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Article

RADAR and its application in Atmospheric and Ionospheric Research

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ABSTRACT

RADAR (Radio Detection and Ranging) is a device which is used to determine the range and velocity of an object or a target by using radio waves. There are different types of Radar and its application is also vast. Radar is used in Defence, in weather monitoring, land survey etc. The application of Radar to monitor atmosphere and ionosphere is discussed in this chapter. There is a short description of the radars engaged in probing the atmosphere and ionosphere in India.

Introduction

RADAR is a short form of **RA**dio**D**etection **A**nd**R**anging. It uses electromagnetic waves (Radio Waves) to detect and calculate the range of an object such as ships, aeroplane, vehicle, spaceships, missiles or any natural environment such as cyclone. Radar can also detect the velocity or angle of the passive object respective to the radar position. So from weather prediction, air traffic control, Space physics to Military application radar has its various applications in our life. Radar is such a type of communication systems where the knowledge of different fields like physics, electrical and electronics engineering, signal processing, big data analysis etc. can be integrated. Radar generates an electromagnetic Radio wave signal, transmits the signal to the Target and then receives the reflected signal from the target to detect its range. To determine the speed of the target/object, radar systems use the principle of "Doppler effect", which is change in frequency of the wave when there is relative velocity between the source and the observer.

Electromagnetic Spectrum: Electromagnetic spectrum refers to the wide span of all types of EM radiation. If we go from Low frequency (Longer wavelength) to High frequency (shorter wavelength) the types of waves are: 1) Radiowave frequency, 2) Microwave frequency, 3) Infrared frequency, 4) Visible ray, 5) Ultraviolet ray, 6) X ray and 7) Gamma Ray.

The different types of EM waves, its frequencies and wavelengths are listed below (**Table 1**):

Table 1: Different types of EM Waves

Types of EM Wave	Frequency(Hz)	Wavelength(m)
Radio Wave	Less than 3×10^9	$> 1 \times 10^{-1}$
microwave	3×10^9 to 3×10^{11}	1×10^{-3} to 1×10^{-1}
Infrared ray	3×10^{11} to 4×10^{14}	7×10^{-7} to 1×10^{-3}
Visible ray	4×10^{14} to 7.5×10^{14}	4×10^{-7} to 7×10^{-7}
Ultraviolet ray	7.5×10^{14} to $3X\ 10^{16}$	1×10^{-8} - 4×10^{-7}
X-ray	3×10^{16} to 3×10^{19}	1×10^{-11} - 1×10^{-8}
γ- ray	Greater than $3X\ 10^{19}$	Less than 1×10^{-11}

Among different types of EM waves, Radio Waves are mainly used in communication. Frequency range and wavelengths of different types of radio waves are given below in **Fig. 1**.

