CHAPTER V

MEASUREMENTS OF RADAR REFLECTIVITY AND COMPARISON WITH ROCKET DATA
Measurements of Radar reflectivity

5.1 Introduction:

The mesosphere, region lying roughly between 60 and 90km altitude, is the intermediate region between the two distinctly different regions of the earth’s environment.

(1) The upper atmosphere where absorption of solar energetic radiations of EUV and X-rays by the major constituent oxygen (to some extent Nitrogen) dominates atmospheric radiation budget and electric and magnetic fields play important roles in physical processes taking place.

(2) Stratosphere, the altitude region of 20km to about 60km where absorption of solar ultraviolet radiation in the 2000Å to 3000Å, a region by the trace constituent in the atmosphere namely ozone, dominates the radiation and the physical processes are largely influenced by the dynamics formed from the weather related regions.

Temperature decreases in the mesosphere until it reaches a minimum of 180-190K at the mesopause height of 80-90Km. The heat balance in this region is determined by the radiative heating of molecular oxygen and infrared radiative cooling of carbon dioxide.
This intermediate region has been and continuously being explored of all regions in the earth's atmosphere. There is a very little absorption of solar radiation and the energetics and dynamics of this region are determined by the transport of energy and momentum from below. Because of the temperature minimum the mesopause was for a long time considered to be a buffer between upper and lower regions without any interaction between the two.

From a variety of observations existence of waves in the atmosphere over a large spectrum of scale sizes are explored. Waves play an important role in the dynamics of the atmosphere and manifest themselves as fluctuations in mean winds, temperature, density, and ionization as well as air glow intensities. The height region of about 80-100km is the region where the effects are most pronounced. As the amplitude increases, at some altitude the wave becomes unstable and gives rise to turbulence. Turbulence in the atmosphere could also be due to shear instabilities convective overturning and critical level interaction when several waves are simultaneously present.

Turbulence creates spatial and temporal variations in the refractive index and thus leads to scattering of electromagnetic and
acoustic waves. Volume reflectivity ($\eta$) is due to atmospheric refractive index variations arising presumably from locally homogenous turbulence. Volume reflectivity is the scattering cross section per unit volume in the atmosphere. It decreases with increasing height upto 50km and then begins to increase. Below 50km, the decrease with height is primarily due to the decrease in atmospheric density and above 50km the scattering mechanism is probably due to the increase with height of the ambient ionization near the bottom of the ionosphere and thereby enhanced neutral turbulence within the mesosphere.

Various mechanisms that give rise to the radar echoes in the tropical mesosphere are not fully understood due to non availability of high resolution and powerful instruments. The newly established Indian MST radar, a high power highly sensitive coherent Doppler Radar, fills this gap. In the present study, this radar system has been used to calculate the radar volume reflectivity and electron density fluctuations in the tropical mesospheric region.
Turbulent eddies have been observed in the Earth's lower atmosphere directly by radar techniques [Crane, 1970; Woodman and Hillen, 1974] and through the effect which they produce on plasma by way of generating plasma irregularities [Sinha, 1976; Thrane and Randal, 1981; Ruster and Klostermeyer, 1987; Thrane et al., 1987; Rubken et al., 1987; Chakrabarty et al., 1989; Blix et al., 1990]. This chapter presents characteristics of electron density irregularities, which we explain to be an effect of neutral air turbulence, as observed on rocket flights. The results pertain to the ionization irregularities in the scale size ranging from 1 to 300 m observed in the D-region of the ionosphere.

The radar volume reflectivity $\eta$ is given in terms of radar observed Signal to Noise Ratio (SNR) and various radar parameters from the basic radar equation is given in detail in the Annexure I.

5.2 Observations:

The primary objective is to investigate the source and characteristics of equatorial mesospheric echoes observed by the MST radar in the mesosphere (55-85 km) by probing the mesosphere with rocketborne, in situ probes at times when strong echoes were seen by the radar.
Campaign mode experiments were conducted from 1998 - 2001 to study the characteristics of the mesosphere with a pulse length of 16µs which corresponds to a range resolution of 2.4 km, IPP=1000 ms and velocity resolution of 0.176ms⁻¹. Radar parameters for Indian MST radar are given in Table 5.1 and the experimental specifications for the experiment carried out to study the mesosphere are given in Table 5.2.

