Doppler Weather Radar and its products - An Overview

Project submitted by

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CERTIFICATE

This is to certified that the project report title "Doppler Weather Radar and its products - An Overview" is work done by Dr. Subhendu Brata Saha, Met-A, IMD Advance Training Course in Meteorological Instrumentation & Information System Batch No. – VIII, ICITC. Under my supervision.

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3. Prelude:

Meteorologists have many tools at their disposal, including Radar, to predict the weather forecast. Radar term is the abbreviation of RAdio Detection And Ranging, i.e. finding and positioning a target and determining the distance between the target and the source by using radio frequency. Radar can decipher how far away precipitation is, its speed and how big droplets or snowflakes are. This data can then be used in computer forecasting models to predict future weather trends, while alerting meteorologists to upcoming precipitation, storms or severe weather.

During World War II, military radar operators noticed noise in returned echoes due to rain, snow, and sleet. After the war, military scientists returned to civilian life or continued in the Armed Forces and pursued their work in developing a use for those echoes. Between 1950 and 1980, reflectivity radars, which measure position and intensity of precipitation, were incorporated by weather services around the world.

Doppler radar emits beams (pulses) of microwave energy from a transmitter into the atmosphere. When these beams collide with objects in the atmosphere such as raindrops, hail stones, snowflakes, cloud droplets, birds, insects, dust particles, trees, and even the ground, some of the energy bounces back towards the radar. A receiver on the radar then collects the reflected energy and displays it in different ways.

4. Doppler Weather Radar Principle:

Doppler effect is a means to measure motion. When the distance between the source and receiver of electromagnetic waves remains constant, the frequency waves is the same in both places. When the distance between the source and receiver of electromagnetic waves is increasing, the frequency of the received wave forms is lower than the frequency of the source wave form. When the distance is decreasing, the frequency of the received wave form will be higher than the source wave form.

Doppler radars not only detect and measure the power received from a target, they also measure the motion of the target toward or away from the radar. Doppler radar makes use of the Doppler Effect to measure velocity of moving targets it detects. It works by detecting the change in the frequency of the transmitted and returned signal arising due to the movement of the target (Figure-1). The velocity component of a target relative to the radar beam is known as the "radial velocity". Radial velocity is determined from Doppler frequency shift of the target. Moving targets change the frequency of the returned signal. This frequency shift is then used to determine wind speed. Doppler radars routinely measure velocities and used to detect wind speeds. Motion towards a Doppler radar is expressed in negative values and

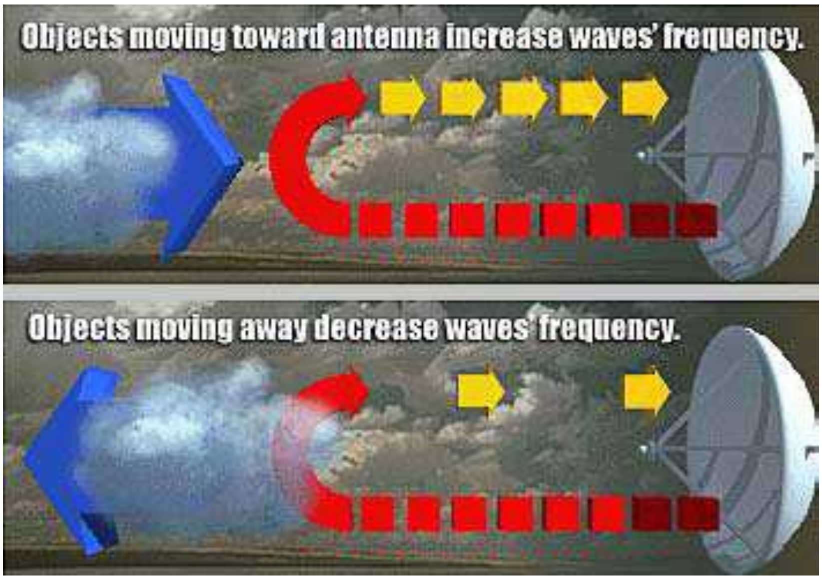

Figure 1: Doppler Frequency Shift by Moving Targets.

motion away from Doppler radar is expressed in positive values. If the target is moving sideways so that its distance relative to the radar does not change, the radar will record zero radial velocity for that target.

5. Types of Doppler Weather Radar:

Doppler weather radar can be broken up in terms of wavelength. This includes the following:

i) **S-Band radar** -> Wavelength: 8 – 15 cm -> Frequency: 2 – 4 GHz.