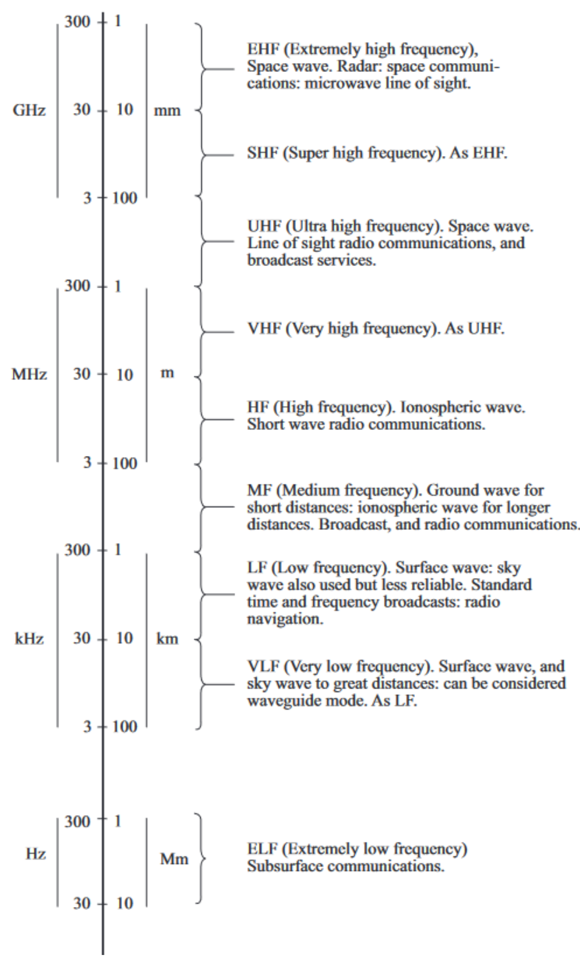

Figure 1**Different types of Radio waves, its frequencies and applications.**
(Source: Electronic Communications by Dennis Roddy and John Coolen)

Radar uses specific ranges of Radiowave frequency for its detection and ranging purposes. The choice of frequency depends on what purposes the radar will be used. Radar Frequency Bands are commonly called as 'letter' band which are given below (**Table 2**).

Table 2: List of frequency bands used by Radar

Band Name	Frequency Range
Very High Frequency or VHF band	50 - 330 MHz
Ultra High Frequency UHF	300-1000 MHz
L band	1-2 GHz
S band	1-4 GHz
C band	4-8 GHz
X band	8-12 GHz
Ku band	12-18 GHz
K band	18-27 GHz
Ka band	27-40 GHz
mm band	40 – 100+ GHz
Source: AIAA (American Institute of Aeronautics and Astronautics)	

Quasi Monostatic Radar: Transmitting and Receiving antenna is different but it is located almost at the same place.

According to types of waveform generated and transmitted by the Radar it is divided into two groups.

(i) **CW** or **C**ontinuous **W**ave radar: - A continuous wave of constant amplitude is transmitted from this type of Radar.
(ii) **Pulsed** Radar- In this type of Radar (**Fig. 2**), signals are transmitted in terms of pulse, where the duration of the pulse i.e. pulse width is very short (1μsec to several μsec). The time between two pulses is known as Pulse Repetition time (PRT).

Again Pulsed Radar can be of two types, (i) Coherent Radar and (ii) Incoherent Radar.

Coherent Radar: In this type of Radar the phase of the transmitted signal is phase stable from pulse to pulse. There is a definite relationship between transmitted signal and reference waveform. Therefore to determine the range of the target the coherent scatter uses both round trip time or the phase of the reflected signal.

Non Coherent Radar: In this case the phases of the transmitted signal are varying from pulse to pulse i.e. it is not constant. So the phases of the reflected signal from the target cannot be used to detect its range.

Radar Range Equation:

We know that the Radar Antenna is not isotropic, it is directional. If the transmitted peak power is denoted by P_t ,Maximum power gain is Ap, then the directional power density at a distance r from the Antenna will be,

$P_d = \frac{P_t . A_p}{4\pi r^2}$ (1)

Where, r is the range or distance from Radar Antenna to the target. The target detection isn't only dependent on the power density of the transmitted wave at the target position, but also on how much power is reflected from the target in the direction of the radar. Therefore it is necessary to know the cross section of Radar.

If S is the Radar cross section then the reflected power $P_r = P_d . S$ (2)

Then the power density at the receiving end (Radar end)will be $P' = \frac{Pr}{4\pi r^2} = \frac{S.Pt . A_p}{(4\pi r^2)^2}$, (3)

Where it is assumed that the receiving and transmitting antenna is at the same location.
If A_0 is the effective antenna aperture, the received power at the Radar end is $P'' = P'.\ A_0 = \frac{S.Pt\ .A_p}{(4\pi r^2)^2}.A_0$. (4)

The effective antenna aperture comes into play because there are losses of radiation which is transmitted by the Radar and therefore the received power is not equal to the transmitted power.

Now for the same receiving and transmitting antenna, $A_p = \frac{4\pi A_0}{\lambda^2}$ (5)
Where λ is the wavelength.

