Doppler radar – A detecting tool and measuring instrument in meteorology

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India Meteorological Department has entered into a new era in exploring the atmosphere with the induction of state-of-the-art Doppler weather radar technology in its cyclone detection radar network. This article describes the salient features of the Doppler weather radar installed at Chennai. Use of Doppler technique combined with digital technology makes it possible to measure directly the wind component along the axis of the radial beam along with range-finding, in addition to a large number of derived products which become available in real time. A few typical examples of multifarious products available from this radar are presented. The scope for its utility in operational weather forecasting, particularly in the fields of cyclone warning and aviation has been highlighted.

RADAR, an instrument developed for detection and range-finding aircrafts and successfully used during World War II, has proven its utility in many fields like meteorology, space research, air traffic control and so on. Initially, weather echoes used to be noise or unwanted signal for radar users. Later, through studies of the signal returned by the hydrometeors (water droplets, etc. in a cloud), much has been achieved in the fields of radar meteorology and atmospheric science. In the past few decades weather radar technology has grown by leaps and bounds, thereby enabling us not only to detect and range-find weather phenomena but also to collect a sea of information revealing their internal structure and hazards that might be harboured therein. The first meteorological observations using radars date from 1940s, as part of efforts to develop equipment to analyse the echoes due to natural precipitation. Earlier radars were of continuous wave-type with separate antenna for transmission and reception (bi-static). Later versions using pulse technique made it possible to use the same antenna (mono-static) for both transmission and reception[1]. By 1960s, radars capable of making quantitative hydrological and speed measurements of the weather systems had become available. Considerable progress was made in the development of data reduction, analysis and display techniques during that period. During the late 1960s, frequency-modulated continuous-wave (FM–CW) radars were developed to have resolution as small as one metre and used to study the Kelvin–Helmholtz shearing instability, internal gravity wave, etc. Thanks to the recovery by the radar of the VHF and UHF fields, the ‘clear air detection technique’ was developed during the 1970s. Depending on the sensitivity and the frequency of operation, measurements in the troposphere and stratosphere can be made in the UHF band (400–1200 MHz), and such radars are called ST (troposphere–stratosphere) radars.

In the VHF band (50 MHz), measurements are possible in the mesosphere also and these radars are known as MST (mesosphere–stratosphere–troposphere) radars. In the low VHF band (40–50 MHz), echoes caused by the Bragg scattering due to variation of humidity and temperature can be measured in clear air as well as in cloudy weather conditions. The MST radars vertically probe the atmosphere up to a height of 100 km. In these radars, the Bragg-scattered or Fresnel-reflected electromagnetic radiations which are frequency-shifted by the moving irregularities are used to estimate the wind velocity through fast Fourier transform (FFT) technique. With improved technology, these radars act as wind profilers to give wind information atop one km above ground level.

One of the greatest advances in radar technology took place in the early 1970s with the development of Doppler radar. The Doppler effect as applicable to electromagnetic radiation is exploited in the design of this instrument. While conventional weather radars can look deeper into a weather system to provide information on intensity, rain rate, vertical extent and provide some information about the liquid water content of the cloud mass, the capability to probe internal motions of hydrometeors and hence to derive velocity and turbulence information has become available only after the advent of Doppler weather radars (DWR). DWR can not only detect the position and strength of weather echoes, but can also measure the speed

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of the multiple tiny targets in them towards or away from the radar (radial velocity). For more details of evolution of radar technology from continuous-wave to pulse-mode radars and thereafter to Doppler, dual-polarization capability radars, and the quantum jump from the erstwhile analogue oscilloscope-type display to the colour-coded computer-based digital displays, the reader is referred to Skolnik[2], David Atlas[3], Doviak and Zrnic[4] and Rinehart[5].

Although satellite-borne visible and infrared cameras can detect and track storms, the radiation sensed by these cameras cannot probe deep inside the storm's shield of clouds to reveal its internal structure. Information on the number of particles having different velocity ranges inside a weather system provided by DWR reveals the internal structure of the system in terms of turbulence, relative motion of particles inside the cloud mass, etc. This unique capability renders DWR an instrument of choice to survey the wind and water fields of storms and the environment in which they form. High-sensitive receivers used in the modern DWRs enable them to sense returns even from clear air turbulence and refractive-index discontinuities. Velocity information from clear air returns made it possible to use DWR for wind profiling in the troposphere, though with limitations. Thanks to the technological advancement in the field of computers, digital signal processing and data communication, many limitations of the radar have been overcome. This has transformed the Doppler radar from a specialist research tool into a basic source of information for the benefit of the masses. Doppler radars are now used in operational weather networks in many countries.

Overview of radar principles

Primarily, the radar consists of a transmitter to generate microwave signal, an antenna to send the signal out to space and to receive energy scattered (echoes) by targets around, a receiver to detect and process the received signals and a display to graphically present the signal in usable form. Magnetrons, klystrons and travelling wave tubes still continue to be the main powerhouse of most radars. They are used in radar transmitters to produce microwave energy of required wavelength and intensity. Though solid-state transmitters have become available, they have not overtaken the age-old vacuum tube technology so far due to their limited power.

