

On optimum rain rate estimation from a pulsed Doppler Weather Radar at Chennai

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सार – चक्रवात संसूचन रेडार (सी. डी. आर.) केन्द्र, चेन्नई में पुराने एनालॉग एस. बैंड रेडार के स्थान पर 10 सें. मी. का एस.-बैंड डॉप्लर मौसम रेडार (डी. डब्ल्यू. आर.) सितम्बर – अक्टूबर 2001 में संस्थापित किया गया। इस शोध पत्र में इस डी. डब्ल्यू. आर. की तकनीकी विशिष्टताओं और क्षमताओं के बारे में संक्षेप में बताया गया है। मार्शल-पामर के रेडार परावर्तकता गुणक (z) और वर्षा की मात्रा (R) के मध्य संबंध सूत्र के आधार पर वर्षा की मात्रा का आकलन करने के लिए इस डी. डब्ल्यू. आर. से नवंबर – दिसंबर 2001 की अवधि में प्राप्त हुए अंकीय आँकड़ों का उपयोग किया गया है। डी. डब्ल्यू. आर. से 100 कि. मी. के अर्धव्यास की परिधि के भीतर रखे गए स्वतः अभिलेखी वर्षामापियों द्वारा मापी गई वर्षा का आकलन, संबंध सूत्र $z = 267 R^{1.345}$ के अनुसार सही पाया गया है। व्यावहारिक उपयोग के लिए मार्च 2002 – दिसंबर 2003 के दौरान इस संबंध की जाँच की गई और यह देखा गया है कि संचित वर्षण के संबंध में रेडार से किए गए आकलन और वर्षा मापी से ली गई माप 15 प्रतिशत की घट-बढ़ के साथ सही पाई गई है। जल-ग्रहण क्षेत्रों में जल के प्रभावी प्रबंधन के लिए जल प्रबंधकों और प्रचालनात्मक जल-मौसम वैज्ञानिकों द्वारा इस रेडार के आधार पर प्राप्त सूचना का उपयोग जल-ग्रहण क्षेत्रों की 24 घंटे की वर्षा के वितरण के संबंध में किया जा सकता है क्योंकि वर्षा के स्थानीय आकलन की तुलना में विस्तृत क्षेत्र आकलन में त्रुटि अपेक्षाकृत कम ही रही है।

ABSTRACT. A 10 cm S-band Doppler Weather Radar (DWR) has been installed as a replacement of an outdated analogue S-band radar at Cyclone Detection Radar (CDR) station, Chennai during September-October, 2001. Technical specifications and capabilities of this DWR have been briefly mentioned in this paper. The digital data obtained from this DWR have been used for the period November-December, 2001 to estimate the rain rate based on the Marshall-Palmer relationship between the radar reflectivity factor (z) and the rain rate (R). The relation $z = 267R^{1.345}$ estimates well the rain rate as measured by the self recording rain gauges located within 100 km radius from the DWR. This relationship has been tested for its operational applicability during March 2002 - December, 2003 and found that the accumulated precipitation from the radar estimation was within an error of 15% from the rain gauge measured values. Information on the twenty four hours accumulated areal distribution of precipitation can be used by the water managers and operational hydrologists for the effective water management over the catchments since the error in rain rate estimation over a wider area is relatively small in comparison to point rainfall estimation.

Key words – Rain rate, Doppler Weather Radar, Radar reflectivity factor, Drop size distribution, Marshall-Palmer relationship, Disdrometer.

1. Introduction

The variability of rainfall, both in temporal and spatial scales, has been studied extensively throughout the world by many researchers based on data from rain gauges which are not normally well distributed over the regions

of study due to various reasons. The rainfall variability over India attracts scientists all over the world due to the fact that a major portion of the Indian sub-continent gets its annual rainfall from the southwest monsoon (June-September) and relatively a smaller region in the southern tip of peninsular India (Tamilnadu in particular and

southern coastal Andhra Pradesh and Telangana, and Kerala) gets rainfall from both southwest and northeast monsoons albeit the contribution by northeast monsoon (October – December) is predominant. Inter and intra-monsoon variability of rainfall has been established with the data from sparsely located surface rain gauges. However to analyse such a variability in a more detailed manner, dense network of rain gauges is required (say at $4 \text{ km} \times 4 \text{ km}$) which may not be plausible in the real world due to cost and maintenance considerations. The variability of rainfall as seen in planetary scale (\sim thousands of km) to meso scale (meso α and β scale \sim a few hundreds km) may also be seen in the local scale (or meso γ scale \sim a few tens km) if sufficient rain gauges are available in the area of study. Such a local scale variability had been studied with the available surface rain gauge data in Chennai and its suburbs and also over the Tamilnadu State by many authors through time series analysis (Ramakrishnan, 1953; Rao and Raghavendra, 1971; Suresh and Sivaramakrishnan, 1997). Though it is an accepted fact that rainfall is a highly variable meteorological and hydrological parameter, precise information about the amount of rainfall especially over catchments is needed for the water managers and planners to devise suitable schemes for the distribution and supply of water for day-to-day living and irrigation purposes and for averting loss of lives and properties due to flash floods.

1.1. Radar as dense network of rain gauges

As rain gauges measure only a point rainfall, to have an accurate estimation of rainfall over catchments a network of rain gauges is used to estimate the areal average over unit time and this information is used in operational hydrology for flash flood forecasting. Though the rain gauge measurements of rainfall are adjudged as standard, the accuracy of areal average depends on the spatial variability of rainfall as well as the density of the rain gauges used to estimate the areal average (Huff, 1970). But as stated earlier and as is well known, it may not be practicable to have rain gauges installed too closely, say atleast one in $4 \times 4 \text{ km}$ grid, due to cost factor, upkeep and maintenance aspects. By comparing the reflectivity factor measured by the radar with the rain rate recorded by the surface rain gauges and extending this relationship to a wider area, the radar is able to measure tens of thousands of point rain fall every minute. However, there are some limitations in these estimates when the distance from the radar is increased (Rinehart, 1999). Combining the accuracy from the surface rain gauge (s) located in the area of interest and the advantage of wider areal coverage from the radar, one can reliably estimate the rain rate (Brandes, 1975; Wilson and Brandes, 1979).

