

An analysis of anomalous propagation parameters and its effect on the intensity of clutter in weather radars

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(Received 11 October 2018, Accepted 15 May 2019)

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सार – मौसम रेडार का उपयोग पूर्वानुमानकर्ताओं द्वारा तूफानों की पहचान करने और इससे संबंधित वर्षा का अनुमान लगाने के लिए किया जाता है। रेडार बीम के विसंगतिपूर्ण प्रसार से मौसम की घटनाओं की गलत व्याख्या हो सकती है और वर्षा का अनुमान करने में त्रुटियां हो सकती हैं। जैसे ही मौसम रेडार विद्युत चुम्बकीय तरंगों को प्रसारित करता है, यह तापमान, दबाव और जल वाष्प की मात्रा पर निर्भर वायुमंडल के अपवर्तक सूचकांक से प्रभावित होने लगता है। वायुमंडल के अपवर्तक सूचकांक को समझना जरूरी है और यह रेडार के बीम प्रसार को किस प्रकार प्रभावित करता है, इसकी प्रतिध्वनियों की बेहतर समझ से मौसम संबंधी स्थितियों के कारण विसंगति होती है जिसका वर्णन बैटन (1973), डोवियाक और ज़निक (2006) और रेनहार्ट (2001) द्वारा विषय विशेष में किया गया है। ऊर्ध्वाधर अपवर्तकता ग्रेडिएंट (VRG) वायुमंडल में रेडियो तरंगों के प्रसार को प्रभावित करता है (गोस्सार्ड, 1977)। इस असंगत प्रसार से रेडार छवियों में धब्बे दिखाई देते हैं। रेडार छवि में मौजूद धब्बे की मात्रा से धब्बों की तीव्रता को विभिन्न समूहों में विभेदित किया गया। विशाखापत्तनम (VSK) स्टेशन पर रेडियो सॉडे से प्रेक्षित डेटा का उपयोग करते हुए विभिन्न ऊंचाइयों पर अपवर्तक प्राचल और तापमान प्रतिलोमन सतह की ऊंचाई की गणना की गई। रेडियो सॉडे से प्रेक्षित किए गए डेटा के मानों की तीव्रता समूहों के साथ तुलना की गई और यह पाया गया कि रेडार के ऊपर तापमान सतह का होना, रेडार के ऊपर VRG की तापमान सतह तथा समुद्र तल से 1 किमी तक की ऊंचाई पर VRG जैसे तीन पैरामीटर धब्बों की अधिकता को ज्ञात करने में प्रभावी रहे।

ABSTRACT. Weather radar is used by forecasters for identifying storms and estimating its corresponding precipitation. Anomalous propagation of the radar beam may lead to misinterpretation of the weather events and associated errors in precipitation estimates. As the weather radar transmits electromagnetic waves, it is affected by the refractive index of the atmosphere which depends on the temperature, pressure and water vapor content. It is important to understand the refractive index of the atmosphere and how it affects the beam propagation of the radar to interpret the echoes better. Meteorological conditions causing anomalous propagation is well described in literature by Battan (1973), Doviak and Zrnik (2006) and Rinehart (2001). The vertical refractivity gradient (VRG) affects the propagation of radio waves in the atmosphere (Gossard, 1977). These anomalous propagation cause clutter to be displayed in the radar images. The intensity of the clutter was differentiated into various groups by the amount of clutter present in the radar image. Refractivity parameters at various heights and the height of the temperature inversion layer were calculated using radiosonde observational data at the Visakhapatnam (VSK) station. The observed values from the radiosonde data were compared with the intensity groups and it was found that three parameters were influential in determining the intensity of the clutter which is the presence of the temperature inversion layer above the radar, the VRG of the temperature inversion layer above the radar and the VRG from the radar to a height of 1 km from sea level.

Key words – Anomalous propagation, Vertical Refractivity Gradient (VRG), Super refractivity.

1. Introduction

Weather radar is widely used by the forecasters for now-casting and estimation of Rainfall. They provide these services by analyzing the Doppler Weather Radar

(DWR) products such as MAX (Z), PPI (dBZ) and PPI (V). Weather radar sends electromagnetic radiation which is influenced by the refractive index of the medium which is atmosphere in this case. Temperature, pressure and humidity in the atmosphere affect the refractivity

index. When the Vertical Refractivity Gradient (VRG) is significant enough, they tend to bend the electromagnetic waves which are termed as anomalous propagation. When the bending towards the Earth is more than that in normal propagation then it is known as Super-refraction. When the VRG is high enough so that the ray bends to an extent that its curvature is more than that of Earth, the ray intersects the ground and this type of propagation is termed as ducting (Bech *et al.*, 2007; Dougherty and Hart, 1976; Justin *et al.*, 2014). The layer in which the VRG is high enough for ducting to occur is called as trapping layer. The region below the top of the trapping layer is called duct (Turton *et al.*, 1988). This trapping layer may be surface based or Elevated. In surface based duct the trapping layers extends to the ground, so the radio waves are brought to the surface. In case of elevated duct where the bottom of the trapping layer is higher than the surface, the propagation gets trapped within the layer without being brought to the surface. However, there is always a possibility of the energy leaking from the top of the duct (Ko *et al.*, 1983; Dougherty and Dutton, 1981; David, 2013; Atkinson and Zhu, 2005). The echoes generated when the radio waves hit the surface or targets close to the surface due to ducting are seen as clutter in the weather radar.