The antenna collimates the microwave energy into a narrow beam while sending it out. Larger the size of the antenna, better the angular resolution. The antenna generally rotates about a vertical axis scanning the atmosphere in azimuth. It is also capable of changing its elevation by rotating about a horizontal axis so that probing of the hemispherical volume of the atmosphere with radar as the centre is possible, according to the scanning strategy decided by the user. Figure 1 shows the DWR block diagram.

A pulsed radar sends out a high-power signal for a brief duration (typically a few microseconds) and then waits for the echoes of the signal from the targets around the radar to reach the antenna. After waiting for sufficient time (typically a few milliseconds), the next pulse is sent out. As the signal pulse travels at the speed of light, it does not take more than a few milliseconds for the signal to cover several hundred kilometres and get back to the radar with a wealth of information. Modern radar receivers are mostly solid-state super-heterodyne type, in which the received energy is mixed with a reference signal of different frequency for scaling it down in frequency for ease of processing. After down conversion, the information contained therein is filtered out and sent for further processing and display. Echoes of meteorological relevance span a wide range of the power spectrum say, from – 110 dBm to about 0 dBm. A single receiver with such high dynamic range (the difference between the weakest and strongest power that it can handle) was difficult to design. Till recently, two receivers, one with logarithmic output to handle higher power and another with linear output to handle weaker power were used. However, radars with single linear receiver and dynamic range higher than 100 dB have now become available.

In modern radars, signal processing is done by dedicated computers incorporated within the system. They are generally known as signal processors. Many commercially available off-the-shelf digital signal processors (DSPs) may be linked together to meet the computational requirement. The signal processor unit performs analogue to digital conversion, quality assurance and applying various corrections to the dataset in addition to performing complex statistical signal-processing jobs. Radar displays are of different types. Plan position indicator (PPI), range height indicator (RHI) amplitude range scope (AR scope), constant altitude PPI (CAPPI), described later in the article, are a few to mention. Earlier radars used dedicated

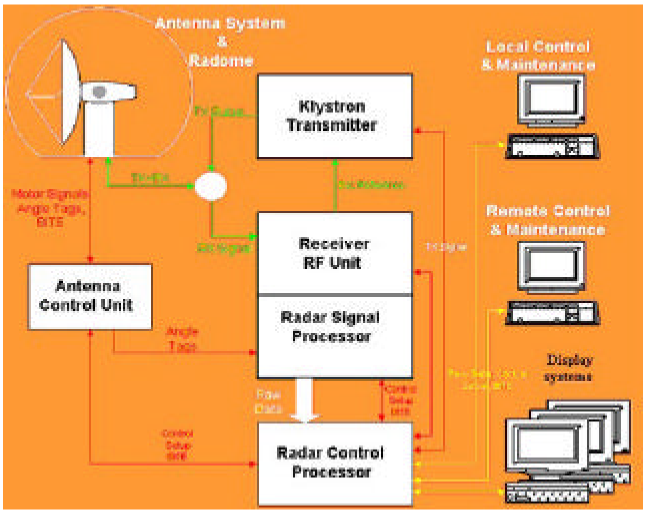

Figure 1. Doppler weather radar block diagram.

cathode ray tubes to display the echoes. Modern radars use computer displays for displaying their products as discussed later in the article.

Weather radars

Radars used in meteorology are mainly distinguished by their operating frequencies. Widely used frequency bands in weather radars are X-band (10 GHz, wavelength $l = 3$ cm), C-band (5 GHz, $l = 6$ cm) and S-band (3 GHz, $l = 10$ cm). X-band radar is used for thunderstorm studies and tracking of airborne balloons for upper-air wind computation. S-band radar is used for rainfall measurements and studies of tropical cyclones and similar synoptic-scale systems. S-band frequency is more suitable for penetrating deep into intense weather systems without much attenuation, whereas they are not suitable for cloud-physics studies as the reflections are too weak from cloud particles. Moreover, size of the antenna and other system components is much bigger in S-band in comparison to other types of radar. C-band radar is a compromise between X-band and S-band radars. C-band radars are widely used in research and operational meteorology. India Meteorological Department (IMD) adopted radar technology for meteorological applications in the early fifties. However, the first indigenously designed and manufactured X-band (9375 ± 20 MHz) storm-detection radar was installed in IMD in 1970. Since then a large number of weather radars in both X-band and S-band have been installed by IMD for storm and cyclone detection. Most of these radars are of the type pulsed-monostatic.

Apart from radars using the above band of frequencies, there are those using much higher frequencies (millimetre wavelength) for cloud-physics studies and much lower frequencies (larger wavelengths) for wind profiling purpose; but these are mostly used in research mode. Mention may be made here of an MST radar functioning at National MST Radar Facility under the Department of Space at Gadanki in Andhra Pradesh, mainly for research purpose. Based on the capability to measure wind, weather radars can be divided into two types, conventional radar measuring reflectivity alone and modern Doppler radar measuring radial velocity (V, component of absolute velocity towards or away from the radar), velocity spectrum width (W, which is a measure of dispersion of velocities within the radar sample volume) and reflectivity (Z) explained in detail later in the article. In DWR, the Doppler effect as applicable to microwaves is exploited; of course, here both the source and observer are colocated, but the echo-producing targets are moving. Since the forward and return trips are subjected to this effect, the frequency shift, which is a measure of relative velocity, is doubled.