1.2. $z - R$ relationship

In order to have a reasonably accurate rainfall data in the absence of rain gauge data over an area of interest, say catchments, the radar measured reflectivity has been used (since late 1940s) to estimate the rain rate as the radar reflectivity (z) as well as the rain rate (R) are functions of the rain drop size distribution. Marshall and Palmer (1948) and Marshall *et al.* (1955) initially proposed such a relation between R and z by means of an equation of the form $z = A R^b$ where 'A' and 'b' are to be estimated based on some sample data of z and R . This relationship, often called as M-P relationship (Marshall *et al.*, 1955) or $z - R$ relationship, has been extensively used for different atmospheric conditions, seasons at various locations (almost all over the world) and the many values of 'A' and 'b' had been documented so far. Though intense echoes are associated with larger rain rates, there is no universal relation between z and R presumably due to the fact that the drop size distribution keeps on varying over different scales and varies between types of rain incidents such as stratiform, convective/thunderstorm precipitation etc. For a detailed description of $z - R$ relationship and different values of 'A' and 'b' [Battan (1973), Doviak and Zrník (1993), Atlas (1990) and Rinehart (1999)]. Raghavan and Sivaramakrishnan (1982) attempted to estimate the 'A' and 'b' coefficients for Chennai for the month of November 1979 from the erstwhile analogue S-band radar having a digital video integrator and processor (DVIP) module. An attempt has been made in this study to estimate the rain rate based on the newly installed Doppler Weather Radar (DWR) at Chennai. A brief description of DWR, Chennai has been given in section 2. Section 3 and 4 covers the data and methodology respectively. Section 5 summarises the results of the present study.

2. Doppler Weather Radar, Chennai

A new state of the art S-band DWR has been installed during September-October 2001 at Cyclone Detection Radar (CDR) station, Chennai in replacement of the outlived analogue radar. This radar has been supplied by M/s Gematronik GmbH, Germany. System specification of the DWR, Chennai has been tabulated in Annexure 1. The radar maintenance is done through Radar VISualisation (RAVIS) software through an ordinary Pentium PC and the normal operation for tracking, archiving and product generation is done by RAINBOW software in SUN Solaris platform. The radar has second trip recovery, velocity unfolding (upto 4 times the unambiguous velocity) and frequency agility facilities. Explanation of these facilities are beyond the scope of this paper and the interested readers may see Doviak and Zrník

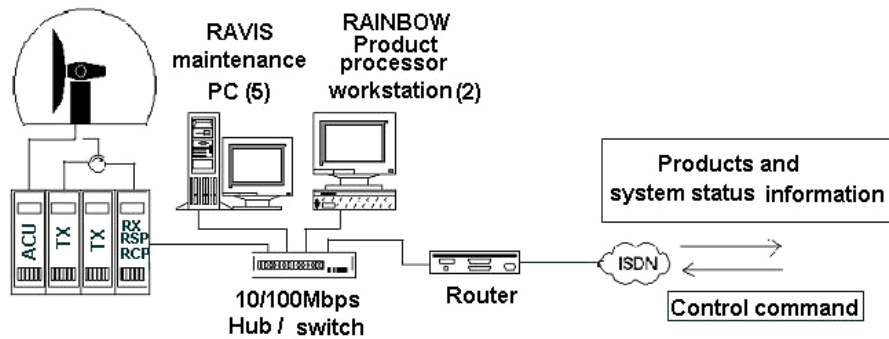


Fig. 1. Block diagram of Doppler Weather Radar, Chennai and its connectivity

(1993) and Rinehart (1999) for details. For the effective removal of ground clutters, fifteen notch filters of velocity band width 0.2 to 2 mps are available. In addition to the above said Doppler notch filters, clutter map facility is also available for the clutter suppression. For correcting the melting layer enhanced reflectivity (bright band correction), algorithms proposed by Smith (1986) and Andrieu and Creutin (1995) have been used. The radar became functional and started acquiring data *w.e.f.* 30 October, 2001 and has been put into operational use from 21 February, 2002. A number of derived products in addition to the base products (Reflectivity, radial velocity and Spectrum width) are also available. At present the radar is connected to outside world with 64 kbps ISDN connectivity though provision exists for its future connectivity through Microwave and satellite links for networking with other radars of India Meteorological Department. The products are disseminated in three hourly interval to various forecasting offices in India through e-mail attachments. In addition to the above, user specific requirements are catered to then and there in near real time and in off-line mode. Fig. 1 depicts the block diagram of DWR with its connectivity. The radar is operated round the clock with different scan strategies depending on the operational and research requirements.

3. Data used

The radar is in continuous operation since 30 October, 2001 and the volume data of logarithmic reflectivity factor ($Z = 10 \log z$), radial velocity (V) and spectrum width (W) of elevations from 0.2° to 19.8° at different steps that are ideal to capture data without any wide gap at different scan strategies have been archived in 4 mm DAT cartridges. The self recording rain gauge (SRRG) data of Airport Meteorological office, Meenam-bakkam, Chennai ($12^\circ 59' 36.6''$ N/ $80^\circ 10' 37.3''$ E),

Indian Air force station, Tambaram, Chennai ($12^\circ 55' N / 80^\circ 07' E$), SHAR Centre, Sriharikota ($13.6645^\circ N / 80.227^\circ E$), Tirutani ($13^\circ 9' N / 79^\circ 32' E$), Keelacheri (46 km west of Radar) and Vellore ($12^\circ 55' N / 79^\circ 09' E$) have been used to interpolate the rain rate received at the surface. In addition, 24 hours accumulated rainfall data from a Class III observatory at Tirupati ($13.40^\circ N / 79.35^\circ E$) and data from a number of reporting rain gauge stations such as Chengalput, Kancheepuram ($12.50^\circ N / 79.45^\circ E$), Ponneri ($13.20^\circ N / 80.15^\circ E$), Tiruvallur ($13.09^\circ N / 79.57^\circ E$), Sriperumpudur, Covelong, Redhills and Ambur were also considered for verification of the accumulated precipitation in 24 hours period. Fig. 2 depicts locations of the rain gauges considered in this study. The antenna feed is located at an elevation of 53 m a.s.l. and hence some of the ground clutters close to the radar site have been eliminated. The rain gauge locations selected in this study are free from beam blockage. The Z data for the period 1 November to 31 December, 2001 have been used along with the SRRG data for the same period to estimate the rain rate upto a distance of 165 km from the Radar site. For verification of the rain rate estimated from z data, the actual rainfall recorded at the surface rain gauges mentioned above for the period 1 March, 2002 – 31 December, 2002 have been used.