Weather radar clutter can be classified into three major groups (i) Ground clutter (land clutter and sea clutter) (ii) Air borne clutter (Biological targets (insects / bird) / Airplanes / Aerosols / Particulate matter) (iii) Interference clutter (Sun/Transmitting Antenna).

These clutters under certain conditions are difficult to distinguish from regular weather echoes and may lead the forecasters to misinterpret weather events and also lead to error in precipitation estimates (Bovith *et al.*, 2008). Though the land clutter with near zero velocities may be filtered by post processing algorithms using the velocity data, it is difficult to remove sea clutter and air borne clutters as they have a higher velocity values (Ryzhkov *et al.*, 2002; Alberoni *et al.*, 2001; Atkinson and Zhu, 2006). Filtering clutter with a higher velocity may remove useful weather data with similar velocities.

The refractive index changes occur due to a decrease in humidity with height which is caused by Temperature inversion wherein a warm dry air lies over a cool moist layer. This usually occurs during the winter period of January-March at Visakhapatnam when there is no rainfall event and radiative cooling takes place in the night and early morning hours. The refractivity as per ITU-R (2015) is given by :

$$N = (n - 1)10^6 = \frac{77.6}{T} \left(p + \frac{4810 \times e}{T} \right)$$

where, T is the air Temperature (K), p is the atmospheric pressure (hPa), e is the water vapour pressure (hPa) and n is the refractive index. VRG between two levels are calculated based on the difference of refractivity between the two layers. The frequency of the electromagnetic wave, the angle of incidence between the beam and the trapping layer also affects the propagation other than the VRG (ITU-R, 2003). As per ITU-R (2003), this expression may be used for all radio frequencies up to 100 GHz with an error less than 0.5%. Increase in the VRG bends the radar more slowly than the normal propagation and a decrease in the VRG causes the beam to bend faster than the normal propagation. Standard propagation occurs when the VRG of the atmosphere is around $1/4r$ (-39 N units per km) where r is the Earth's Radius. The VRG is given by dN/dZ with units in km^{-1} . N (Refractivity) is a dimensionless quantity. The effect upon propagation for different ranges of dN/dZ is given in Table 1 (Bech *et al.*, 2007).

When the VRG is less than -157 km^{-1} , the radio waves reach the surface (surface ducts) leading to the presence of ground clutter in the products. In case the VRG is between -157 km^{-1} to -39 km^{-1} the super-refractive condition brings the ray much closer to the surface making it prone to pronounced airborne clutters. The VRG can be obtained from radiosonde observations which provide the values of atmospheric parameters at different heights (Bech *et al.*, 1998).

Weather radars are equipped with post-processing algorithms which compensate for the partial beam blockage occurring due to the complex orographic features in the surrounding mountains. These algorithms work on the assumption of normal propagation, but in super-refractive conditions where the beam is bending towards the earth surface thereby lowering the height of the beam, a totally blocked beam may be considered as partial blocked leading to incorrect corrections in all the pixels of the particular radar ray (Bech *et al.*, 2007).

2. Data and methodology

The Analysis was done at Doppler Weather radar station Visakhapatnam, India (Lat. $17^\circ 44' \text{ N}$ Long. $83^\circ 22' \text{ E}$). A Gematronik GmbH, 10 cm wavelength non-polarimetric radar at a height of 148 m above mean sea level was used to study the anomalous echoes. The scan involves 10 elevations of 0.2° , 1.0° , 2.0° , 3.0° , 4.5° , 6.0° , 9.0° , 12.0° , 16.0° , 21.0° . The main products generated are Max (Z) 250 km, PPI (Z) 250 km, PPI (V) 250 km, PPI (Z) 500 km. The radiosonde ascents were taken from cyclone Warning center which is 6 km away from DWR station. The radiosonde sensor used is GPS sonde of JINYANG RSG 20A model. The ascents are taken at around 0000 UTC.

The effect of clutter in the products due to anomalous propagation was predominant in the months of January, February and March due to temperature inversion during night time and early morning caused by radiative cooling (Basha *et al.*, 2013; Kamran, 1990). The radar and radiosonde data used for the analysis is from January 2018 to March 2018. In the three months, radar was non-operational for 11 days out of the total 90 days period and radiosonde ascents were not taken on 5 days out of the total 90 days. Number of days both the radar and radiosonde data was available is 74 days.