Application -> This radar's longer wavelength allows the beam to penetrate through several bands of precipitation, expanding the range for analysis further than the C-Band radar. As with all radars, the further the beam is away from the radar site, the higher the beam is above the ground. Therefore, what is analyzed aloft is not always what one would experience at the ground level. However, the ability to see and analyze precipitation returns from greater distances does help the meteorologist to generate alerts further in advance. This radar is the most expensive of the three radar bands.

ii) **C-Band radar** -> Wavelength: 4 – 8 cm -> Frequency: 4 – 8 GHz.

Application -> C-Band radars are often intended for short-range weather observation but can be used in medium to long-range precipitation analysis. The wavelength of the radar beam can penetrate through moderate to heavy bands of precipitation to identify what is beyond the closest precipitation band. However, the beam does attenuate (that is, loses its strength) much more than the longer wavelength S-Band and therefore does not recognize precipitation rates as accurately as the S-Band. These radars are generally smaller and less expensive than S-Band weather radars, but more expensive than the smaller X-Band radar.

iii) **X-Band radar** -> Wavelength: 2.5 – 4 cm -> Frequency: 8 – 12 GHz

Application -> X-Band radars have a smaller wavelength that makes them more sensitive to lighter particles. These radars are also more susceptible to attenuation as the smaller wavelength does not allow the radar beam to penetrate through heavy precipitation bands. This can block the radar from seeing past the initial band of precipitation to identify what could be approaching. The X-Band radar generally uses a smaller antenna dish and therefore is much less expensive than C- and S-Band radars.

6. DWR System and Components:

RF transmitter of Doppler Weather Radar generates high power microwave radiation in pulses, an antenna to send the signal out to space and to receive scattered energy (echoes) from targets around, a servo system to move the antenna in a planned schedule scan, a receiver to detect and process the received echo signals and a display unit to graphically present the signal in user understandable form (Figure 2). Magnetrons, klystrons and travelling wave tubes still continue to be the main RF oscillators of most radar transmitters.

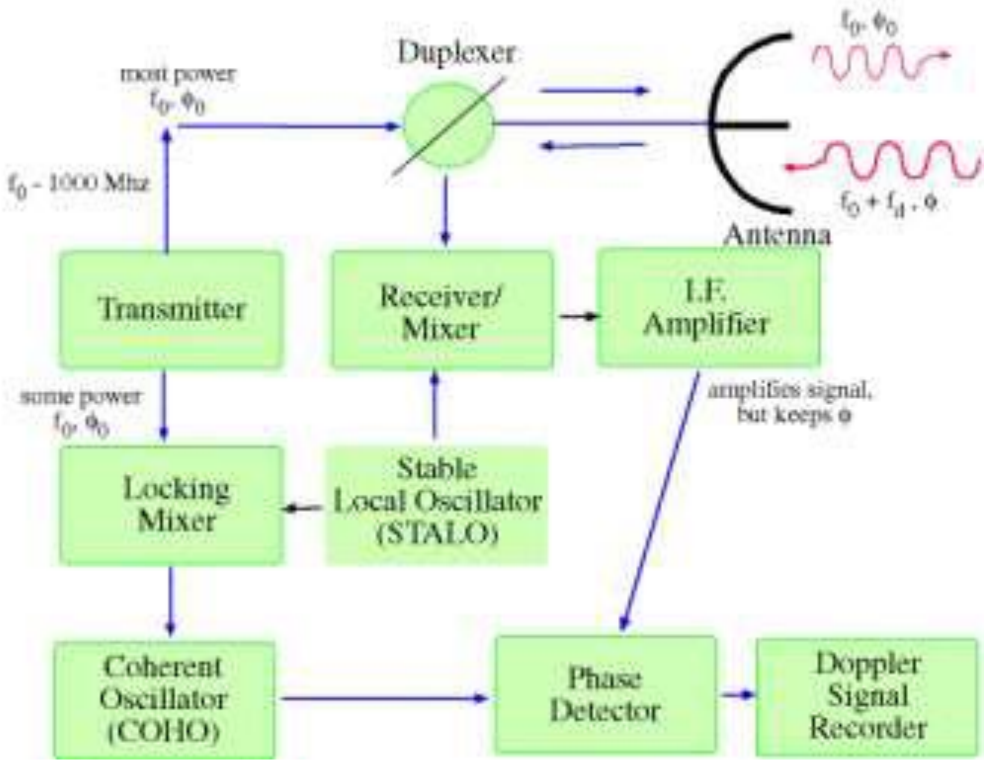

Figure 2: Block Diagram of Doppler Weather Radar

The basic components of Doppler Weather Radars have included:

Transmitter: The transmitter generates the RF energy either in oscillator mode, or in Amplifier mode from a stable RF Source (STALO). Klystrons (Figure 3) are used for this purpose most of the time in DWRs for the purpose of coherence to detect the phase differences in the transmitted and received frequencies. RF Power transmitters of the order of 500 KW are common, whereas transmitter with 1000 KW power is also used in a IMD radar. Though general working voltages are of the order of 1KV, some transmitters use high voltages of the order of 70KV.