4. Methodology and computation

Northeast monsoon is normally quite active during the month of November over Tamilnadu, especially over coastal Tamilnadu, Chennai and its surrounding received copious rainfall during November 2001. The radar was operated continuously during November with different scan strategies. A typical 250 km scan strategy has been furnished in the Annexure 2. The radar transmitter and receiver has been well calibrated. The receiver calibration

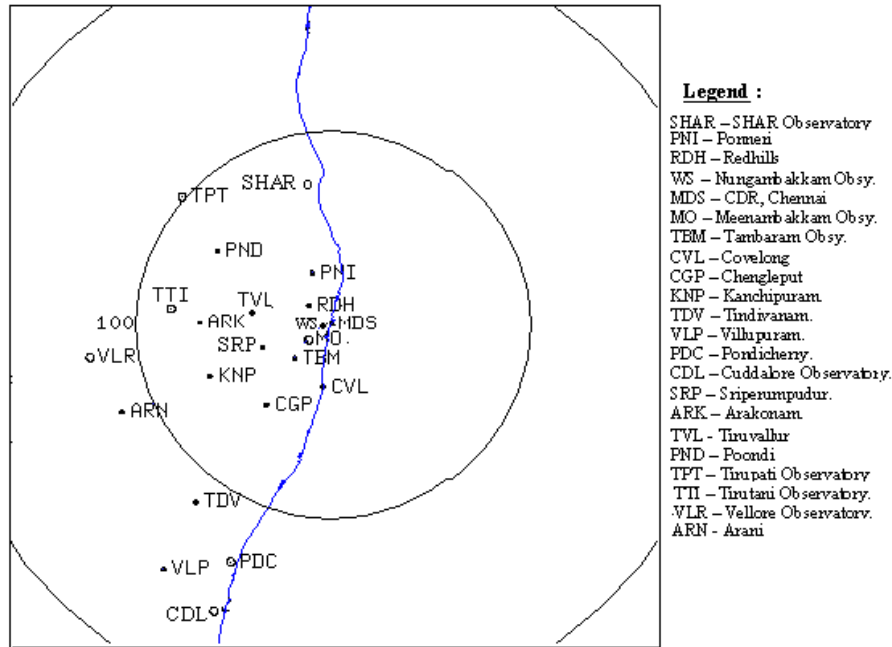


Fig. 2. Locations of rain gauges (within 165 km radius from DWR, Chennai) used for validating rain rate estimated from DWR, Chennai

had been done as a matter of routine, once a week and the results are stored in the digital receiver for its use despite the fact that though there was no appreciable change in its parameters. For determining the $z - R$ relationship during November – December 2001, volume scans of 250 km range were repeated with a periodicity of 10 minutes interval so that the Z data can be used for estimating rain rate by comparing with the suitably interpolated SRRG data, since no telemetry type rain gauges are available in the region under study. Reflectivity at 1.0 km constant altitude layer was considered and the mean value of z was computed from the different scans falling in the thirty minutes window for all the locations wherein SRRG are available and considered in this study. Since z is normally related to the rain rate and rain rate varies widely in time scale also, in the absence of fast response tilting bucket and telemetry type rain gauges, thirty minutes accumulated precipitation has been interpolated from the SRRG chart to obtain rain rate per hour rather than considering the rain fall received during one hour as the later method masks the variability considerably.

4.1. $z - R$ relationship

A typical scatter plot of 260 values (Fig. not shown) of thirty minutes mean linear reflectivity ($\text{mm}^6 \text{m}^{-3}$) *vis-a-vis* accumulated rain fall during the

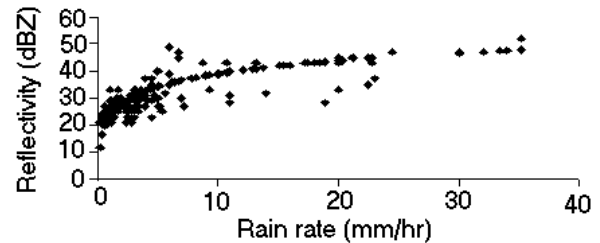


Fig. 3. Scatter plot of rain rate per hour *vis-à-vis* logarithmic radar reflectivity factor (dBZ) during 1-10 November 2001

same period converted into rain rate (mm/hr) showed that the relationship between rain rate and reflectivity factor is non-linear. Since only Z , the logarithmic reflectivity factor, often called as reflectivity factor (dBZ), is being used in day-to-day usage a plot of dBZ *vis-à-vis* rain rate has been displayed in Fig. 3. It can be seen that the relationship between dBZ and R is non-linear. This observation is in agreement with the original idea of Marshall *et al.* (1955) to fit the raindrop size distribution (DSD) into a power law profile, *viz.*, $z = A R^b$. In the absence of disdrometer, since we have no means to have the DSD with us for estimating the reflectivity as an independent source, the thirty minutes mean linear reflectivity has been regressed with the rain rate (mm/hour) based on the thirty minutes realized precipitation (interpolated from the SRRG charts) for the period 1 November– 31 December, 2001. The

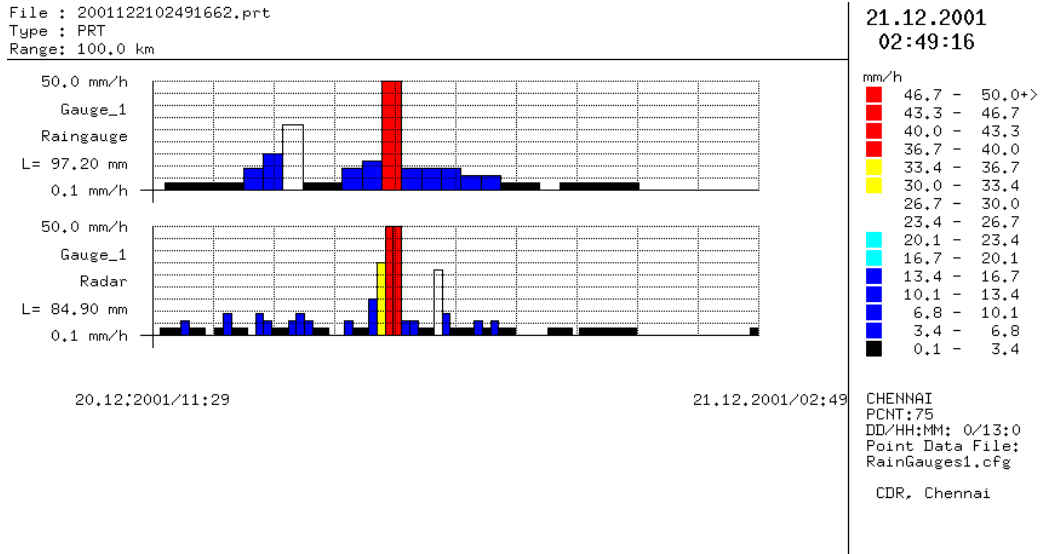


Fig. 4. Sample plot of rain gauge recorded rainfall and radar estimated rainfall over Air Force station, Tambaram on 21 December, 2001