In analogue radars, the receiver output is monitored and processed continuously. However, in digital radars, the receiver output is monitored at regular but fast intervals of the order of a microsecond or less, and the instantaneous output power is digitized and used as the representative echo power for the sample volume between that and the next sample. Instantaneous power output of the receiver contains returns from a fixed volume of the atmosphere called range bin. The bin size is a function of pulse width and antenna beam width. For a nominal 1 μs pulse and 1° wide beam, the bin size would be 150 m × 1°. For a receiver sampling rate of 1 μs, inter-bin spacing would also be 150 m. In the above scenario, the signal processor would get data samples 150 m wide in space repeated every 150 m, giving a continuous effect.

For a maximum range of 300 km, pulse repetition frequency (PRF) should be less than or equal to 500 and the corresponding inter-pulse listening period would be 2 milliseconds. Assuming antenna scan rate of 3 rpm, scan period for 1° in azimuth would be around 56 ms during which period, returns from nearly 28 pulses would be available for processing. Averaging *returns* from 28 pulses would improve the quality of data by filtering out random noise-signals. This is known as time-averaging.

A series of data points or bins thus obtained by averaging returns during the period between two antenna positions separated by 1° constitute a ray. Data acquisition is done bin-by-bin to form a ray, ray-by-ray to form a slice and slice-by-slice to form a quasi-cylindrical volume. As the short-pulse width is 1 μs, the smallest possible radial resolution is 150 m while the azimuth and elevation resolutions vary continuously throughout the ray due to beam-spreading, with range at the rate of about a km for every 60 km. It is meaningless to process data with a range resolution of 150 m when the azimuth and elevation resolutions are of the order of 5 to 6 km. In such situations, if a few range bins are clubbed together and treated as a single data point, the load on the processor can be reduced without sacrificing the data quality. This is known as range-averaging. The number of range bins clubbed together can typically be 2 to 8 depending on other scan parameters such that the resolution in all three dimensions is of the same order.

Digital signal processors

DWRs employ high dynamic-range linear receiver and DSPs to extract information from the received echo power. Linear receiver output in intermediate frequency (IF) and analogue form is converted to digital form in the analogue-to-digital converter and fed to digital filters to split the power into in-phase (I) and quadrature (Q) components. DSPs process the raw I/Q data and perform phase and amplitude correction, clutter filtering, covariance computation and produce normalized results. These normalized results are tagged with angle information, headers and given out as a data set. Covariance computation is based on pulse pair processing. This includes computation of the autocorrelation functions $R0$, $R1$ and $R2$ at selectable lags. Since the signal is complex linear in nature, intensity estimation consists simply of integrating the power in the linear channel ($I^2 + Q^2$) over range and azimuth. The resulting power estimate is corrected for system noise, atmospheric attenuation and transmitter power variations. The signal processing of the linear channel ends with the estimation of reflectivity, mean radial velocity and velocity spectrum width.

Doppler principle as used in radar and its limitations

Elementary knowledge of wave physics is sufficient to understand that if the difference in path traversed by two consecutive radar pulses (due to radial shift of target position during the pulse interval) is less than or equal to one wavelength of the radar, the same is unambiguously distinguishable and accurately measurable in terms of the phase difference between the two consecutive echo pulses received (provided the pulses are coherent). Path difference in excess of this limit will create an ambiguity in determining the phase difference (in excess of 2Π rad). Half of the phase difference is due to the forward trip and the other half is due to the return trip. Thus, only half of the observed path difference and corresponding phase shift is due to change in position of the target, limiting the maximum usable phase shift to Π rad. Half of this ($\Pi/2$ rad) is used to measure positive radial motion and the other half for the negative radial motion. $\Pi/2$ rad phase shift corresponds to quarter wave length ($l/4$) path shift. In this way, it is not difficult to visualize that the maximum unambiguously measurable velocity is equal to quarter wavelength ($l/4$) times the pulse repetition frequency (PRF). Symbolically, the same is expressed as $V_{max} = (l/4)$ *PRF.

Longer wavelength radars can measure larger radial velocity unambiguously for the given PRF. Larger the PRF, larger the radial velocity measurable unambiguously from a given radar. Unfortunately, larger the PRF shorter the unambiguously measurable range [$R_{max} = C/(2*\mathrm{PRF})$]. Thus there is a compromise between maximum unambiguous range and velocity, the product of which is a constant ($Cl/8$), where C is the velocity of light. This is widely known as *Doppler dilemma*.