Therefore putting the value of A_p we can get the value of $P' = \frac{S.Pt\ .A0^2}{4\pi r^4 \lambda^2}$ (6)
Now radar can detect maximum range, when received power is minimum.
Therefore $r_{max} = (\frac{S.Pt\ .A0^2}{P_{min} 4\pi\lambda^2})^{1/4}$(7)
Equation 7 is known as the radar range equation.

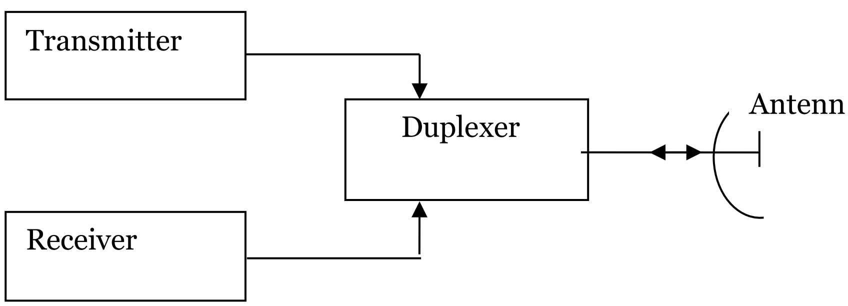

Figure 2 Block diagram of Pulsed Radar

Radial Velocity: Radar can determine the radial velocity of the target from the rate of change of range and also from the Doppler shift. Continuous wave is transmitted by the Radar and after reflection from the target, if the frequency difference between the transmitted and reflected signal can be determined, then the relative velocity of the object can be calculated.

If V is the relative velocity of the object with respect to the source, f is the frequency difference and λ is the wavelength of the transmitted signal from the Radar, then $V = \frac{f.\lambda}{1.03}$

In the Electro Magnetic spectra, the frequency ranges from 300 MHz to 40 GHz, are used by Radars mounted on aircrafts or satellites for Earth observation and monitoring from the sky. Though optical sensors on the satellites also take images, Radar is more effective because optical sensors depend on sunlight for the reflected light, so at night optical sensors do not work. Whereas Radar generates its own sensor, so it can work both in day and night.

Radar and its application in remote sensing:

From forest mapping, to map the damage caused by any calamity, weather forecast, sea status estimation, Radar remote sensing can be a very good technique(Batool et al. 2020).

When Radar transmitted signal falls on a target with a flat surface, reflection will occur. But when the signals are reflected from small particles present in the air the scattering comes into play. When the wavelength is much longer compared to the particle dimension then Rayleigh scattering takes place.

Radar images are formed with pixel and how many pixels are formed is dependent on the amount of backscattered energy. When a signal is reflected from a smooth surface it appears dark and when from rough surface it appears lighter in shade.

Radar for probing Atmosphere and Ionosphere:

The upper part of Earth's atmosphere is the Ionosphere which is the region of sufficient ionization. The main source of ionization in this region is X-rays and EUV rays emitted from the sun. As a result many overlapping layers are formed in the ionosphere such as D, E and F regions respectively staring from ~80 km to above in the atmosphere. It is observed that at about 350 km height in the F region of the ionosphere, the ion density becomes maximum. The peak density of the ionization is dependent on time of the day, season and latitude of the place, solar activity during that time and also on various irregular and random disturbances in the ionosphere. To probe the Earth's upper atmosphere and ionosphere, Backscattered Radar is a very useful device. Backscatter means the signals reflected from the target will directly go back to the RADAR. There are two types of backscattered Radar- (i) coherent backscattered radar (ii) incoherent backscattered radar.

When the velocity of different frequency of waves depend on that frequency in any medium, then it is said to be dispersive medium. It is verified that Earth's ionospheric region is also a dispersive media with varying refractive index due to ionized particle. When a radio wave passes through the ionosphere and if its frequency is equal to the critical or plasma frequency f_N of the ionosphere, the wave suffers total or partial reflection. This principle is used in HF radars and ionosondes. But in the situation, when the frequency is greater than the plasma frequency, incoherent scattering occurs due to the thermal motion of the free electrons present in the ionosphere. This phenomenon is called Thomson scattering or incoherent scattering. One of the most famous incoherent scatter Radar is situated at *Jicamarca situated at Peru (*Geographic latitude 11.95°S, Geographic Longitude 76.87°W and Geomagnetic latitude ~ 0.5°S dip latitude). Using incoherent scatter radars data, ionospheric density of electron, temperature of electron & ion and plasma velocity can be found out.