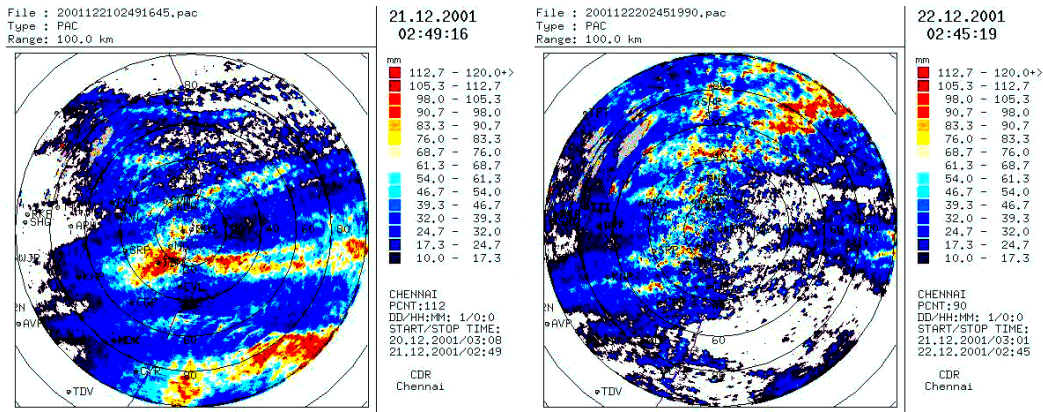


Fig. 5. Areal accumulation of rainfall within 100 km radius from DWR, Chennai

coefficients ‘A’ and ‘b’ are estimated through power regression technique. For this regression, ‘no rain data’ (*i.e.*, $R = 0$ mm/hr) have been excluded to avoid computational errors due to logarithmic values of indeterminate quantities and those period with rain rate higher than 0.2 mm/hour were alone considered. The estimated co-efficients were $A = 267$ and $b = 1.345$. (*i.e.*) $z = 267R^{1.345}$.

4.2. Generation of point rainfall total (PRT), surface rainfall intensity(SRI) and precipitation accumulation (PAC) from $z - R$ relationship

PRT is the total rainfall accumulated over a Cartesian point on the surface of earth for a period of time

and the SRI is the rain rate (mm/hr) at any instant over an area. Having defined a $z - R$ relation, the following procedures have been adopted to generate PRT and SRI.

- (i) Rainfall attenuation correction ($0.0044R^{0.11}$ dBZ/km) is applied to the polar volume data (Hitschfeld and Bordan, 1954).
- (ii) The polar volume data is converted into curvature corrected cylindrical data.
- (iii) For a user defined surface layer (this height is normally selected to avoid clutters, if any present even after applying Doppler clutter filter and to cover the desired areal extent by the lowest radar beam), a search is

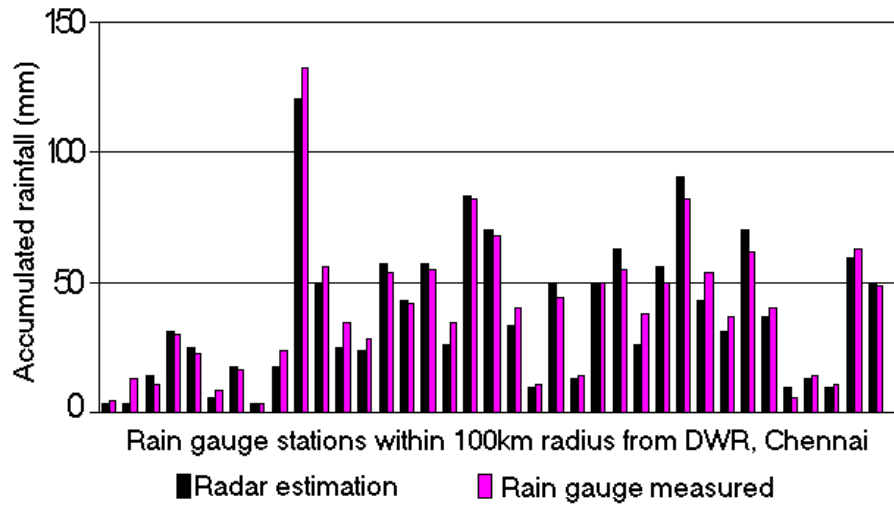


Fig. 6. Comparison of radar estimated and rain gauge measured 24 hrs precipitation during 11 November – 22 December, 2001 within 100 km radius circle from DWR, Chennai