Some special features available in modern DWRs

Frequency agility for reducing the acquisition time

Transmit-frequency is shifted by 1 MHz from pulse to pulse for four consecutive pulses and the cycle is repeated. This facility is used to increase the equivalent number of independent samples for the given antenna scan rate (time integration). Increase in the number of independent samples enhances the accuracy of the estimation in both reflectivity and velocity.

Phase diversity for second-trip recovery

Pulsed radars are known to suffer from multi-trip or second-trip echoes. This happens when the first pulse of energy goes beyond maximum unambiguous range r_{max} and sometimes gets returned by a weather at a distance say r. The radar displays it at a distance ($r–r_{max}$) superposed on the normal display. Phase-coding of the transmitted signal is employed to filter out range-overlaid echoes. This phase-coding helps in identifying the second-trip echoes from the first-trip echoes for effectively filtering and displaying them in their appropriate range.

Staggered PRF for velocity unfolding

The maximum radar range is related to the PRF in inverse proportion, while the maximum velocity is related to PRF in direct proportion. Thus for a given range, there is an upper limit for maximum velocity measurable unambiguously. But there are techniques to double or triple the maximum unambiguous velocity by staggering the PRF or using dual PRF. Pulse-transmission rate is toggled from a high value to a low value and vice versa, for every set of fixed number of pulses. The velocity estimates from both sets can be combined suitably to increase the composite unambiguous velocity. Velocity aliasing can cause the two velocity estimates to vary significantly, and these differences can be used to resolve the true velocity. (For further details on these features, see refs 4 and 5).

Products and applications of weather radars

A number of products are available from weather radars. From non-Doppler radars, information on reflectivity factor alone is available, whereas from DWRs, in addition to reflectivity, radial velocity and spectrum width information are also available as base data. These data can be used directly for base-products display and also for deriving further products based on standard algorithms. A few products which are commonly used in operational meteorology are briefly described here.

Base products

Reflectivity factor (Z), radial velocity (V) and velocity spectrum width (W) are the three base data directly observed/measured by the radar. The radar reflectivity factor is defined as $Z = 10 \log_{10} [\sum (N_i D_i^6)/(1\ \mathrm{mm}^6/\mathrm{m}^3)]$, where N is the number of droplets of diameter D_i to $D_i + dD$, dD being the diameter interval used in making the measurements, present in unit volume of sample being probed. For the conditions prevailing in most of the weather systems and for the wavelengths used, the scattered power received back is directly proportional to Z (derived by Lord Rayleigh in 1870s). Hence the weather signal power available at the receiver output is a direct measure of Z. Autocorrelation of time series formed by the received power spectrum is the basis for deriving Z and other Doppler moments. The zeroth lag autocorrelation $R0$ of the time series is proportional to weather signal power, and hence Z is computed from it. Mean radial velocity of hydrometeors inside the sample volume is given by the first lag autocorrelation $R1$, and the velocity spread inside the sample volume is obtained from the first and the second lag autocorrelations $R1$ and $R2$ together, assuming a Gaussian distribution. The base data available from DWRs are generally displayed in the following formats.

PPI: The PPI(Z) is quite similar to conventional radar scope display of Z for a given elevation at all azimuth values, with colour-coded schemes for display and storage in digital form. This display is possible for all elevations at which data are collected. This product is available for display immediately on completion of the scan. This is the most widely used form of weather radar display. A typical PPI(Z) display has been depicted in Figure 2 *a*.

The PPI(V) gives the *radial velocity* (for a selected elevation) on a PPI scope (see Figure 2 *b*). The radial wind component towards (–ve) and away (+ve) from the radar site is of some importance for the tracking of weather systems and in aviation forecasting.

PPI(W), which shows the velocity spectrum width indicating turbulence, is of immense use in nowcasting the occurrence of microburst, wind shear, etc. for aviation. This product is used for issuing airfield warnings in some countries based on their experience to nowcast the possibility of turbulence in the airfield. A typical display of PPI(W) has been depicted in Figure 2 *c*.

RHI: This is another widely used form of display of base products in the two-dimensional Cartesian coordinate system, having the curvature corrected range as x-axis and height as y-axis for an elevation scan at a fixed azimuth. A similar display with more flexibility of selecting the cut axis is available from a volume scan of a modern DWR which is generally known as *vertical cut* and is shown in Figure 3.

CAPPI: This is a colour-coded display for an user-defined altitude of any of the Z, V or W in a PPI scope. As such, it displays weather phenomena as occurring over a curved surface parallel to the earth's surface. A typical CAPPI display is shown in Figure 4.