2.1. Calculation of intensity of anomalous propagation

Forecasters mainly use MAX (Z) and PPI (Z) products for their forecasting purpose. These products are configured to display with a minimum value of 0 dBZ or 20 dBZ based on the operational requirements. On visual analysis of MAX (Z) and PPI (Z) images it was found that the clutter was higher in MAX (Z) echoes than in PPI (Z) images. This may be because the PPI (Z) displays the clutter seen from the lowest elevation of 0.2° only but MAX (Z) displays the clutter from all elevations though it is likely that the clutter is confined to lower elevations echoes. The intensity of anomalous echoes has been based on MAX (Z) products as it contains the clutter information of multiple lower elevation scans.

Two preprocessing methods that are applied during data processing of DWR Visakhapatnam gather relevance to the current analysis. First is the clutter filter (IIR Doppler 7) that removes the clutter echoes with a radial velocity width of 0.79 m/s and depth of 40 dB. As this filter is applied, most of the ground clutters get reduced however sea clutter and air borne clutter which have higher velocities than 0.79 m/s remains. Second is the partial beam blockage correction algorithm, where the dBZ correction for corresponding blocking angle is calculated as per Hannesen and Loffler-Mang (1998). This is done based on the Digital Terrain Elevation Model (DTEM) data provided. The degree of blocking is determined based on this data and appropriate correction is provided. No correction is provided for completely blocked beam. In the case of DWR Visakhapatnam there is a hill located in the south western part of radar station with the highest point at 358 m which is included in the DTEM data and in normal conditions, appropriate correction of data value is made for the partial beam blocking. During super-refractive conditions where the beam is more bent towards the Earth, the beam is completely blocked by the mountain and no correction is required but as per DTEM, the beam is considered as partially blocked and correction is provided for the entire ray which can be seen in the Images.

TABLE 1

Vertical refractivity gradient thresholds for different propagation conditions

Characteristic	dN/dZ (km ⁻¹)
Sub-refraction	> -39
Normal	-39
Super-refraction	< -39
Ducting (Super-refraction)	< -157

Interference clutter from sun and other antenna sources are unlikely to be influenced by anomalous propagation of Radio waves from the weather radar as these clutter arise not due to the back scattering from propagation of Radio waves of the radar but due to Radio Interference from a different source. As sun Radiates in all frequencies of spectrum it also radiates in the frequency of the radar. The receiver of the radar detects this signal and displays as a line of echo from center to horizon, this usually occurs during sunrise and sunset. For Visakhapatnam station, the time of sunrise in the month of January to March is mostly after 0030 UTC while the radar observation taken for the study is at 0000 UTC which is before sunrise. In case of interference from active sources, the images were visually verified for presence of any signature of interference clutter as they are usually seen as a ray of echo from the Antenna source to the weather radar (Saltikoff *et al.*, 2015).

The Influence of the anomalous propagation has been classified into three categories namely High, Medium and Low based on the amount of clutter signatures present in the MAX (Z) image on a clear weather day. The display image selected for analysis is chosen from 0000 UTC observation of DWR as this closely coincides with the radiosonde observations. The number of pixels in the image is 600 × 600. The categorization of intensity is found by calculating the percentage of pixels having value of 0 dBZ and above out of total number of pixels in a clear weather.

2.1.1. Removing observations with weather echoes

Though January to March season does not have any significant rainfall, there were some instances of rainfall which were represented in the radar image as weather echoes with reflectivity higher than 0 dBZ. This may lead to incorrect calculation of clutter present in the image as the weather echoes will also be considered as clutter. To avoid this, a visual verification of MAX (Z) and associated PPI (V) and PPI (Z) images of all 71 days was done and the images containing the weather echoes were removed from the categorization of intensity.

TABLE 2

Classification of clutter intensity based on amount of clutter present

Intensity	% of clutter
High	20% and above
Medium	10% to 20%
Low	Less than 10%

2.1.2. Calculation of clutter percentage and categorization

The amount of clutter present in the image (% of clutter) is calculated by the following formula:

$$= \frac{\text{Number of clutter pixels with 0 dBZ and above}}{\text{Total number of pixels (600} \times \text{600)}} \times 100$$

The categorization of anomalous propagation based on percentage of clutter is done as given in Table 2. This categorization is not universal, but has been chosen based on the residue clutters left in processed images.

2.1.3. Physical verification of clutter intensity

The intensity categorizations were also visually examined with corresponding images for ascertaining the findings. In few clutter free observations, the % of clutter calculated had been higher due to the presence of noise. Further, evaluation revealed that the algorithm could not attribute for the reduced signal to noise ratio (SNR) in the data. This led to the algorithm modification to correlate with variation with the next observation after 10 minutes, as an additional control measure. This led to quality removal of 12 data sets bringing down samples used to 62 from 74.

On the basis of above procedure, from a total of 62 valid radar observations, 13 are categorized as High intensity, 13 as Medium intensity and 36 of Low intensity which is also pictorially depicted in Fig. 1.