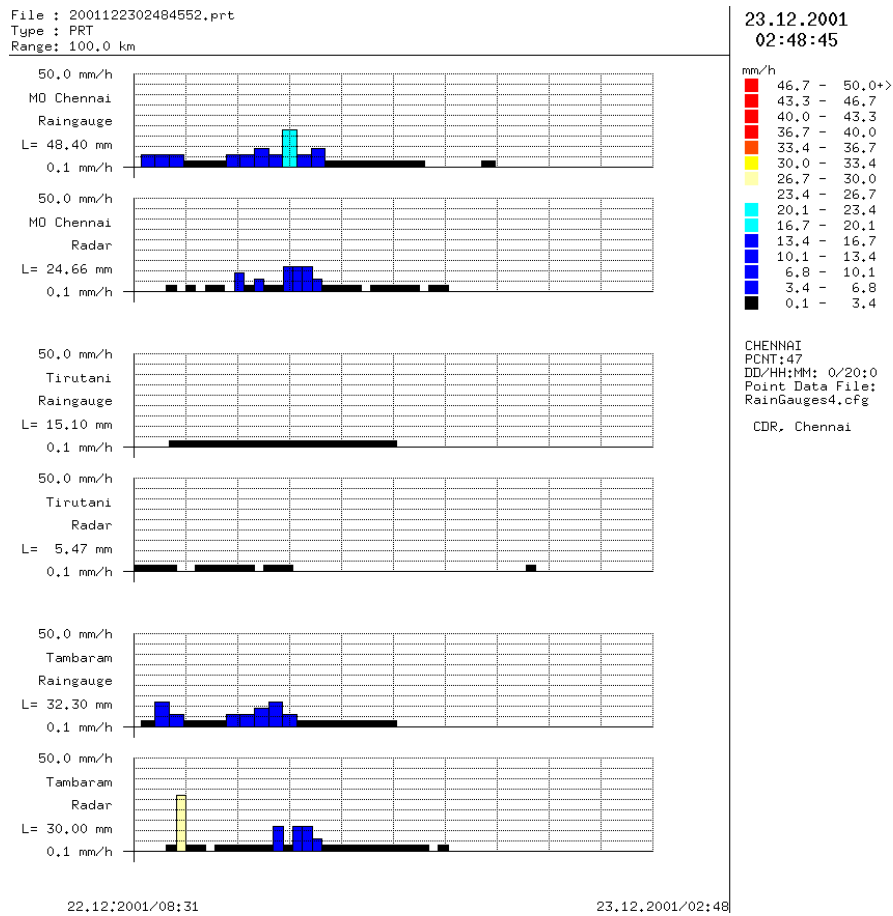


Fig. 7. Radar estimated rainfall and rain rate and that actually measured by self recording rain gauges located at (a) Airport Met. Office, Meenambakkam, (b) Tirutani Observatory and (c) Tambaram air force station on 23 December, 2001

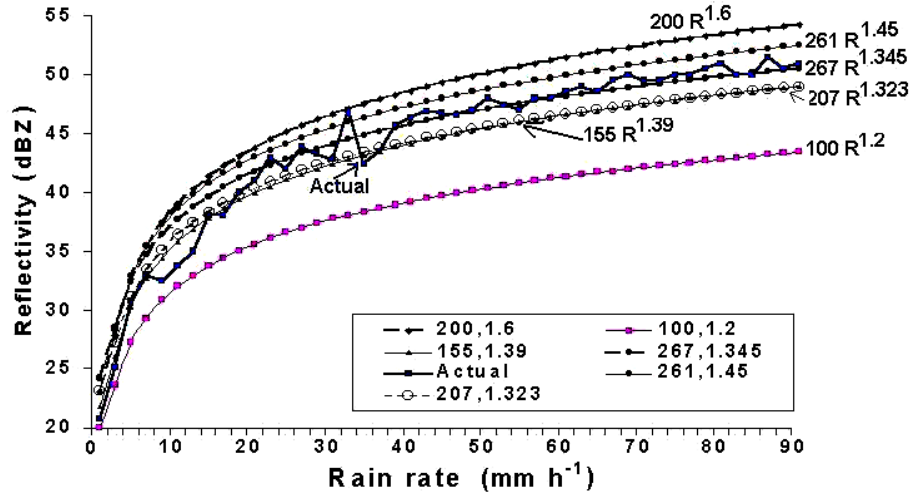


Fig. 8. Comparison of rain rate estimated through various schemes with the actual rain rate measured at different SRRG locations located within 100 km radius from CDR, Chennai for various rain spells during November - December 2001

made from the cylindrical grid data which is just above the surface layer specified by the user. If the user defined surface layer is not visible from the radar, then that grid point is assigned with 'no data'. It has been well established by Wilson and Pollock (1974) that the radar estimation agrees well with the rain gauge value of precipitation when the Z data is considered at a height below 1800 m.a.g.l. but it is an underestimation by ten times if the Z values are considered at a height of 4200 m a.g.l. Though the bright band occurs at a height well above 5200 m over Chennai, in order to avoid the bright band (despite the fact that correction for bright band is applied as stated in section 2) as well as the obstructions from Nagari Hills of height about 600 m (60-70 km northwest of DWR) and to get better agreement with rain gauge measurement, in the present case, we have selected surface layer of 1.0 km. The SRI is generated based on the z - R relationship, viz., $z = 267 R^{1.345}$, for each grid point on the surface layer. The PRT is generated by time integration of the SRI values over the rain gauge locations under consideration.

The PAC product, which is a second level product taking input from the specific SRI, accumulates the rain rate and works out the total rainfall over a user specific radius circle from the radar for the pre-defined period. This product starts automatically as and when a new SRI is generated. As the rain rate varies minute by minute, the interval between two consecutive SRIs should be kept as minimum as possible. In other words, for generating any

hydrological product, the repetition time of volume scans should be brought as minimum as possible – otherwise the product generated may be differing from the ground truth by a large margin. The product is ultimately displayed in a colour coded format of the accumulated rain for a period ranging from 10 minutes to a number of days. The estimated z – R relationship has been tested with SRRG data recorded at Air Force station, Tambaram which is about 22 km south-southwest of Radar for the period December 2001 and found that the estimated rainfall over a period of 2 to 24 hours, depending on the rain spells, have been agreeing well within absolute error of 15%.

A sample plot of point rainfall total comparing the rain rate and actual rainfall as estimated from radar and as recorded by SRRG has been displayed in Fig. 4. The total accumulated precipitation on 21 December, 2001 at Indian Air Force station, Tambaram was 97.2 mm whereas the radar estimation was 84.9 mm. Though the peak rain intensity has been almost accurately estimated from the radar data, one can see some deviations between the realized precipitation and radar estimation as well. It may be mentioned here that the radar estimation is based on z data collected at ten minute interval while the rain gauge data is an interpolated value of thirty minute interval, of course with subjectivity as well (as discussed in section 4.1). This limitation besides the other sources of error (being discussed in section 4.5) could explain the differences between the rain gauge measured precipitation and that estimated through radar data.

4.3. Comparability of radar estimated rain rate with the surface measured rain rate

Arial distribution of 24 hrs accumulated rainfall has been generated for 100 km radius circle from DWR, Chennai and a typical display is shown in Fig. 5. The 24 hours accumulated rainfall values (0301 UTC to the 0300 UTC of the next day) were compared with the rain gauge measured values during 11 November – 22 December, 2001 and found that there is fairly a good agreement between them. The root mean squared error is 15%. Fig. 6 shows the comparison between the radar estimated precipitation with that measured by rain gauges located within 100 km radius from CDR, Chennai. The correlation coefficient between radar estimated and the rain gauge measured 24 hrs rainfall was 0.97.

Though the fitting agrees well with the realized accumulated precipitation for rain spells of 2 to 24 hours, there had been some deviation between the radar estimated accumulated precipitation and the SRRG / rain gauge measured ones, due to various constraints as listed in Rinehart (1999) and Atlas (1990). A typical plot of difference between the radar estimated rainfall and the SRRG measured rainfall have been depicted in Fig. 7. The accumulated value of rainfall has been mentioned on the left hand side of the figure itself for both radar and rain gauge. While there is a good agreement in the case of Tambaram air force station observatory (located about 22 km south-south west of DWR), the error between the radar estimated and SRRG value is significant in the case of Meenambakkam airport (located about 18 km southwest of DWR) and Tirutani observatory (80 km west of DWR). Nonetheless, the fitted $z - R$ relationship, viz., $z = 267R^{1.345}$ has a correlation coefficient of 0.98, the standard error of coefficient 'A' is 8.85 and the coefficient of determination is 0.97 (i.e., 97% of variance of R is explained by z) certifying the goodness of fitting.