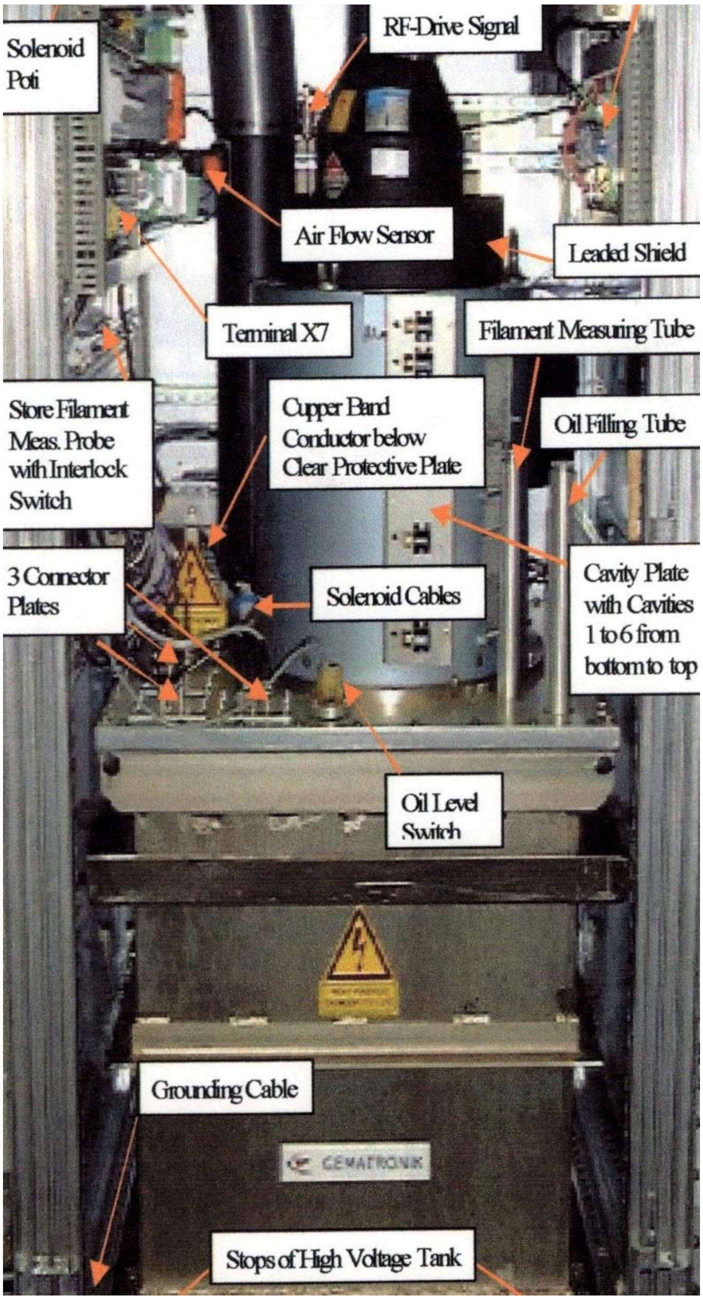

Figure 3: Klystron

RF Oscillator Tubes: Magnetrons, Klystron, Thyratron are the popularly used tubes in weather radars. Magnetrons are mostly used in conventional non-Doppler radars. After improved technology Magnetrons are also being used in DWRs. Klystrons are used in DWRs particularly to achieve high coherence between the transmitted and received pulses. These Klystrons are used as Amplifiers where the output power & pulse repetition frequency is controlled by modulator circuits.

Wave guides: RF power is transmitted to the antenna using wave guides which are also known as travelling wave tubes. Wave guides are hollow metal tubes with rectangular cross section, made from aluminum or gun metal. In the waveguide chain where ever bends are required L-bends and U-bends are used. Flexible wave guides are also used where-ever links are to be negotiated slightly, during installation.

Antenna / Radar Dish: A Radar antenna is generally a parabolic dish antenna that is very sensitive with high gain. It is generally designed to generate beam of about 1-degree beam-width for generating high resolution data sets. Modern radar tools are composed of a large radar dish and a protective layer to shield it from deterioration (Figure 4). The dish can rotate in order to gather data and information from different areas. Meanwhile, an antenna sends pulses into the atmosphere and receives the reflected pulses. As the energy signal interacts with objects, energy waves scatter with some bouncing back to the weather radar.