2.2. Calculation of refractivity parameters from radiosonde data

Radiosonde ascents were taken every day at around 0000 UTC/0530 IST. The observed values are temperature, pressure, humidity, wind direction and wind speed with a temporal resolution of 1 second. The refractivity (N) for each observation at a particular height is calculated based on the formula as given below :

$$N = (n - 1)10^6 = \frac{77.6}{T} \left(p + \frac{4810 \times e}{T} \right)$$

where, T is the air Temperature (K), p is the atmospheric pressure (hPa), e is the water vapour pressure (hPa) and n is the refractive index. The water vapour pressure (e) is given by the formula :

$$e = 6.11 \times 10^{\left(\frac{7.5 \times T_d}{237.3 + T_d} \right)}$$

where, T_d is the dew point temperature ($^{\circ}\text{C}$) which is obtained from the temperature and humidity values in radiosonde observation.

Refractivity is calculated based on curved Earth and beam propagating in a straight line. In case of considering Earth to be flat, the beam appears to bend upwards which is taken into consideration by Modified refractivity. Modified Refractivity is calculated from the following formula to verify the types of anomalous propagation differentiated based on Refractivity index.

$$M = N + \frac{z}{10^{-6} r}$$

where, z is the height and r is the radius of Earth in meters.

Based on the Refractivity index, following parameters were calculated.

2.2.1. Height of temperature inversion layer from the radar station [Htir (m)]

The radar is situated at a height of 148 m above mean sea level and height of the feed horn is 170 m above mean sea level. The Radio waves are incident on the atmosphere at the height of the feed horn. The height of temperature inversion layer considered from the level of the station is calculated as Htir. It was also observed that there were elevated layers of temperature inversion which were present much higher than the height of the radar and not at the level of incidence of radio waves (Sarma, 1990).

2.2.2. Vertical refractivity gradient of the temperature inversion layer

As the Refractivity is known for each height level, the vertical refractivity gradient observed in the layer of temperature inversion VRG (Htir) was calculated as per below formula :

$$= \frac{\text{Value of } N \text{ at Htir} - \text{Value of } N \text{ at Radar height}}{\text{Htir(km)} - \text{Radar height (km)}}$$

The refractivity gradient is calculated only up to the top layer of temperature inversion from the height of the