4.4. Comparison of parameters of different $z - R$ relations

The fitted $z - R$ relationship has been compared with the actual ground truths measured by rain gauges located within 100 km radius from CDR, Chennai during the period November-December, 2001 and the results have been presented in Fig. 8. For the purpose of comparison, we have considered different $z - R$ relationships obtained by Raghavan and Sivaramakrishnan (1982) for Chennai, Narayana Rao *et al.* (1999 and 2001) for Gadanki (both for northeast monsoon rainfall) and Yuter and Houze (1997) over Pacific. From this plot, a quick inference one can make is that while Marshall-Palmer relation ($z = 200R^{1.6}$) grossly underestimates the rain rate over Chennai, estimate $z = 100R^{1.2}$ based on Raghavan and

Sivaramakrishnan (1982) has been overestimating the rain rate. The relationships $z = 155R^{1.392}$ and $z = 178R^{1.51}$ of Narayana Rao *et al.* (2001) estimate more or less the same R beyond 40 mm/hr and matches the low rain rates reasonably well. The estimation attempted in this paper, viz., $z = 267R^{1.345}$ appears to have some error in estimating the low rain rates but performs extremely well in higher rain rates. Yuter and Houze (1997) relationship, viz., $z = 261R^{1.45}$ is somewhat underestimating the rain rate over Chennai albeit better than that estimated by Marshall-Palmer.

It can also be seen that the estimate ($z = 100R^{1.2}$) based on Raghavan and Sivaramakrishnan (1982) has been overestimating the rain rate (about 300% error) when the Z value exceeds 45 dBZ. One of the possible reason for this could be that the coefficients obtained by them were based on the Z data from the Digital Video Integrator and Processor (DVIP) for a range of dBZ values (in steps of 5 dBZ iso-echo levels) and perhaps not that accurate as we now obtain from the modern digital radars. Though the rain rate based on $z = 267R^{1.345}$ agrees fairly well with the SRRG measured rain rate, it may be possible to decide the best fit only after verifying its validity with a large volume of data in the ensuing years.

4.5. Sources of errors and the ways adopted to avert them

Considerable work has been done to identify the parameters of the drop size distribution (DSD) from the types of rains such as stratiform, convective, thunderstorm etc. Even within a particular type of rain, the parameters of the DSD are quite often varying. Atlas and Chmela (1957) concluded that 300% error in estimating the rain rate from the same reflectivity factor Z of two different stratiform type precipitation in view of the difference in their DSD. As such it is very much necessary to know to the DSD to estimate rain rate remotely from the radar. However, the DSD can not be determined from the radar and for this purpose we need to adopt filter paper technique [Rinehart (1999) for details] or use measuring instruments like Disdrometer (DIStribution of rain DRoPsize METER). While the filter paper technique is a time consuming process and somewhat crude way of estimating the DSD, the installation of Disdrometer at closer grid (say 4×4 km) costs very high. Depending on the calibration, two different sets of "A" and "b" parameters can be worked for two different radars probing the same area. Hence calibration of radar also plays a vital role in rain rate estimation (Doviak and Zrnica, 1993). The rain rate estimation from radar is subjected to possible sources of errors such as (i) evaporation beneath the radar beam (ii) incomplete beam filling (iii) reflectivity enhancement by melting layer which is

often referred as the bright band (iv) advection of droplets by winds close to the ground which are beneath the lowest beam of the radar (v) calibration of radar (vi) underestimation in the absence of large droplets in drizzle and orographic enhancement of rain either below the radar beam or blocked by the hills.

In the present method we mostly used the Z at a height of 1000m a.g.l. (covering 100 km radius) and in no case Z from radar beam exceeding 170 0m (covering 165 km radius from DWR) was used. Hence we avoided the possible error as mentioned in section 4.2 [referring to Wilson and Pollock (1974)], besides the advantage that the evaporation when the drops are falling from a higher height before reaching the ground also has been avoided to a certain extent. With this we avoided the error of type (i) listed above. The bright band correction has been applied to the basic Z data before it is subjected for estimating the rain rate based on the method suggested by Smith (1986) and Andrieu and Creutin (1995). Calibration of radar (receiver linearity validation) had been done at regular intervals (once in a week) and corrections were applied to the digital receiver. The radar antenna height (54 m) is chosen such that the nearby hillocks do not block the beam and the Z data was considered at a height of 1km so that orographic enhancement is avoided.

So long as the shape of the rain drops are spherical and their size are within the Rayleigh region (size of scatterers is less than one-third of the wave length of the radar), the radar reflectivity factor (z) is defined as the sum of sixth power of the scattering particle diameter. But the rain rate (R) is approximately proportional to 3.67^{th} power of the rain drop size (Ulbrich, 1983; Sauvageot and Lacaux, 1995). The relationship between drop size and z and R suggests that R does not have any unique relationship with z but depends on the drop size distribution (DSD). As such the radar derived rain rate has the following uncertainties (Ulbrich, 1986; Austin, 1987; Smith, 1990; Joss and Waldvogel, 1990; Rinehart, 1999).

- (i) The natural variability of DSD.
- (ii) The precipitation rate at the surface is estimated from the radar measurement aloft which may be overestimations in view of rain not reaching ground wither due to drifting and/or evaporation taking place before reaching the ground.
- (iii) Operational applications of radar estimated rain rate over large areas need not yield good result (as obtained from well-defined field experiments between the rain gauge and radar estimated rain values) since the ideal conditions of rain gauge locations might not have been fulfilled.

