{1}{2T} = 2v_{\text{max}}/\lambda.$$

Therefore the maximum radial velocity which could be unambiguously measured would be

$$v_{\text{max}} = \lambda/4T.$$

Signal processing hardware/software

The Pune system has a coherent I-Q channel receiver subsystem which passes on the video signal to a 14 bit A/D converter located on a DSP board placed in a PC slot in a standard PC environment. The DSP card carries out operations like decoding (for coded mode of operation), coherent integration and DFT calculations, and incoherent integration of a set number of spectra. The incoherently integrated power spectra for each beam position are then passed on to further offline signal processing, leading to estimation of first three moments corresponding to the power, Doppler shift (proportional to mean wind velocity) and the spectral width (a measure of the turbulence). From the radial velocities measured in the three beam positions the meridional, zonal and vertical velocities are calculated. In the higher height mode of observations, a four-pulse sequence of complementary codes, such as A, A’, B, B’ are used where A and B are 8 bit complementary codes and A’ and B’ are inverse of A and B respectively. The use of subsequent digital signal processing, where A, A’ and B, B’ are suitably added before passing the complementary pair code for appropriate decoding, eliminates any instrumentation dc bias.

The clutter problem

A common problem with wind profilers, particularly in the lower height mode of operation, is the presence of ground clutter. This radar is no exception to this and the present approach to tackle/minimize this problem is two-fold, namely, (i) Erection of almost a $2\lambda$ wavelength clutter fence around the antenna array; (ii) Enforcing a null at the zero frequency in the spectral plane and interpolation over the clutter peak. This however does affect the measurement of atmospheric signal with a truly or close to zero velocity since some of the Doppler bins in the vicinity are also slightly affected by this procedure.

In addition to the clutter, there is at times the problem of 50 Hz electrical supply modulation which introduces stray spectral peaks. These peaks however tend to be symmetric in the spectral domain and are easily identified leading to their elimination.

Quality control of data

Signal continuity modelling

Before embarking on the calculation of the spectral moments, the average noise in the spectral frame for each range bin is estimated by using the Hildebrand/Sekhon algorithm as is the standard practice in profiler work. The atmospheric signal in each spectral frame (corresponding to radial velocities) is then identified by using a multiple peak detection scheme in conjunction with a suitable check on the continuity of the signal between consecutive range bins. The continuity scheme, at present, uses a spectral window of width equal to 1/5th of the Nyquist frequency (the unambiguous velocity) centered around a well-defined peak at a lower range bin where the signal-to-noise ratio is suf-fi-
ciently large. The scheme thus picks the maxima in the spectrum in successive range bins consistent with this model restriction. This model has the limitation, it may be noted, in that it imposes a compounded threshold, imposing simultaneously a limit on speed shear as also angular shear and the two cannot be selected independently. This is to some extent similar to the median filtering on meridional and zonal winds as used by some researchers while processing the NOAA profiler data. The algorithm is also partly similar to the procedure followed by May et al. There is scope for further modifications in the scheme for improving on the continuity model and this matter is under discussion with the SAMEER design team so that they could make modifications in their source code of offline signal processing software.

**Consensus averaging**

Each of the three spectral frames corresponding to the three beams are normally obtained in 4–6 min depending on the number of coherent integrations, incoherent integration and the number of FFT points used in the observations. Thus in a span of about one hour of observation period a total of at least ten sets of Doppler profiles are available. Moments of each of these sets are estimated to calculate the power, radial velocities and the spectral width for all the observed range/height bins. The radial velocity values for each beam obtained for a given range bin, over the total observation period are then passed through a process of consensus averaging which helps to eliminate to a large extent the effects of transient interfering signals, outliers and random spiky, noise. The consensus averaged radial velocities are then used to calculate the zonal, meridional and vertical wind velocities representative of the mean wind in the hour of the observation. The equations are

\[
\begin{align*}
    u &= (v_{\text{re}}-w\sin\theta)/\cos\theta, \\
    v &= (v_{\text{mn}}-w\sin\theta)/\cos\theta, \\
    w &= v_{\text{rz}},
\end{align*}
\]