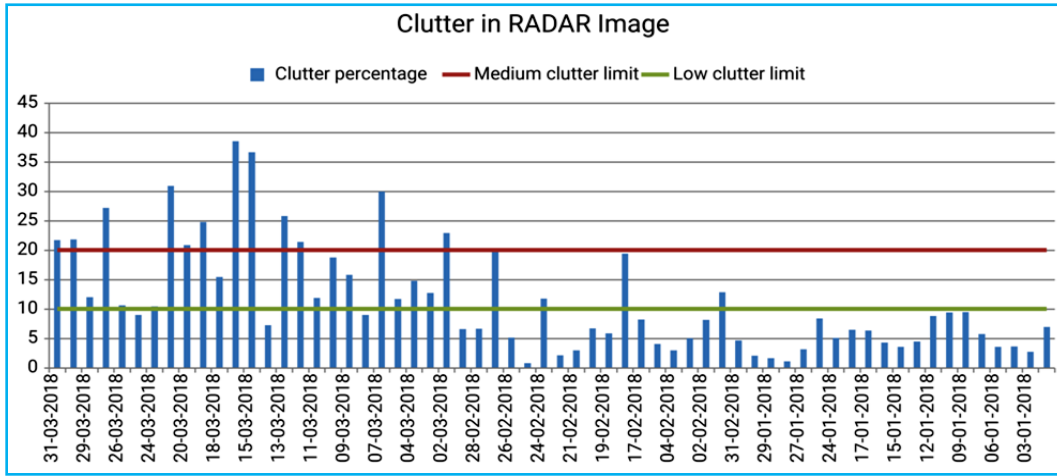


Fig. 1. The amount of clutter percentage present in the RADAR Image

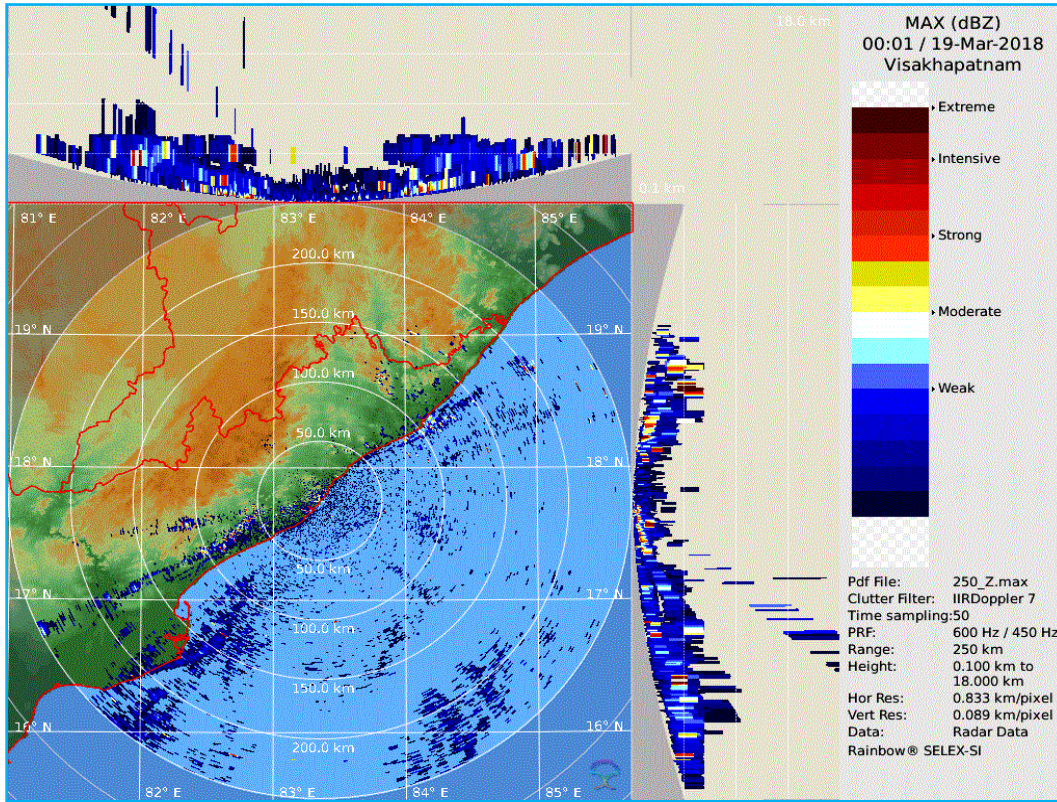


Fig. 2. 25% clutter (High intensity) seen on 19/03/2018 0000 UTC from DWRVSK

radar and not for any specific height so that the VRG value is not increased due to the prevalence of normal atmospheric conditions over the temperature inversion layer (Sarkar *et al.*, 1992).

To effectively deviate a radar beam from the surface, the layer should have a minimum depth as given by :

$$D_{min} = \left\{ C\lambda \left(-\frac{\partial N}{\partial Z} \right)^{\frac{1}{2}} \right\}^{\frac{2}{3}}$$

where, C is 400 for surface ducts and 263 for Elevated ducts, λ and D_{min} are in meters (Lopez, 2008). dN/dZ is the VRG and λ is the wavelength of the radar which is 10 cm. For a wavelength of 10 cm the minimum