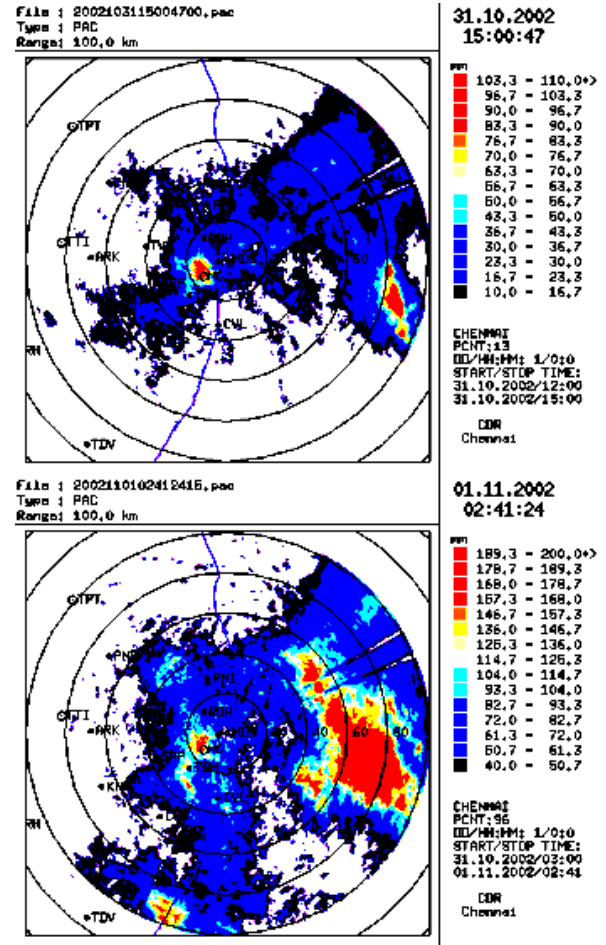


Fig. 9. Display of accumulation of precipitation based on radar estimation ($z=267R^{1.345}$). Heavy to very heavy rainfall recorded during three hours (1200 – 1500 UTC / 31 October, 2002) and twenty four hours (0300 UTC / 31 October – 0300 UTC / 01 Nov, 2002) by various rain gauges have been precisely estimated

- (iv) The presence of updrafts and downdrafts significantly alters Z value.
- (v) Though the errors caused by the DSD can be brought to a factor of two by spatial and temporal averaging, the errors at longer ranges, by not seeing precipitation close to ground, are quite dominant and often ignored. As such it has been concluded by Zawadzki (1984) that the DSD introduces one, but not the most severe, of the many errors in estimating R .

Despite the above uncertainties, radar estimated rain rate and thereby the accumulated rainfall will be useful as a first hand information to know about the amount of water accumulated over a wider area. This information is

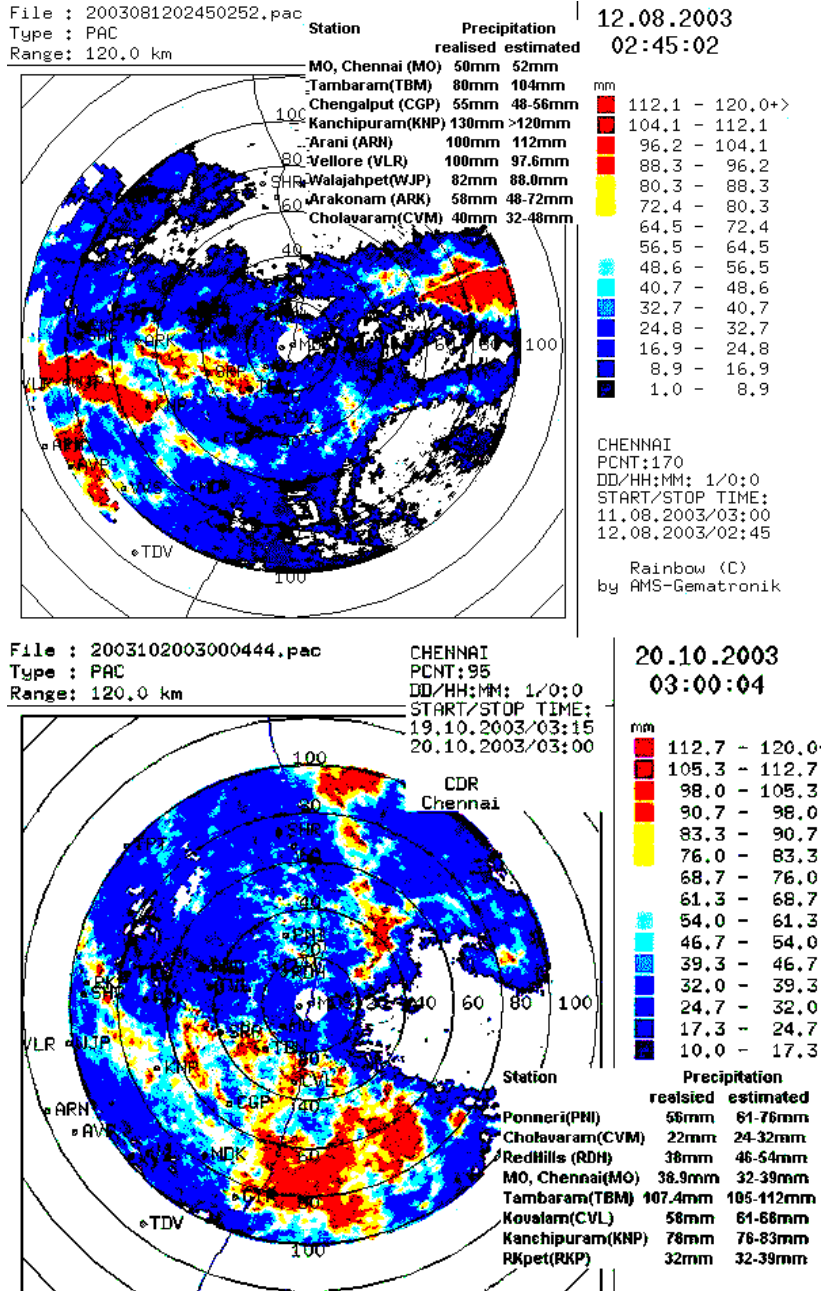


Fig. 10. Comparison of twenty four hours accumulated precipitation based on estimation from radar data with rain gauge measured rainfall during 11-12 August 2003 (representing southwest monsoon) and 19-20 October 2003 (representative of northeast monsoon)

helpful to work out the level of ground water table, issue of flash flood forecast, plan for irrigation and water supply operation etc. Since a rain gauge samples an area of about 0.05 sq m. whereas the radar with a typical pulse length of 150 m samples a volume of several hundreds of cubic meters of rain area in 100 km radius, the amount of

information received from the radar may be equal to that obtained from a few lakhs of rain gauges installed in the catchments with 150 m grid spacing. Till such time, the other techniques such as the installation of dual-polarisation radars to avoid errors arising from the horizontal polarization measurements and densely packed

automated weather stations are available, it is desirable to have the rain rate estimated through radars which gives some information if, not most accurate, to the operational hydrologists for devising suitable water conservation scheme.