where \(v_{\text{re}}, v_{\text{mn}}\) and \(v_{\text{rz}}\) are the consensusly averaged radial velocities, along east, north and zenith respectively; \(u, v\) and \(w\) are zonal, meridional and vertical velocities and \(\theta\) is the elevation angle of the tilted beams. The mean horizontal wind speed and direction are calculated as

\[
    ws = \sqrt{u^2 + v^2}, \quad \text{wd} = \tan^{-1} u/v,
\]

where \(v\) is along the north and \(u\) along the east. There is an alternate provision to introduce consensus averaging on the 6 min \(u, v\) data from which hourly average \(ws\) and \(wd\) can be calculated. This provision would be particularly useful in the presence of intermittent precipitation during hourly observation.

**Temperature profiling**

**The RASS option with the wind profiler radar**

As noted earlier, the refractive index gradient fluctuations caused by turbulence lead to RADAR backscatter. In a profiler, the mean wind which carries the fluctuations with it give rise to Doppler shift of the radar return signal which is proportional to the mean wind velocity. Let us consider a situation where an acoustic wave at a wavelength \(\lambda_a\) is propagating vertically upward in the atmosphere above the site where profiler radar is located. The propagating acoustic wave creates regions of compressions (higher density) and rarefactions (lower or zero density). The distance between successive compressions or rarefactions is equal to \(\lambda_a\). If the wind profiler radar is simultaneously operating at a (radio) wavelength \(\lambda_R\) and if \(\lambda_R = 2\lambda_a\), the radar backscatter from the successive compression can add in phase enhancing the intensity of the backscatter; since the acoustic wave is propagating at the velocity of sound at the given height in the atmosphere, the measurement of the signal Doppler shift leads to estimation of temperature since the speed of sound is dependent on it. The propagating acoustic wave has in effect created ‘frozen in-discontinuities’ in the refractive index gradients in the atmosphere. The condition that \(\lambda_R = 2\lambda_a\) is known as the ‘Bragg match condition’. We however note that the temperature in the atmosphere varies with the height and hence the speed of sound would vary with height as the wave propagates up. If only a single acoustic note/frequency is set up for transmission, the Bragg match condition would not be valid at all heights in the atmosphere; the problem is overcome by transmitting a series of acoustic pulses over a certain range of frequencies depending on expected variation of the acoustic velocity in the atmospheric region of interest, so as to maintain the Bragg match condition up to the desired height.

In the wind profiler operating with ~74 cm (404 MHz), the range of acoustic frequency lies between 800 Hz and 1000 Hz to cover the Bragg match up to heights of over 3 km. The radar receives strong echoes from this artificially generated reflectivity grating and the resulting Doppler shift of the radar return signal is a measure of local sound speed in the particular radar volume. The local sound speed \(C_s\) is related to the virtual temperature by the relation

\[
    T_v = \left(\frac{C_s}{20.047}\right)^2.
\]

Therefore, a vertical profile of sound speed (measured/estimated from the Doppler shift of the radar return form the artificially created reflectivity grating) leads one to evaluate the vertical profile of virtual temperature in the atmosphere. The process or mechanism of RASS echoes is thus more or less deterministic, in contrast to the stochastic nature of clear air echoes generated by clear air turbulence which is advected through the radar volume by the background wind, leading to measurement of the latter from the Doppler spectrum estimates of the clear air echoes.

In RASS the speed of sound measured by radar is affected by the local air motion and the velocity of air must be
subtracted from measured $C_a$ to obtain accurate temperature measurements. If $w$ is the vertical wind speed (or the radial wind speed as measured by the radar) we may write:

$$T_v(\circ C) = \frac{(C_a - w)^3}{401.92} - 273.16.$$ 

It can be seen that a vertical wind speed of 0.3 m/s would result in a temperature error of about 0.5°C unless the air motion is properly measured and subtracted from the RASS data. It is tacitly assumed in the above that the radar volume is a dry atmosphere. This is not true in the lower tropospheric region where RASS temperature profiling experiments are carried out and give useful information. Typically for relative humidity of around 30%, $\beta \sim 0.744$. This humidity correction could be applied if surface humidity and lower tropospheric (height) humidity readings are available from observations of RS/RW sounding experiment at the site of the profiler/RASS.