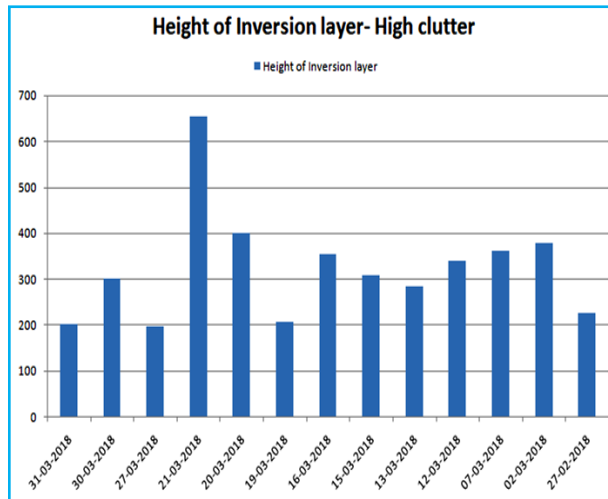


Fig. 3. Height of Inversion layer in high clutter images

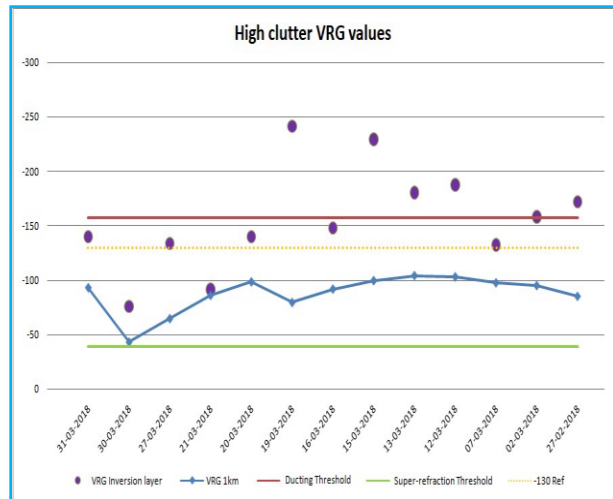


Fig. 4. VRG values at Inversion layer and 1 km in high clutter image

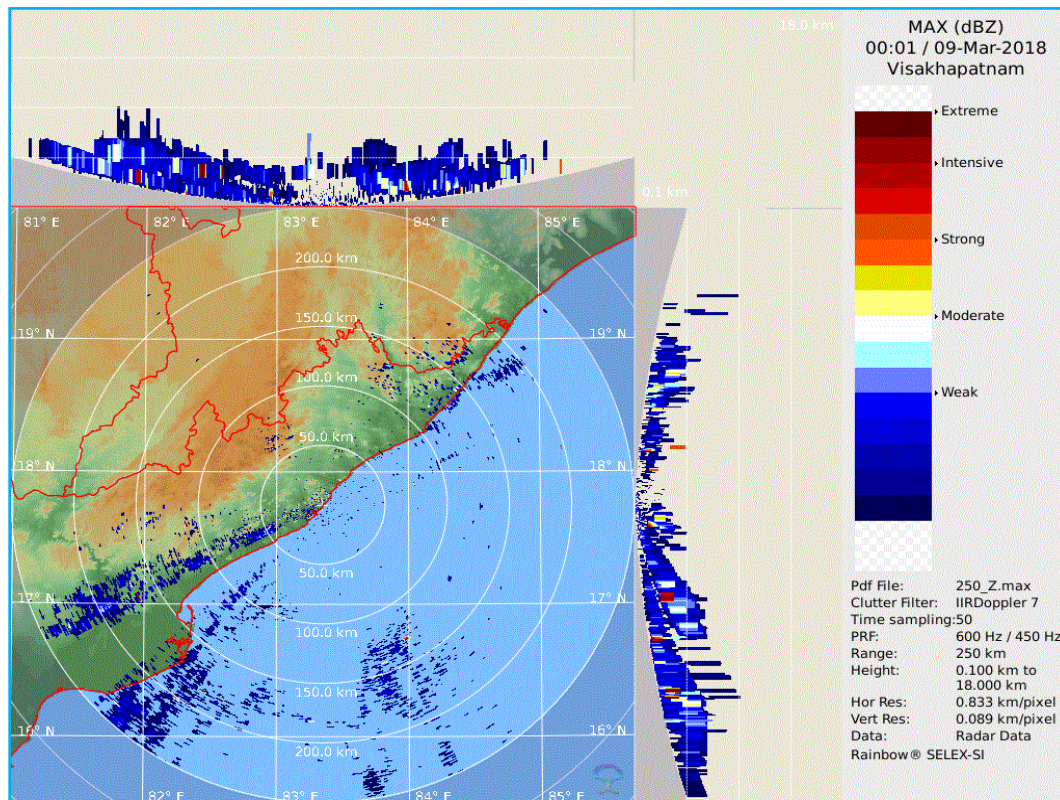


Fig. 5. 15% clutter (Medium intensity) seen on 09/03/2018 0000 UTC from DWRVSK

depth required for a ducting layer ($dN/dZ = 157 \text{ km}^{-1}$) to deviate most of the radar beam is around 22 m for a surface duct and 16 m for elevated duct. As the height of temperature inversion layer varies from 50 m to 600 m, the VRG for the temperature inversion layer from radar is calculated to find the effect of height of the temperature inversion layer (which acts as a ducting layer) on the intensity of clutter.

2.2.3. Vertical refractivity gradient from the height of radar to 1 km above mean sea level

As temperature inversion is not the only cause for clutter and it was observed that clutters were found in cases when there was no temperature inversion. The general VRG values of the atmosphere from the height of the radar to 1 km above sea level are calculated