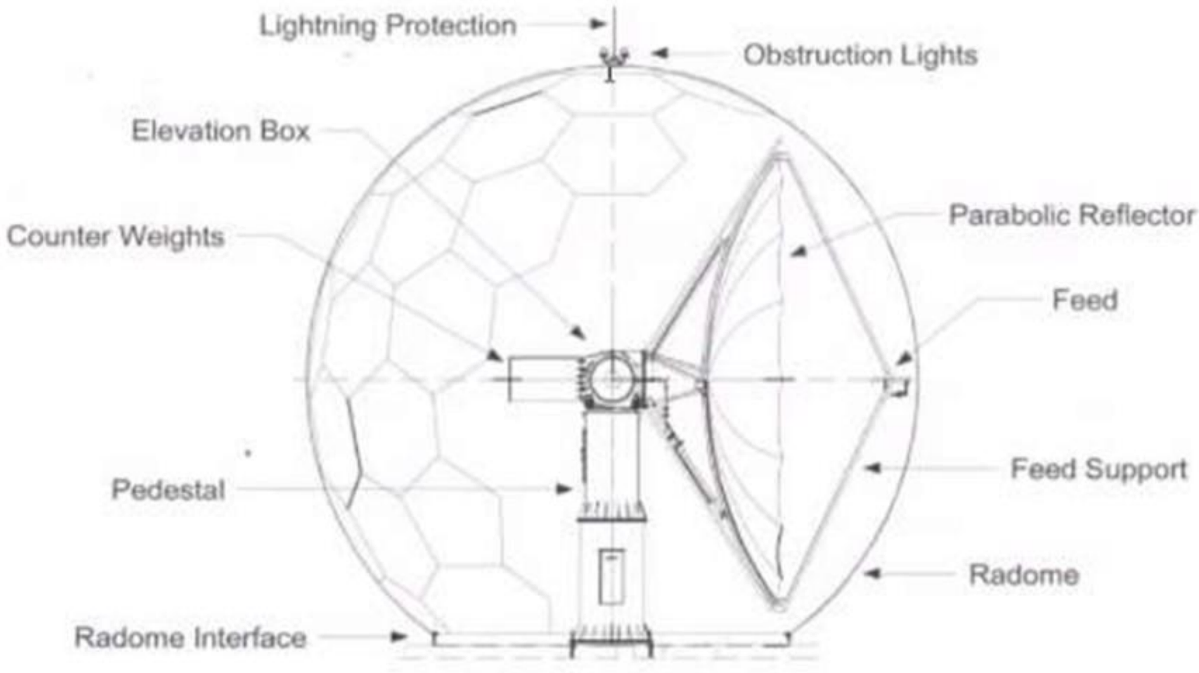

Figure 4: DWR Antenna and Radome

Duplexer: The same antenna is used for transmitting and receiving the RF Signals. The switching is done by duplexers. Duplexers allow the receiver to be cut-off from antenna during transmission to safe guard the receiver. Circulators are one type of duplexers and when ferrite materials are used as core of these circulators, they are known as ferrite circulators.

Receivers: Receivers are divided into two types basically. RF Front end amplifiers are RF booster amplifiers that increase the signal strength of received energy. Mixer-amplifier actually mixes the Received energy with STALO frequencies and the generated Intermediate Frequency IF is used for further processing. In general, 10 MHz or 30 MHz are the IF frequencies. Some radars use two-stage IF mixing.

Signal Processors: Signal processing is the most complicated of all radar hardware. It involves deriving the echo properties/radar base parameters from the received signals. Algorithms like Pulse pair and Fast Fourier Transformation (FFT) techniques are used for this. The basic output of the Receiver consists of information on Amplitude and Phase of the received signal. From amplitude information we deduce the intensity of the back-scattered signal and from Phase information we deduce the radial velocity of the moving targets.

Servo System: The Servo system is the hard ware part of remote control of antenna. It consists of antenna gear assembly, motor systems, position encoders, servo controllers and a control console. Modern servo systems are operated based on computer programs/scan schedule stored in workstation of radar controller.

Radar Controllers: A modern DWR needs coordinated operation between transmitter, receiver, servo, antenna, data collection, signal processing and display systems. This needs a central monitoring and control of all the operations flawlessly. A Radar controller is a programme that takes care of all these operations, based on the inputs from the operator either in manual (immediate) mode or in automatic (pre-programmed) mode. Most of the modern radars are generally operated in fully automatic mode that takes care of the operation, calibration, data acquisition, product generation and data dissemination.