5. Validation during March 2002 - December 2003

The $z - R$ relationship obtained in this paper has been used in near real time during 2002-2003 for estimating the rain rate during pre-monsoon (March – May), southwest monsoon (June – September) and northeast monsoon (October – December) season since the parameters of $z - R$ relationship was estimated based on November – December 2001 data which comprises of both convective and stratiform type precipitation. Moreover, as the rain rate varies with drop size distribution a wide range of $z - R$ relationships could be possible for different time scales, say from minute to intra and inter-seasonal variability. For a detailed discussion on the different $z - R$ relationships derived throughout the world and the varying degree of their efficacies in estimating rain rate with many fold errors [Battan (1973), Atlas (1990) and Raghavan (2003)]. Using different relationships for convective / stratiform precipitation for different seasons, without actually knowing the type of precipitation beforehand, poses problem in operational applications. We strongly believe that the intricacies in estimating rainrate through radar may continue even if the radar network is augmented by installing digital radars at 100 km \times 100 km grid points since the rain measured by rain gauge and radar would be two different entities in spatial dimensions.

In order to ascertain the efficiency of the $z - R$ relationship obtained in this paper, we used this relationship in real time and compared the accumulation of precipitation on day-to-day basis during March 2002 – December 2003. The performance was reasonably good in estimating the accumulated precipitation within $\pm 15\%$ on an average though there were cases the estimation was well within $\pm 5\%$ deviation from the ground truth. Since the precipitation during pre-monsoon 2002 and 2003 was very subdued, we confine our presentation to southwest and northeast monsoon seasons only. A sample validation to represent heavy rainfall event has been shown in Fig. 9. Meenambakkam airport (marked as MO in the figure) recorded 10 cm between 1200 and 1500 UTC on 31 October, 2002. The 24 hours rainfall from 0300UTC/ 31 October to 0300 UTC/ 1 November, 2002 was 20 cm and Tambaram air force station (marked as TBM) recorded 14 cm rainfall during the said period. Rainfall recorded at the catchments vary from 4 cm to 13 cm during the said period and a few other rain gauges recorded 1-2 cm rainfall in twenty four hours. There is a good agreement between the ground truth and the radar

estimated precipitation for both the three hourly and twenty four hours period of exceptionally heavy rainfall incidence. The estimation of this wide ranging of precipitation in shorter duration (3 hours) as well as in twenty four hours duration within a radius of 100 km from DWR certifies the usefulness of the coefficients derived in this paper.

Fig. 10 shows a sample validation to represent precipitation during southwest monsoon and northeast monsoon 2003. For the sake of comparison, the rain gauge measured rainfall values and that estimated through radar have been presented in the these figures with relevant station codes. The radar estimation through $z = 267R^{1.345}$ is quite good.

6. Summary and conclusion

On most occasions, the radar estimation of the total rainfall through $z = 267R^{1.345}$ was comparing well with the rain gauges measured rainfall value and the error limit was well within the root mean squared error of the development sample based on which the coefficients of the $z - R$ relationship has been developed. However we may have to verify the applicability of these relationships for a longer period to arrive at a conclusion to select the best relationship. The parameters of the M-P relation can be fine tuned if we receive the rain rates in near real time from a well established telemetry type rain gauge network. There is a proposal to induct a network of few Disdrometers and a number of telemetry type rain gauges within 100 km radius from the DWR, Chennai and it may take some time for its actual implementation. However, since it has been found that areal distribution of precipitation as derived by applying $z = 267R^{1.345}$ matches well with the rainfall measured by a number of ordinary and self recording rain gauges located within 165 km radius from DWR, Chennai, this relationship may be used by the operational hydrologists for better water management.

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ANNEXURE 1

System specification of Doppler Weather Radar, Chennai

	Transmitter
Type	Klystron Amplifier
Peak power	750 kWatts
Modulator	Hard switched, switch array, solid state
Frequency	2875 to 2878 MHz
Pulse width	1 μ s(short pulse) and 2 μ s (long pulse)
Pulse Repetition Frequency	250-1200 in short pulse & 250-550 in long pulse
	Receiver
Type	Double super heterodyne
Stable Local Oscillator / First Local Oscillator	2400 MHz
Second Local Oscillator	465, 466, 467, 468 MHz
Intermediate Frequency	10 MHz
Noise figure	Better than 1.5 dB
Minimum Digitally Detectable Signal	-114 dBm in long pulse and -112 dBm in short pulse
Digital part of the receiver	
Band width	1 MHz in reflectivity & 0.5 MHz in velocity mode
A/D conversion	40 MHz, 12 bits
Signal processing	10 DSP chips of 120 MFLOPS/sec each
Simultaneous output	Reflectivity, Velocity and Spectrum width (8bits)
Minimum range bin spacing	75m
Maximum number of range gates	2000
Dynamic range	Better than 95 dB
	Antenna
Reflector type and diameter	Prime focus feed, 8.5 m
Polarisation	Linear, Horizontal
Scan rate	3 to 36 $^{\circ}$ /s (0.5 – 6 r.p.m)
Beam width	\sim 1 $^{\circ}$
Gain	44.5 dBi
	Radome
Panel type	Epoxy-foam sandwich
No. of panels	66 in five layer structure
Shape of panels	Hexagonal and pentagonal
Diameter	11.6 m
Attenuation	Less than 0.7 dB (one way) at 10 mm/hr
Sidelobe degradation	Less than 1 dB
	Computers and peripherals
Work station	Two SUN ULTRA10 systems
Monitoring, maintenance and control systems	Five Pentium/AMD PCs
Real time raw data displays	Three 2k \times 2k flat screen monitors
4 mm DAT drive	1
DLT drive	1
Heavy duty Inkjet printers	2
Black and White Laser printer	1
Un-interruptible Power Supply	60 KVA

ANNEXURE 2**Scan strategy of 250 km volume scan for Z, V, and W parameters with dual PRF**

Scan range	: 250 km;	Pulse Repetition Frequency	: 600/480 Hz
Range resolution	: 0.5 km ;	Range Sampling	: 2
Antenna speed	: 9 deg/sec;	Time sampling	: 66
Unambiguous velocity (with velocity unfolding)	: 62.58 mps.		
Clutter to signal ratio	: 25.0 dB		
Log threshold	: 3.0 dB		
Signal Quality Index	: 0.25		
No. of antennal elevation steps	: 12		
Elevation angles	: 0.2, 0.7, 1.3, 2.0, 2.7, 3.4, 4.0, 4.8, 5.9, 7.8, 11.2, 19.8°		
Total time taken for each volume scan	: 8 minutes		