Maximum display: It is a display of three partial images into a single imagery (Figure 5). The central portion of

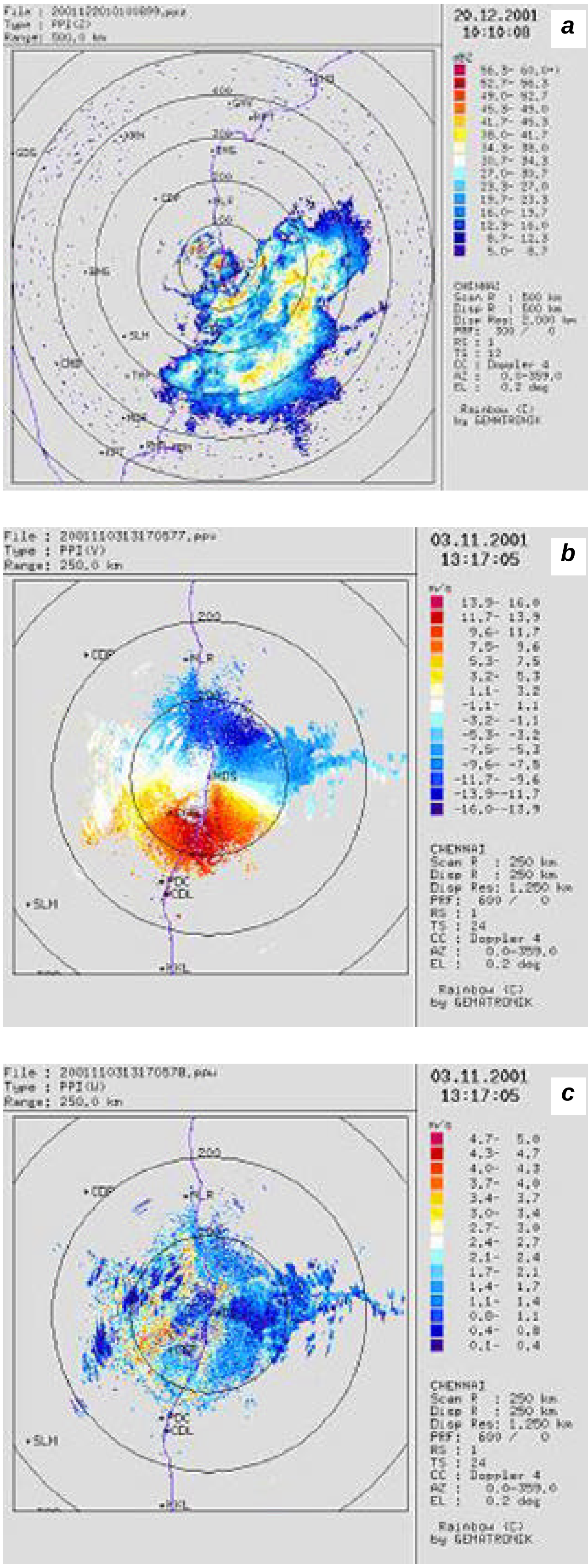

Figure 2. Plan position indicator display of ***a***, Reflectivity; ***b***, Radial velocity; and ***c***, Spectrum width.

the imagery is a PPI displaying the highest value of the parameter (*Z*, *V* or *W*) chosen for a volume scan. The top portion of the imagery is the north–south view of the highest measured value in Cartesian *Y*-direction. The right-hand side portion of the imagery is the highest measured value in the west–east Cartesian *X*-direction. Height scales are provided for *X* and *Y* direction view of imageries placed at the top and right-hand side.

Derived products display

The following derived products are generally available from a DWR.

Surface rainfall intensity (SRI): This is an image of rainfall intensity based on Marshall–Palmer equation[6] ($Z = AR^b$, where *R* is rainfall intensity and *A* and *b* are constants to be determined) for a user-defined layer. The values for *A* and *b* vary from season to season and place to place. Also the values of *A* and *b* predominantly depend on the type of cloud (drop size distribution). Data from disdrometers can be used for fine-tuning the values and data from rain gauges are used for calibrating the radar for rainfall estimation. The coefficients *A* and *b* have been empirically estimated based on the data collected from the DWR, Chennai and the surface rain gauges situated within 150 km radius circle from the DWR, Chennai during the period 30 October–20 November 2001. Though these values yielded good results when tested for rest of November and December 2001 (northeast monsoon season), it is to be tested rigorously and adapted for other seasons and different types of weather events before formulating a method for adjusting the *M-P* relation for a meaningful estimation of rainfall in the tropics. A typical SRI picture at 1214UTC (1744IST) of 13 May 2002 is shown in Figure 6 *a*.