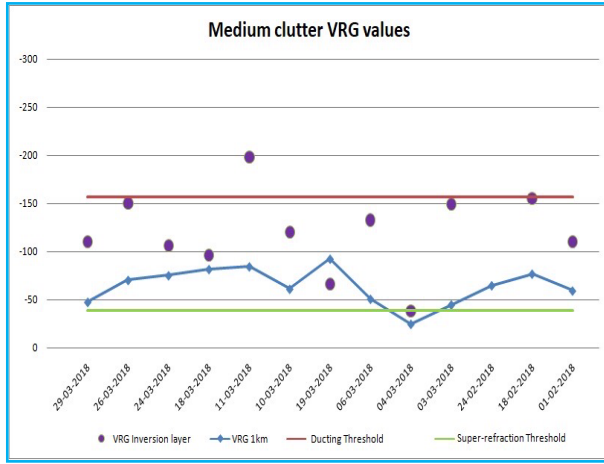


Fig. 6. VRG values at Inversion layer and 1 km in medium clutter image

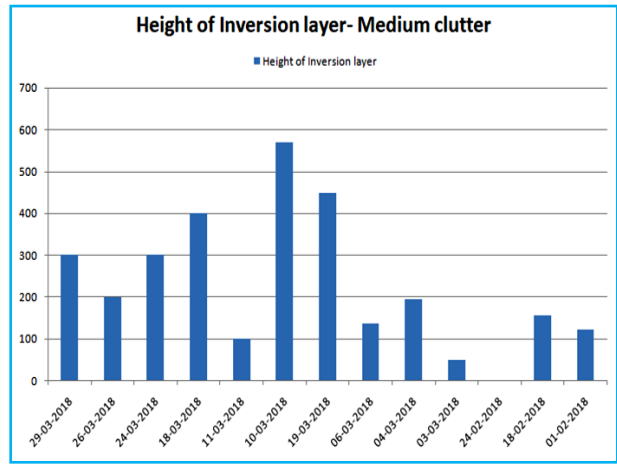


Fig. 7. Height of Inversion layer in medium clutter images

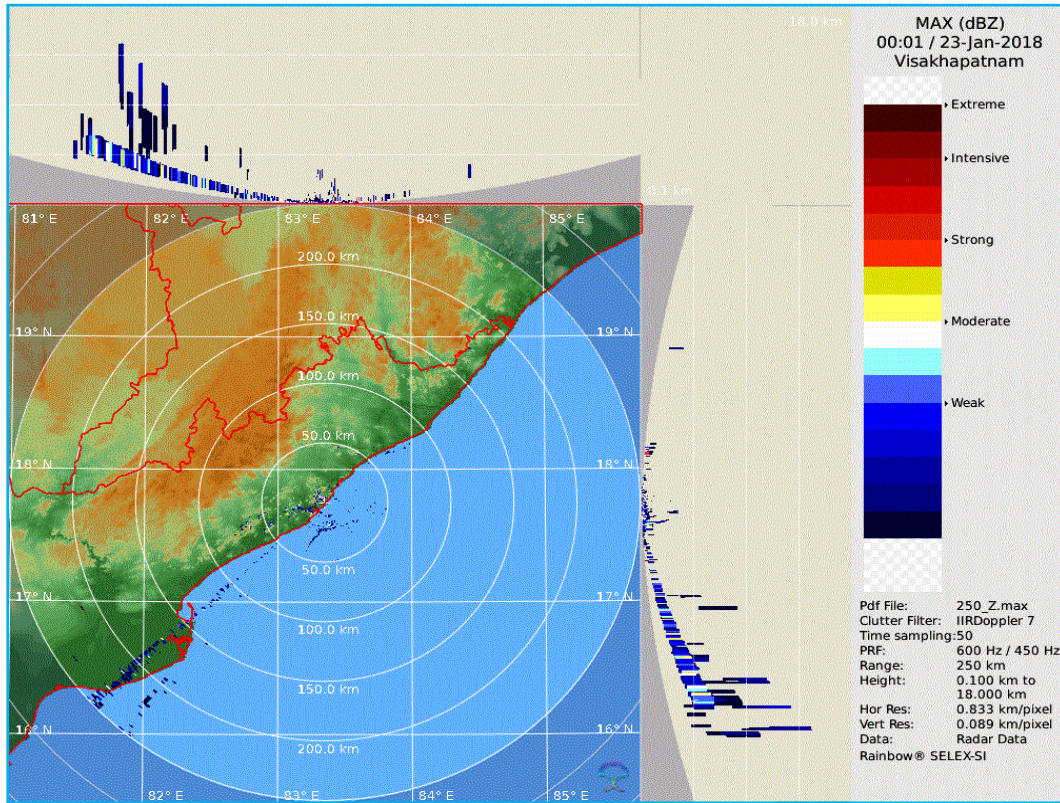


Fig. 8. 6% clutter (Low intensity) seen on 23/01/2018 0000 UTC from DWRVSK

irrespective of the presence of any temperature inversion VRG (1 km) by the following formula :

$$= \frac{\text{Value of } N \text{ at } 1 \text{ km} - \text{Value of } N \text{ at Radar height}}{1 \text{ km} - \text{Radar height (km)}}$$

This is calculated to ascertain the intensity of the clutter when there is no temperature inversion and its associated VRG values in the atmosphere.

3. Results and discussion

Based on the above observations the following results were obtained.

3.1. High intensity clutter

In case of high intensity clutter where the amount of clutter was greater than 20% (Fig. 2), temperature inversion

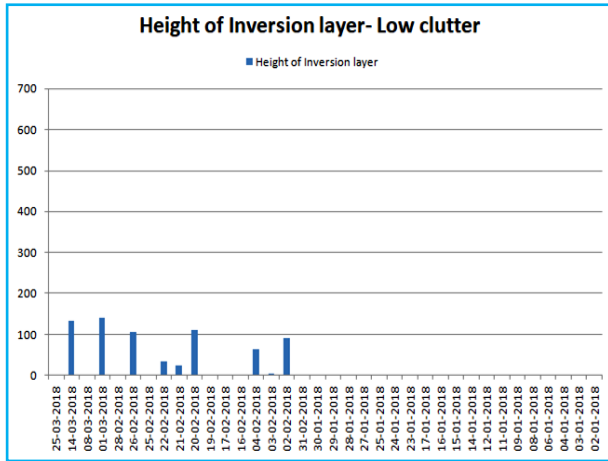


Fig. 9. Height of Inversion layer in Low clutter image

layer was present above the radar in all 13 observations in which 69% of the observations had the inversion layer from the radar height and remaining had elevated layer. The height H_{tir} of the temperature inversion layer is more than 200 m in all 13 observations as shown in Fig. 3. The VRG (H_{tir}) is less than -157 km^{-1} (Ducting) in 46% of observations and between -39 km^{-1} to -157 km^{-1} (superrefractive) in 54% of observations. Out of the total observations, the VRG (H_{tir}) for 84% of the observations is less than -130 km^{-1} making the values skewed towards ducting as shown in Fig. 4.