On the other hand, when instabilities (Rayleigh Taylor instability) develop in the ionosphere (Perkins 1975) and when it is aligned with Earth's Magnetic field, it causes coherent scattering of HF, VHF and UHF signals. This technique is mainly helpful to observe the irregularities developed in the ionosphere. Clear air turbulence developed in the lower part of Earth's atmosphere i.e. neutral atmosphere causes variation in refractive index due to change in temperature, humidity etc. Due to this reason in the neutral atmosphere (in Troposphere and stratosphere) also, irregularities are formed causing coherent scattering of signals. At mesosphere, neutral air turbulence can occur resulting in mesospheric and D-region irregularities; as a result again coherent scatter of radio signals can happen. Some radars operating in VHF or HF bands can track mesosphere, stratosphere and troposphere called MST radars.[5] When the signal is perpendicular to the magnetic field and the wavelength is equal to the scale size of the irregularities, The MST radar can probe the ionosphere also. MST radar at Wuhan, (29.5° N, 114.1° E) China is an example of this type of radar. Qi et al.2022 observed the descending tropopause during a rain event in June 1-2, 2015 from Wuhan. They also found vertical wind velocity from the MST radar data.

To determine the wind velocity vector in the neutral atmosphere or the ion velocity in the ionosphere, incoherent scatter radar uses Doppler beam swinging technique (**Fig. 3**). The principle of Doppler Beam Swinging technique is that the radial velocity of the wind component which is parallel to the radar beam, is proportional to Doppler shift of the Radar backscattered signal. By this technique, the east, west, and vertical components of the wind can be calculated. Sinha et al. 2017 showed techniques of the uses of wind profilers for definite targets such as Clear Air Turbulence, Ionosphere Activity and Precipitation Echoes.

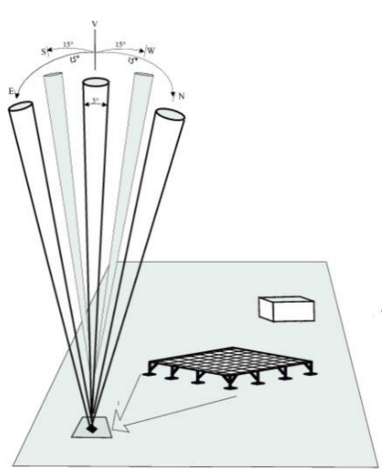

Figure 3 Doppler Beam Swinging

Sometimes for Atmospheric wind measurement LIDAR (Light Detection and Ranging) is used where instead of Radio wave Laser light is used.

In case of MST radar, spaced antenna array (**Fig.4**) is used. This technique is also known as Spaced Antenna (SA) Drift Technique (Hocking 1983; Kumar et al. 2013). The echoes, which are reflected signal from the atmospheric irregularities, are received in multiple spaced antennas producing a diffraction pattern on the ground.