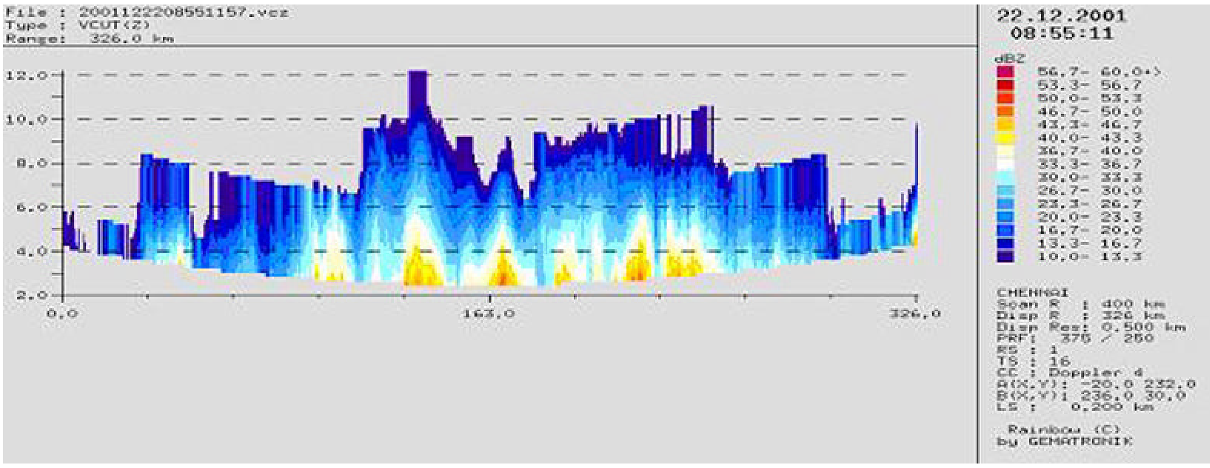

Figure 3. Vertical cross-section of a weather cluster in a selected orientation.

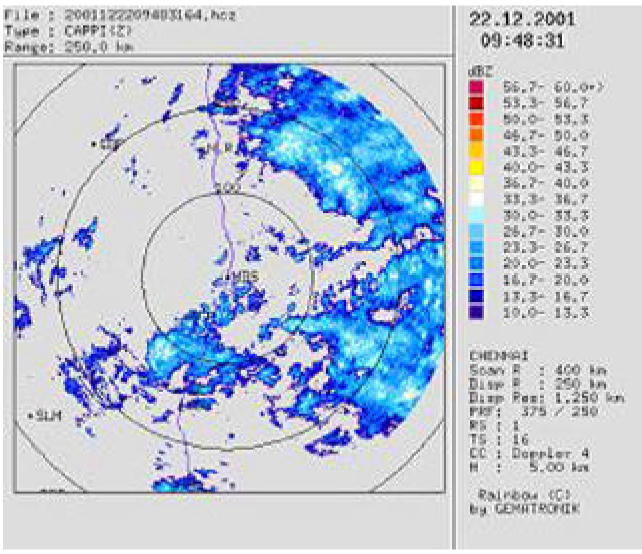

Figure 4. Constant altitude plan position indicator display of reflectivity.

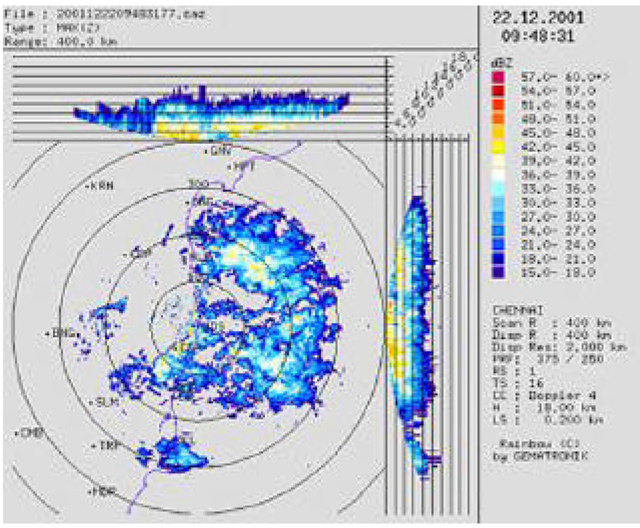

Figure 5. Maximum display of radar reflectivity factor.

The accumulated precipitation (*PAC*) *and long-term precipitation accumulation* (*PAL*): This can be calculated and displayed as a second-level product based on SRI for a period ranging from a few hours to a year. Point rainfall total (PRT) for any particular place can also be determined. Though it has been reported by researchers that the parameters *A* and *b* have temporal and spatial variations in view of changes in rainfall characteristics and drop size distribution, these parameters appear to estimate the precipitation rate to a fairly good degree of accuracy. The precipitation accumulation from 0300UTC/13 to 0302UTC/14 May 2002 is displayed in Figure 6 *b*.

The radar-estimated precipitation values almost tally with the realized ground truths (i.e. the rainfall recorded from 0830IST/13 May 2002 to 0830IST/14 May 2002) at Tirupati (90 mm), Ambur (30 mm) and Sholingur (20 mm). Precipitation estimation by the radar can be useful to work out water inflow in catchments and flash-flood forecasting in almost real-time basis in the absence of conventional rain-gauge network. Moreover, radar estimation over the vast oceanic area can play a vital role in understanding the hydrological cycle which has an impact on climate and climate change. Since it is too early to fix the values of *A* and *b* based on the limited period of study, further analysis for different seasons is being carried out to get a realistic precipitation estimation using the radar.

Wind products

The following wind products are available from a DWR.