The value of VRG (1 km) is less than -39 km^{-1} (Super-refractive) in all observations. As both ducting and super-refractive conditions contributed to the clutter, it is likely that the air borne clutter and the ground clutter together contributed to the high intensity of the clutter. As in most of the cases, the depth of the inversion layer is more than 200 m with a refractive gradient of less than -130 km^{-1} , it is likely that the super refractive bending of radio-waves is closer to the ground at lower elevations leading to an increased level of clutter.

3.2. Medium intensity clutter

In case of medium intensity clutter where the amount of clutter is between 10%-20% (Fig. 5), temperature inversion layer is seen in nearly 12 out of 13 observations in which only 50% of the observations had the inversion layer from the radar height and 50% had elevated inversion layers. But in both types of inversion layers the VRG(H_{tir}) is between -39 km^{-1} to -157 km^{-1} (super-refractive) in 92% of the observations as shown in Fig. 6. Ducting level VRG (H_{tir}) of less than -157 km^{-1} has been recorded only in 1 observation. The height of the inversion layer is between 50 m to 200 m in case of inversion layers present at radar height but between 150 m

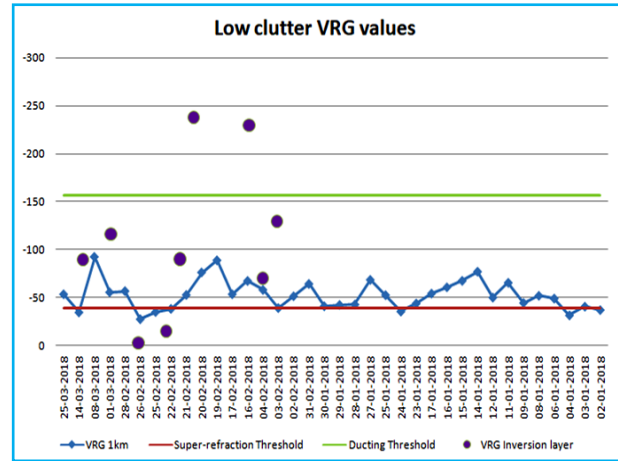


Fig. 10. VRG values at Inversion layer and 1 km in Low clutter images

to 400 m in elevated layers (Fig. 7). The VRG (1 km) is less than -39 km^{-1} (super-refractive) in all of the cases. As, there was no ducting conditions present in inversion layers, the clutter may be contributed mainly by air borne clutters due to super-refractivity. This could be the cause for the reduced amount of clutter compared to the high intensity clutter.

3.3. Low intensity clutter

In case of Low intensity clutter where the clutter level is below 10% (Fig. 8), temperature inversion is seen in only 25 % of observations (Fig. 9) with VRG (H_{tir}) less than -39 km^{-1} (Super-refractive) in 7 out of 9 observations. The Height of the inversion layer in such cases is below 100 in 55% of observations and between 100 to 150 m in the remaining ones. The VRG (1 km) is less than -39 km^{-1} (super-refractive) in 80% of cases out of the total observation (Fig. 10).

The main contributor of the clutter is likely to be partial beam blockage correction. It was seen in images of low intensity clutter that echoes from a single region in the south western sector where a hill is present contributed to the clutter percentage. On visual inspection, it was observed that if the region of partial beam blockage correction is ignored then only 10 of the total 36 observations can be considered to contain significant clutter. Seven out of the 10 observations had an inversion layer. In the remaining 26 observations nearly 73% had VRG(1 km) between -39 km^{-1} and -60 km^{-1} (Super-refractive) which is skewed towards normal propagation VRG levels. It can be inferred that in the 10 observations, the clutter may be contributed by air borne clutters and partial beam blockage correction due to super-refractivity level VRG (H_{tir}) and in remaining 26, the bending of radio waves was closer to normal propagation due to

super-refractivity level VRG (1 km) being skewed towards normal propagation causing only the partial beam blockage correction to be the major contributor of clutter.

4. Conclusions

Based to the present study the main factors affecting the intensity of the clutter are :

- (i) Presence of temperature inversion layer above the radar and its height
- (ii) The Vertical Refractivity Gradient (VRG) of the temperature inversion layer above the radar
- (iii) The Vertical Refractivity Gradient (VRG) from the radar to a height of 1 km above sea-level

The intensity of clutter presence can be adjudged by the parameters as below :

- (i) High intensity : Presence of temperature inversion layer of a height greater than 200 m with a Vertical refractivity Gradient of the temperature inversion layer to be in ducting and near ducting propagation conditions.
- (ii) Medium intensity: Presence of temperature inversion layer greater than 50 m with a vertical refractivity gradient of the temperature inversion layer to be in super-refractivity propagation conditions.
- (iii) Low intensity : Vertical Refractivity Gradient from the radar to 1 km above sea level is in super-refractive and near normal propagation conditions.

Dual polarization radar improves the ability to detect non-meteorological echoes thereby improving the forecaster's skill in identifying storms and estimate precipitation.

Acknowledgements

Authors are grateful to Director General of Meteorology India Meteorological Department, New Delhi, Head (Instruments) IMD, New Delhi, Deputy Director General of Meteorology, Regional Meteorological Centre, Chennai, for encouraging this research work.

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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