7. DWR Base Products:

The base products obtained from radar are reflectivity **Z** expressed in dBZ, radial velocity **V** expressed in m/s and spectrum width **W** expressed in m/s.

a) **Reflectivity (Z)**:

Reflectivity describes the water content in a cloud echo. It, however will present the reflectivity/ back scattering of other types of echoes. Hence this product describes the basic echo properties and its nature. In case of clouds higher dBZ represents higher water content and its capability to deliver higher rain rate. It also indicates the possibility of hail associated with high dBZ values, in case of convective clouds. Any objects like hills, ships, aircrafts etc have highest reflectivity due to reflection in addition of back-scattering and but seldom they have any significant velocity values. Echoes of short duration are known as angel echoes which will disappear in subsequent scans. In stratiform clouds with heights generally above 6 Kms, we will have a bright band layer at about 3.5 to 4.5 kms height depending upon the freezing level in the atmosphere. The bright band occurs just below the freezing level when the melting ice particles mimic like very large drops, contributing largely to the dBZ comparing to the surroundings. This is an error found in stratiform clouds mostly. Thunder clouds or CB clouds have an important role in the interpretation of radar echoes. The most important feature of these clouds is that they will have high reflectivity brimmed by very steeply falling reflectivity. High spectral width is noticed for these echoes.

b) Radial Velocity (V):

Radial velocity indicates the velocity sensed by the radar antenna in its direction. It always gives a Cosine component of the actual wind if there is an angle between the wind and antenna. Since Cos90 is Zero, the antenna cannot sense any wind if the wind is perpendicular to the position of the antenna. Similarly, since cos0 and Cos 180 are +1 and -1 respectively, at two positions the radial velocity is actual velocity with different signs. Positive sign indicates wind leaving the radar and Negative sign indicates the wind approaching the radar. Unless Constant Altitude Plan Position Indicator (CAPPI) product is used the Radial Velocity is always defined on a conical surface depending on the elevation angle. If target is moving in the direction of radar beam i.e. $\Theta = 0$ degree then doppler frequency shift, $f_d = 2v/\lambda$, whereas if target is moving tangentially to radar beam $\Theta = 90$ degrees then $f_d = 0$ and radial velocity measured will be zero, which is a basic limitation of the Doppler radar.

c) Spectrum width (W):

The Doppler shift associated with a single target is $f_d = (2v \cos \Theta)/\lambda$

where,

f_d is the frequency shift in hertz,

v is the velocity of the target in meters/second,

λ is the wavelength in meters,

θ is the angle defined by the direction of target travel and the radar line of sight to the target.

Now when there are many targets like in rain, then each rain drop is a target moving with different velocities. Then in a sample volume of rain, each raindrop will produce a frequency shift corresponding to its radial velocity. A Doppler processor processes all the returned signals to produce a single velocity for the entire sample volume which is a mean velocity of the sample, known as the radial velocity. Now in the sample volume there is a distribution of frequencies from the thousands of rain drops present. The distributions of frequencies show how variable the velocities are within the volume. Therefore, the spectrum width term means the width of the spectrum of frequencies detected which is measure of variability of velocity within the sample volume i.e., how variable are the velocities in the sample. This is also defined in terms of variance of the velocity which is essentially the average departure of individual velocities from the mean velocity of the sample. The spectrum width (W) is correlated to turbulence in the atmosphere.

8. DWR Derived Meteorological Products:

(a) Plan Position Indicator (PPI):

In Plan Position Indicator product (PPI) reflectivity (Z), radial velocity (V) or spectral width (W) is presented on a conical surface of a constant elevation as an output image. The displayed range is the slant range and this is different for different elevations. PPI displays for reflectivity (Z) and radial velocity (V) are given in Figure.5(a & b). Figure 5(a) is a PPI display of reflectivity generated from DWR Kolkata during “AMPHAN” super cyclone of May 2020. Eye of the cyclone is clearly visible and is small in size. Figure 5(b) shows PPI display of velocity for same cyclone. The figure shows a couplet (2Ds) of two maximum radial velocities of opposite direction. The maximum radial velocity in the couplet corresponds to observation when radar beam is parallel to wind direction in the rotating wind field in the eye-wall region and can be taken as true maximum wind for calculating other parameters like storm surge, pressure departure etc.