(i) Display of radial velocity vs azimuth for a fixed elevation and slant range (velocity azimuth display, VAD).
(ii) Based on certain assumptions, it is possible to derive horizontal wind from the radial wind and display the same in a PPI scope for a selected elevation and range. This display has a provision for incorporating another PPI product as underlay. A typical picture of this type is shown in Figure 7 *a*.
(iii) The radial, azimuthal, elevation, horizontal and vertical shears can be calculated from base velocity data and used as a tool for generating appropriate warnings for the aviation community. They can also be used as input in thermodynamical modelling of weather systems.
(iv) Using a linear wind-field model, horizontal wind velocity and direction in a vertical column above the radar site can be derived for a set of equidistant layers. This is generally known as volume velocity processing (VVP). A picture of this type, usually known as vertical time section by the meteorological community, is depicted in Figure 7 *b*. This display is useful for identifying the passage of wave-type disturbances over a station.

Warning products

Base data available from DWR can be further processed for automatic generation of warnings in case of one or more of the observed parameters exceeding the set threshold value. Presence of hail or tornado vortex signature (TVS), occurrence of severe weather conditions like heavy rain, wind shear exceeding set limits, etc. could be set as criteria for generation of warnings.

Summary and conclusion

This article has given a bird's-eye view of the facilities and products available from modern DWRs. The displays shown in this article have been obtained from the newly installed DWR at Chennai. This radar has been imported from M/s Gematronik, Germany.

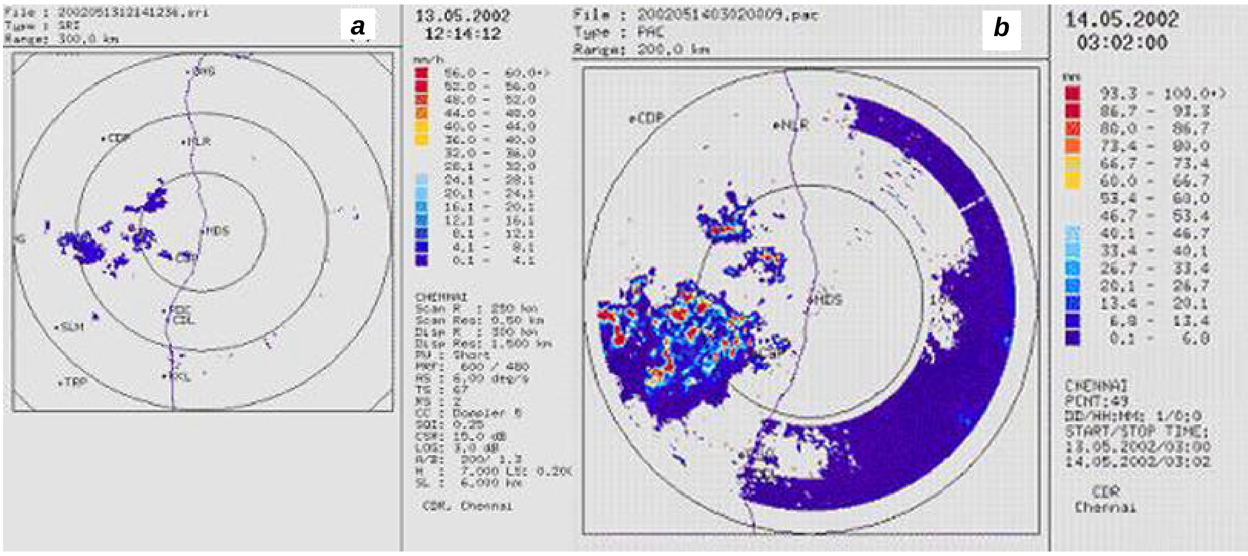

Figure 6. Display of ***a***, Surface rainfall intensity at 1214UTC/13 May 2002, and ***b***, Precipitation accumulation from 0300UTC/13 to 0302UTC/14 May 2002.