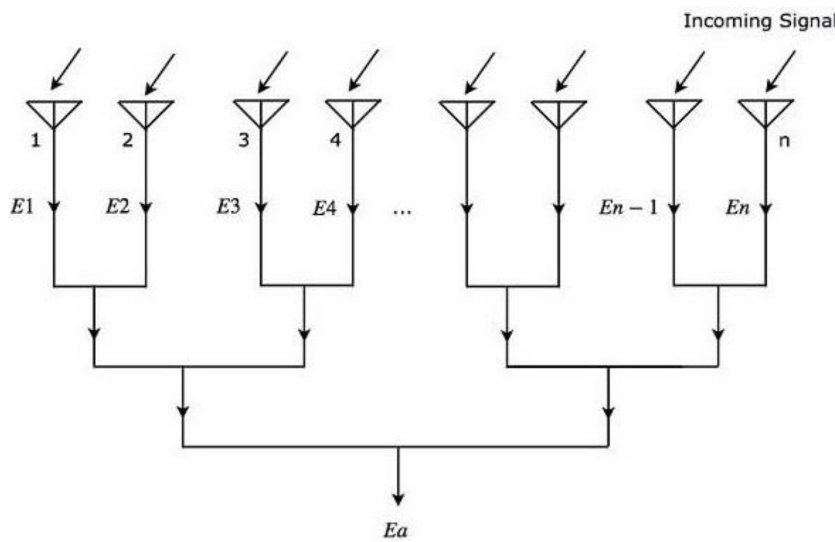

Figure 4 Spaced Antenna Array

Zhang et al. 2019 analysed the Jicamarca incoherent scatter data with the magnetometer data to determine the ionospheric electro-dynamic over this region during September 06-11, 2017 geomagnetic storm. Smith et al. 2015 combined both incoherent and coherent scatter radar data over two solar cycles in the Jicamarca region. They found out the plasma drifts not only in the main F-region of ionosphere, but also in the bottom side and topside F-region with the Incoherent Scatter Radar data. They also detected the occurrence and morphology of Equatorial Spread F (ESF) when the radar is operating in coherent mode. Singh et al. 2016 worked on boundary layer evolution over Himalayan Region from the observation of Radar wind profiler.

MST and ST RADAR FACILITY in INDIA:

1. MST Radar NARL: At the National Atmospheric Research Facility (NARL), formerly known as NMRF (National MST Radar Facility) is situated at Gadanki, Tirupati, India (Geographic Latitude 13.5°N, Geographic Longitude 79.2°E, magnetic latitude 6.5°N). (**Fig. 5**) It is a research organisation where different types of atmospheric, ionospheric and even planetary experiments are going on. They have a) Advanced MST Radar, b) X- band dual polarisation radar c) Lower Atmospheric Wind Profiler, Gadanki Atmospheric wind Interferometer (GIRI) d) Micro Rain Radar etc. The key thrust area of research here is to study the Electrodynamics of the ionosphere. The other areas of investigation are to track the plasma irregularities formed in the low latitude ionosphere, to find out the coupling process between lower and upper part of the ionosphere, Space weather impacts on the low latitude ionosphere, to quantify Stratosphere-Troposphere exchange process, real time weather forecast and modelling of multi scale evolution of weather etc. The RTI (**R**ange **T**ime **I**ntensity) map generated at Gadanki is shown in **Fig. 6**. The updrafting and downdrafting of plasma depletion in the low latitude ionosphere was observed by Rao et al. (1997) while observing Gadanki MST backscattered Radar data along with the pulsed Doppler Radar data from Trivandrum (Geographic latitude 8.5° N, Geographic longitude 77° E; geomagnetic latitude 0.3° N). Not only ionosphere, lower atmosphere can also be probed

by the VHF Radar. Chakravarty and Datta (2007) got the backscattered echoes from Mesosphere and analysed the result.