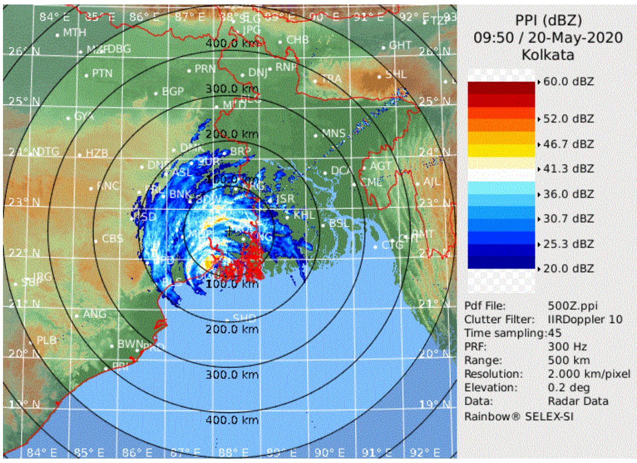

Figure 5(a): Reflectivity (Z) during super cyclone AMPHAN

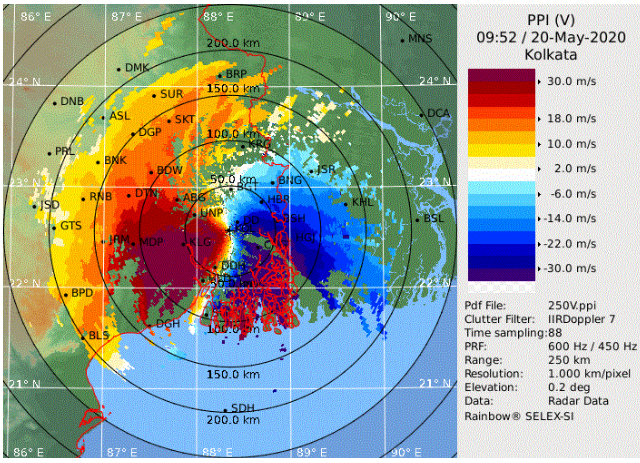

Figure 5(b): Radial velocity (V) during super cyclone AMPHAN

(b) Range Height Indicator (RHI):

Range Height Indicator product is generated by presenting reflectivity or velocity on a x-y graph with the range on the X-axis and the height on the Y-axis. A Cartesian grid is displayed as an overlay to facilitate reading height of clouds. This grid is seen bending along the X-axis to due to correction for earth curvature. A sample RHI product is illustrated in Figure-6.

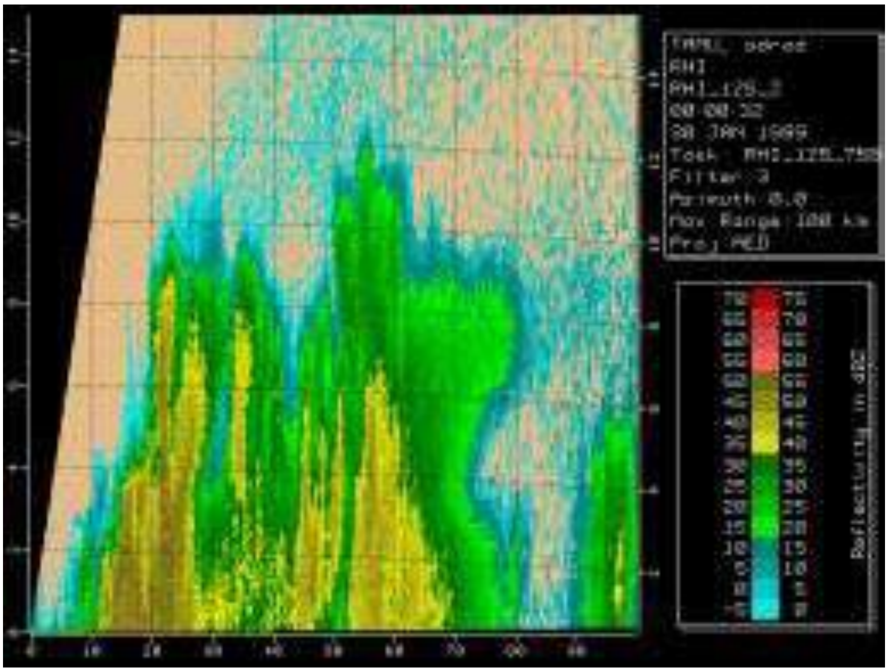

Figure 6: Range Height Indicator (RHI)

(c) Maximum Display (MAX):

The Maximum Product takes a polar volume raw data set, converts it to a Cartesian volume, generates three partial images and combines them to the displayed image. The height and the distance between two Cartesian layers are user definable. The partial images are:

i) A top view of the highest measured values in Z-direction. This image shows the highest