The frequency range of acoustic transmissions for RASS experiment can be estimated from the lapse rate of temperature with height. In the typical Indian tropical lower troposphere, the lapse rate of temperature is close to 6.5°C/km. Over a height range of 3 km (over which RASS echoes are expected), the temperature decrease would thus be close to 20°C from the surface temperature value. Taking the surface temperature as equal to 300 K, we calculate that the Bragg match acoustic frequency range for the 404 MHz profiler/RASS combination would be approximately between 980 Hz and 940 Hz, i.e. an acoustic band width of 40 Hz. In practice one may use a linear acoustic sweep of sweep width 40 Hz or a stepped approximation to such a sweep. The Pune system hardware uses a digital acoustic step frequency generator with a programmable step size.

**Observations and discussion**

The observations during the southwest monsoon season (June–September) at Pune are taken as a pilot study. The number of observations and the heights up to which data are obtained are shown in Figure 2 with statistical details in Table 2. The lowest height coverage is 1.05 km; this limitation arises because of finite recovery time of the duplexer (diode) subsystem which is typically 4 $\mu$s.

<table>
<thead>
<tr>
<th>Table 2. Statistics of daily height June–September 2003 (km)</th>
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<tbody>
<tr>
<td>Mean</td>
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<tr>
<td>Mode</td>
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<td>Median</td>
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<td>Standard deviation</td>
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There has been no opportunity so far for direct comparison of the WP/RASS data with onsite measurements by other techniques. WP data is therefore compared for the trends with the available monthly average normal winds from RS/RW Mumbai, Pilot Balloon data of Pune and current monthly average of RS/RW data for Mumbai for the months June–September 2003. These trend comparisons are encouraging as can be seen from Figures 3 a, b and 4 a, b shown for July 2003. Only higher height (> 3 km) data from WP system is used for comparison with the Mumbai RS/RW data, since lower height winds are more prone to local features. All the data sets clearly show a decreasing wind speed up to 5–7 km which then increases for higher heights. Wind direction changes from south/south-westerly to north/northeasterly for both the data sets. Change over occurs between 6 and 8 km. Standard deviation values of the wind speed for July 2003 for WP/RASS and RS/RW are comparable.

The RASS system also measures atmospheric virtual temperatures which are obtained by measuring the Doppler shifts from the ‘frozen in discontinuities’ created by the traveling acoustic wave. Bragg matched spectra (35 in number) are averaged to obtain one temperature profile in about one minute. A set of five such profiles are then averaged to obtain the average virtual temperature profile over a five-minute period.

The normal temperature values for Pune are taken from records of RS measurements carried out by IMD. Figure 5 shows a comparison of the WP/RASS measured profile for July 2003 and corresponding normal profile as deduced from IMD RS measurements. Although the trend of the two profiles matches; there appears a constant bias of approx. 2.8°C, the WP/RASS values being consistently higher than the RS data normal values. The difference of a maximum of about 0.8°C is explainable since WP/RASS measures virtual temperatures. This issue is being further looked
Figure 3 a, b. Trend validation of wind speed (July 2003).
Figure 4a, b. Trend validation of wind direction (July 2003).
Figure 5. Comparison of RASS temperature with RS normal, Pune, July 2003.

Figure 6. Typical power spectra for NS, EW and zenith beams.
into. Figure 6 shows typical display of power spectra for the three beams as observed from which moments are estimated leading to computation of $u$, $v$ and $w$.


ACKNOWLEDGEMENTS. The work was carried out as part of a project sponsored by DST, New Delhi. We thank DG, IMD and D. R. Sikka for continuous support and encouragement during the work.

Received 7 November 2003; revised accepted 17 June 2004

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