Figure 5 : 53 MHz MST Radar at NARL

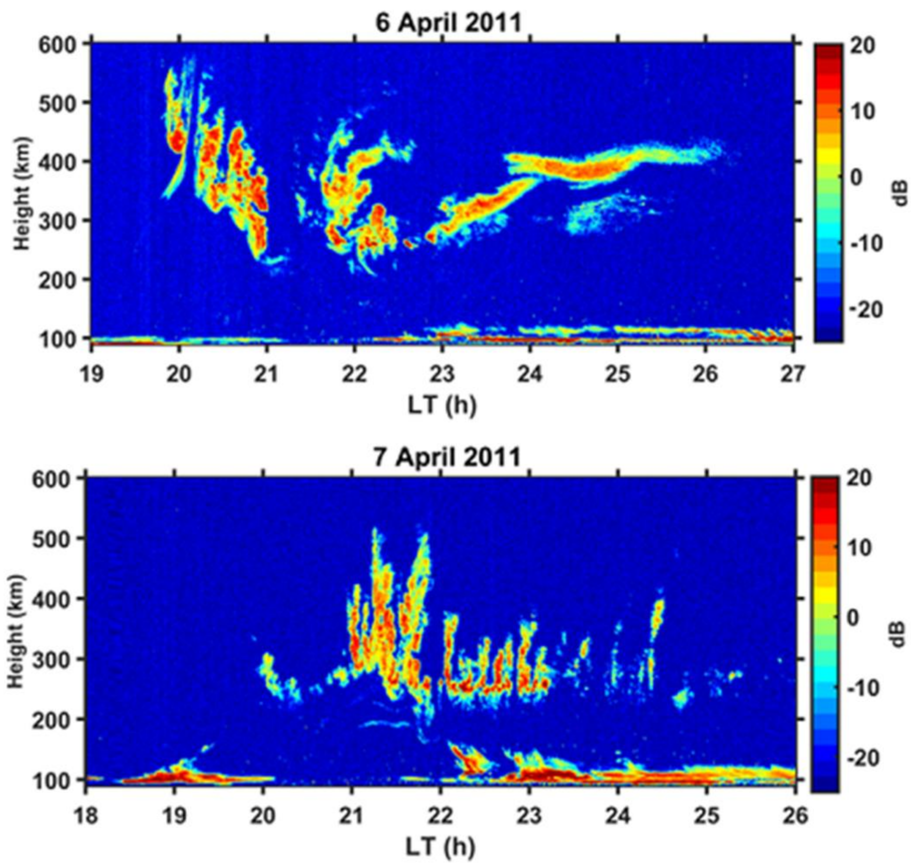

Figure 6 RTI map generated by MST radar at Gadanki.

2. ST Radar (**Fig. 7**) at Calcutta University Haringhata Campus: Institute of Radio Physics and Electronics, University of Calcutta has recently established a ST Radar at ionospheric Field Station, Haringhata (Geographic latitude 22.93° N, Geographic longitude 88.50° E; magnetic dip: 36.2° N) under DST (Department of Science and Technology). The operating frequency is 53 MHz. Here different atmospheric processes like Lower atmospheric turbulence, convection process of the troposphere, D, E and F region irregularities, Vertical coupling from lower atmosphere to the ionosphere etc. are studied. Paul et. al. (2021) found the existence of ionospheric E region irregularities by the ST radar echoes from Haringhata, India.

Figure 7 ST Radar at Kolkata

3. ST Radar at Cochin: It is a Stratosphere-Troposphere (ST) wind profiler radar, operating in 205 MHz, installed at the Cochin University of Science and Technology, Kerala, (Geographic Latitude 10.04° N; Geographic Longitude 76.33° E) with the support of SERB (Science Engineering Research Board), Department of Science and Technology (DST). The primary goal of this Radar is to understand the characteristics and path of the Indian summer monsoon at its gateway at Cochin.

4. ST Radar at ARIES: Aryabhatta Research Institute of Observational Science (ARIES) (Geographic Latitude 29.4 °N, Geographic Longitude 79.5 °E) at Nainital has set up 206.5 MHz ST radar under the support DST in central Himalaya, for monitoring the wind and to understand the dynamics of the lower atmosphere. Jaiswal et al. (2020) estimated the turbulence parameter in the troposphere region while analyzing the backscattered data of ST Radar situated at ARIES, Nainital.

5. ST Radar at Guwahati University: A clear air weather ST Radar operating at 212.5 MHz, has been established at Guwahati University Campus (Geographic Latitude 26.14° N, Geographic Longitude 91.73° E).

Conclusion:

Radar has its wide application in military, navigation of aircraft and ship; it is also applicable in space physics. Lower Atmospheric (Troposphere stratosphere Mesosphere) dynamics and variability can be monitored by VHF and HF Radar installed at different parts of India. Day to day variability of the upper atmosphere (Ionosphere) can be examined by the analysis of radar echoes. The drifting of ionospheric irregularities in the low latitude ionosphere can be calculated which is helpful for communication.

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