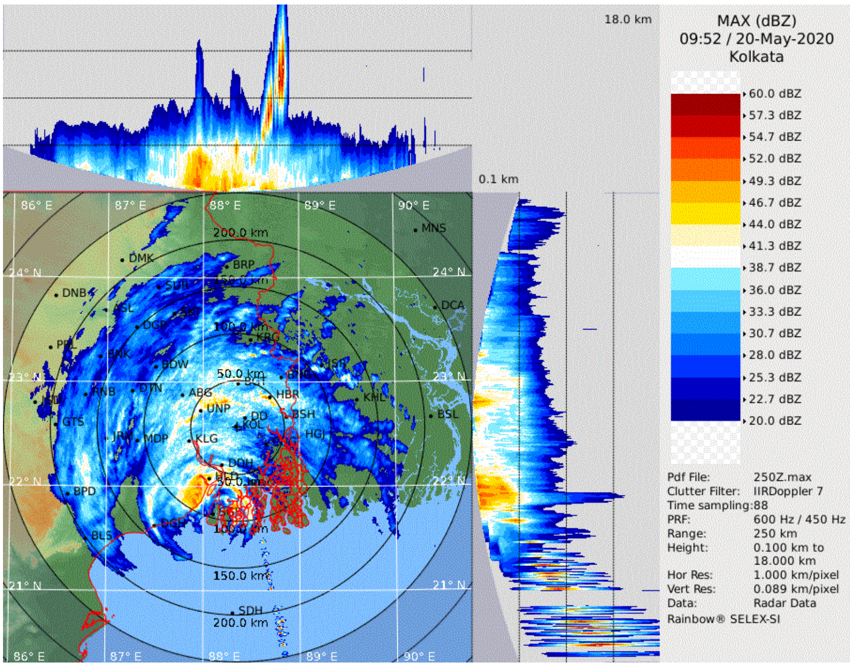

Figure 7: Max Z product of AMPHAN super cyclone

measured value for each vertical column, seen from the top of the Cartesian volume.

ii) A north-south view of the highest measured values in Y –direction. This image is appended above the top view and shows the highest measured value for each horizontal line seen from north to south.

iii) An east-west view of the highest measured values in X-direction. This image is appended to the right of the top view and shows the highest measured value for each horizontal column seen from east to west.

This single product provides distribution of parameters measured by DWR in three dimensional spaces. A Max Z product during super cyclone AMPHAN observed from DWR Kolkata is illustrated in Figure 7.

(d) Surface Rainfall Intensity (SRI):

The Surface Rainfall Intensity (SRI) generates an image of the rainfall intensity in a user selectable surface layer with constant height above ground. A user definable topographical map is used to find the co-ordinates of this surface layer relative to the position of the radar. This map is also used to check for regions, where the user selected surface layer is not accessible to the radar. These parts of the image will be filled with the NO DATA value. Conversion of reflectivity to rain-rate is performed using the well-known Z – R relation (Marshall and Palmer, 1948), viz., $Z = A*R^b$, where the adaptable parameters 'A' and 'b' vary in space, time (season) and type of precipitation such as convective, stratiform etc. A typical SRI product based on the Z – R relation, during a severe thunderstorm observed from DWR Kolkata on June 2021 is shown in Figure 8. The rain rate estimation from radar is subjected to possible sources of error such as (i) evaporation beneath the radar beam (ii) incomplete beam filling (iii) reflectivity enhancement by melting layer which is often referred to as the bright band (iv) advection of droplets by winds close to the ground which are beneath the lowest beam of the radar (v) in-frequent calibration of radar resulting in change in radar constant (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.

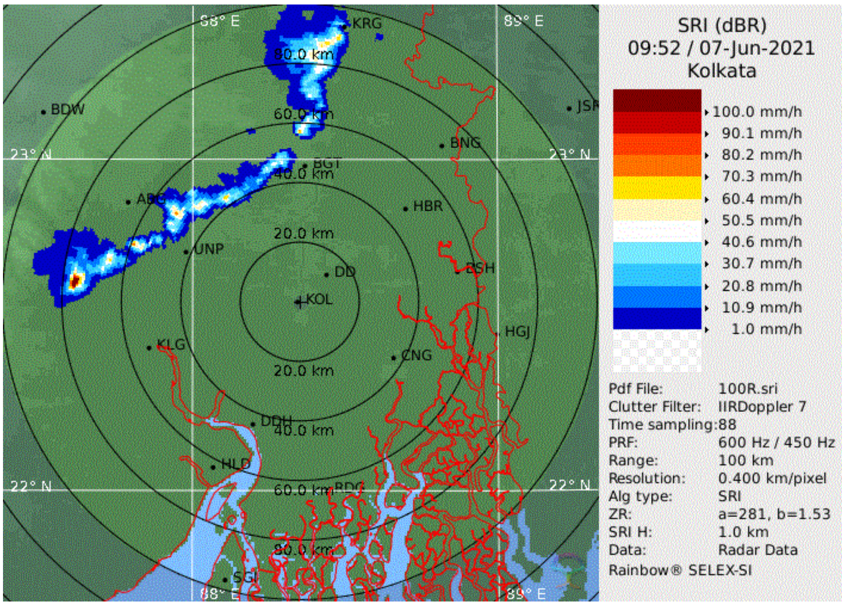

Figure 8: Surface Rainfall Intensity (SRI) during a severe thunderstorm observed from DWR Kolkata on June 2021.