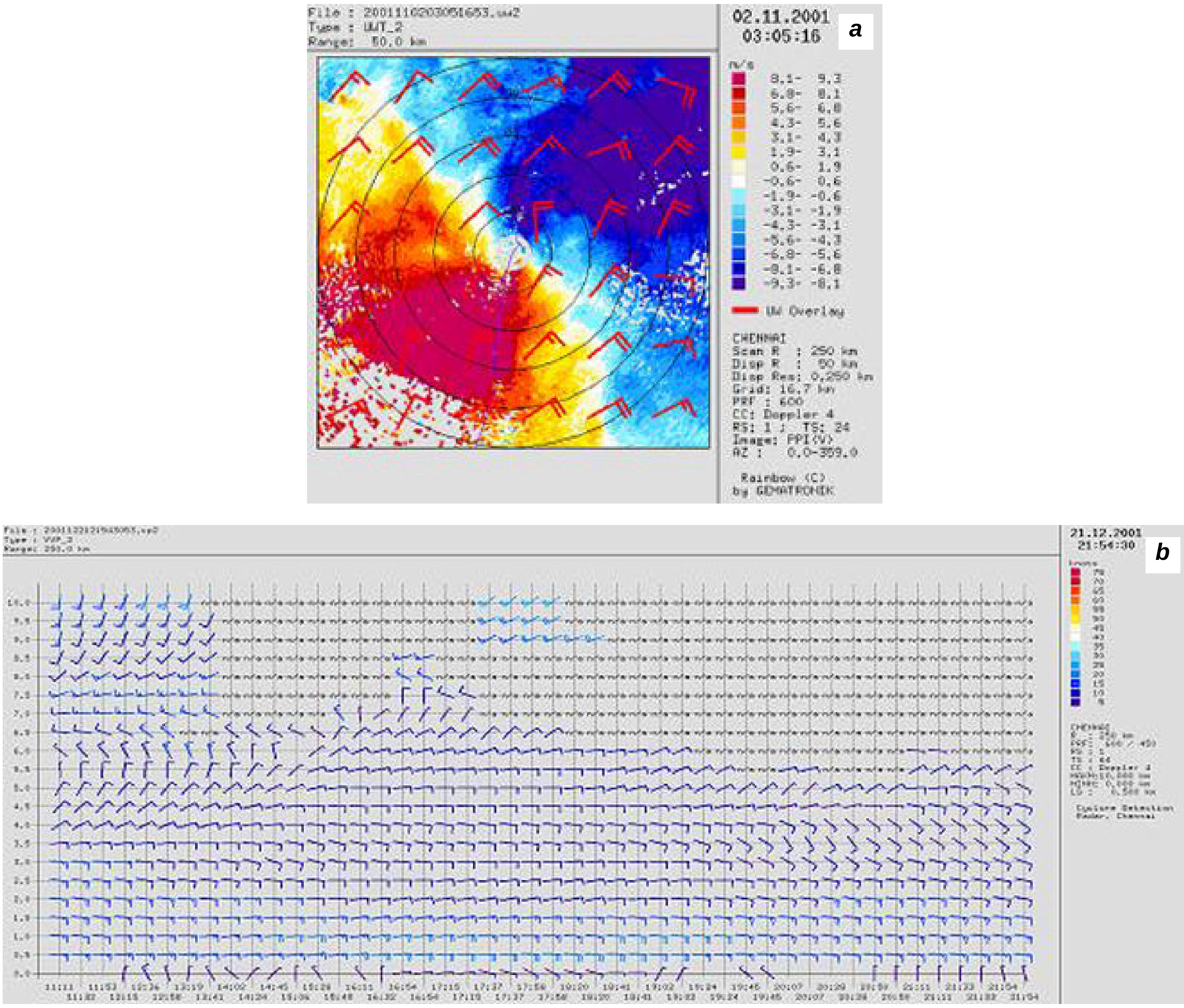

Figure 7. ***a***, Display showing the horizontal wind vectors plotted over an underlay of PPI(*V*), and ***b***, Vertical time section of horizontal wind vector derived from volume velocity processing.

Radar Development Cell of Indian Space Research Organization, Bangalore in collaboration with Society for Advanced Microwave and Electronics Engineering and Research, Indian Institute of Technology – Madras, Electronics and Radar Development Establishment, National Aerospace Laboratory and Thumba Equatorial Rocket Launching Station has developed a DWR for IMD indigenously, and the same has been installed at SHAR Centre, Sriharikota. This radar having all the capabilities of modern DWRs[7] is under test and evaluation stage, and yet to be put into operational use. One more imported radar from M/s Gematronik, Germany installed at Cyclone Detection Radar Station, Kolkata is also to be made operational after satisfactory site-acceptance testing.

With these radars and future plans of installation of DWRs at Machilipatnam, Visakhapatnam and Paradeep, the cyclone warning capability of IMD will further improve. The intensity of cyclones affecting the eastern coast of India can be estimated more precisely from the radial wind information obtained from the DWR network. The prediction capability of the movement of cyclonic storms and rain-rate estimation can also be improved by adopting improvised algorithms using digital data. In addition, aviation forecasting will get a boost as a number of products of this radar relating to turbulence/wind shear would now be available. Besides the operational utility of the various products, the DWR opens a new era in research opportunity, especially in areas like genesis of a cyclonic storm, understanding its structure and predictability of its movement and landfall, with special emphasis on storm surge.

1. Rogers, R. R., The early years of Doppler radar in meteorology. in *Radar in Meteorology* (ed. David Atlas), Am. Meteorol. Soc., Boston, 1990, p. 806.

2. Skolnik, M. I., *Radar Handbook*, McGraw Hill, New York, 1970, pp. 24.1–24.40.
3. David Atlas (ed.), *Radar in Meteorology*, Am. Meteorol. Soc., Boston, 1990, p. 806.
4. Doviak, R. J. and Zrnic, D. S., *Doppler Radar and Weather Observations*, Academic Press, London, 1992, 2nd edn, p. 562.
5. Rinehart, R. E., *Radar for Meteorologists*, University of Rinehart Publications, ND, 1999, 3rd edn, p. 428.
6. Marshall, J. S. and Palmer, W. M., The distribution of raindrops with size. *J. Meteorol*., 1948, **5**, 165–166.
7. Viswanathan, G., Indigenous Doppler weather radar for cyclone detection, weather surveillance and other meteorological applications. Proceedings of TROPMET-2000, Indian Meteorol. Soc., Cochin Chapter, Kochi, 2001, pp. 56–65.

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