(e) Volume Velocity Processing (VVP):

The Velocity Azimuth Display (VAD) was originally limited to only one elevation angle. If we want to find out the velocity estimations over different heights, then we need to process a volume data comprising the VAD data of various elevation angles. As the name implies this product computes and displays the mean radial velocity at different heights in a cylindrical volume around the radar. The display format is mean radial velocity in colour codes on height over azimuth display. The radius of data volume is to be kept low, typically 20 to 30 km, to have meaningful values. The raw data comes from a volume scan covering sufficient number of elevations to get wind information from the desired upper level at the selected range. The horizontal wind vector and the kinematics of wind field can be derived by adopting suitable algorithms and the display can be in the form of a vertical time section of horizontal wind. A sample Volume Velocity Processing (VVP) product during a severe thunderstorm of June 2021 observed from DWR Kolkata is shown on Figure 9.

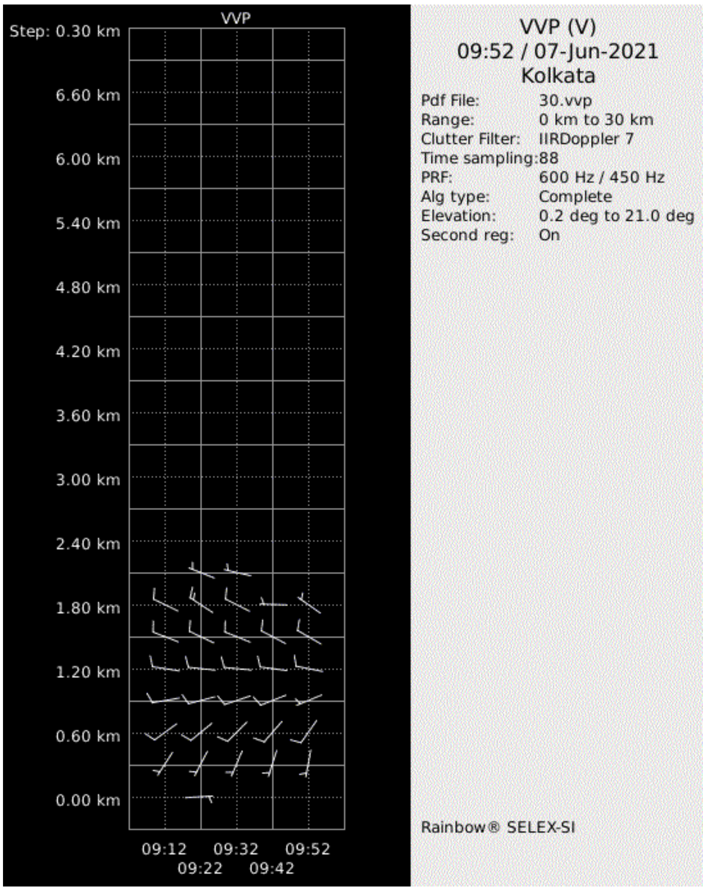

Figure 9: Volume Velocity Processing (VVP) during a severe thunderstorm observed from DWR Kolkata on June 2021.

9. Conclusion and Future Enhancement:

The Doppler radar used in weather forecasting measures the direction and speed, or velocity, of objects such as drops of precipitation. This is called the Doppler Effect and is used to determine whether movement in the atmosphere is horizontally toward or away from the radar, which aides in weather forecasting. Doppler radar provides high-quality data compared to standard radars. Doppler radar is used by a meteorologist to diagnose rainfall as well as provide data on the flow of wind in the atmosphere.

With the invent of dual-pol technology in the modern duel polarized doppler radar, the picture becomes two-dimensional because the radar sends both horizontally and vertically polarized electromagnetic waves. As these perpendicular fields bounce off an object and are received back at the radar, a computer program separately processes information about the horizontal and vertical dimension of the particles. This cross-section now gives forecasters a measure of the size and shape of the object.

Phased array radars have been used by the military for many years to track aircraft. NSSL's MPAR program is investigating the potential to determine if both the aircraft surveillance and weather surveillance functions can be combined into one radar in the near future.

Also, Radar research at the NOAA National Severe Storms Laboratory has taken another step forward with the 2018 installation of the Advanced Technology Demonstrator at the National Weather Radar Testbed facility. The Advanced Technology Demonstrator, or ATD, is the first full-scale, S-band, dual-polarization phased array radar built from the ground up and designed specifically for use as a weather radar.

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