The volume reflectivity is calculated and is plotted as hourly averages of vertical profiles in the five beam directions East, West, Vertical, North and South and are shown in figures 5.1, 5.3, 5.5 for summer for the years 1998, 1999 and 2001. The hourly average of electron density values are also calculated and are presented in figures 5.2, 5.4 and 5.6. As we discussed in the previous chapter, the main scattering layer is around 75 km and the strength of this layer decreases temporally. This can be clearly seen for the three years of observations. There is small aspect sensitivity present and it can be attributed to the spatial variations of turbulence. In the daytime solar radiation causes ionization of electrons in the mesosphere and as time advances, the ionization decreases and relatively the backscatter strength decreases. This mechanism is visualized in the next figure where the radar derived
Fig. 5.1 Height profiles of hourly average of radar reflectivity observed on different summer months for 1998, 1999 and 2000 from East, West, Vertical, North and South beams.
Fig. 5.2: Height profiles of hourly average of $\Delta n$ observed on different summer months for 1998, 1999 and 2000.
Fig. 5.3 Height profiles of hourly average of radar reflectivity observed on different equinox months for 1998, 1999 and 2000 from East, West, Vertical, North and South beams.
Fig. 5.4 Height profiles of hourly average of $\Delta n$ observed on different summer months for 1998, 1999 and 2000.
Fig. 5.5 Height profiles of hourly average of radar reflectivity observed on different winter months for 1998, 1999 and 2000 from East, West, Vertical, North and South beams.
Fig. 5.6 Height profiles of hourly average of $\Delta n$ observed on different winter months for 1998, 1999 and 2000.
Fig 5. Comparison of Rocket observed density values with radar observed Signal to Noise Ratio on 19/4/93 and 19/4/99 showing the correlation between the 3m irregularity occurrence and maximum SNR in the same region.
electron density fluctuations are plotted. The maximum fluctuation in electron density values are observed during the noon time at a height where we are getting the maximum return echo and it decreases with time explaining the relation between the solar radiation and the ionisation processes in the mesosphere. The same process is observed in other seasons also but with a change in the occurrence height. The electron number density is also varying in different seasons. The seasonal dependence of the radar derived reflectivity calculated from the radar signal to noise ratio also has got a seasonal variation.

The percentage amplitude of 3m irregularities are determined using the data from the main and/or duct channel, whenever available (channels 1 and 2). An assumption is made that the velocity of the tracers (electrons) is much smaller than the velocity of the rocket ($\approx 1.5$ km s$^{-1}$), the temporal fluctuations in the electron density as seen by a moving rocket represent spatial structures of tracers in the medium, the electron density structures are explained. Sinha’s [1992] result on the spectrum of 1-15 m irregularities was by passing the Langmuir probe current (which is proportional to the electron density) through a set of eight filters. On some of these where both the channel data were present, we have normalized the filter channel data (which is in arbitrary units) with
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instruments show maximum explaining the correlation between the radar backscatter and the presence of 3m irregularities.

Rocket observations on 4th May 1983 are shown in figure 5.8 and the interpretations are the same as in fig 5.7. The major scattering layer observed from both the instruments is correlated fairly.

5.3 Results

The radar reflectivity calculated using the formula given in Appendix I varies from $10^{-17}$ to $10^{-20}$ /m. The seasonal variation is not very clear as the variation in the reflectivity is not much. But the electron number density clearly varies with season and we find a maximum of electrons in the summer season. The electron number density has a variation from 1-45 electrons in summer and 1-30 electrons in equinox and 1-20 electrons in winter throughout the period of observation. The same is compared with the rocket data from the nearby equatorial station, SHAR and is explained in detail below.

Electron density data of two rocket flights in 1987 and in 1999 were investigated to identify the irregularities produced by the neutral turbulence mechanism. The irregularities were experimentally observed in two scale size ranges, namely 15-300 and 1-15 m and published by
Sinha, 1987. During the daytime the region where these irregularities have been observed lies generally between 60 and 82 km by the rocket flights. The 15-300 m irregularities with smaller amplitude and 1-15 m irregularities were found to have a vertical extent ranging between 1 and 12 km. On all the occasions when 15-300 m and/or 1-15 m irregularities were observed, the direction of the electron density gradient was always positive, that is, electron density increased with increasing altitude. Another feature of the 1-15 m irregularities which emerges very clearly from Sinha’s study and Gupta, 1984, is that the signal appears abruptly on all channels, indicating that the appearance of these irregularities is very sudden, corresponding to intermittence of turbulence observed using the MST radar.

Results of 1-15 and 15-300 m irregularities presented from rocket flights show that during daytime the irregularities are present in the region of 60-82 km. The percentage amplitude of the irregularities is much larger when they are observed at lower altitude (60-75 km) as compared with that when these are observed at higher altitudes (75-82 km).
The results for rocket observed irregularities also show that these irregularities do not occur continuously in altitude but at discrete levels. Such levels differ from flight-to-flight, confirming to the ground-based MST radar observations that generation of these irregularities is quite intermittent as it has already been explained. This has the result that these irregularities occur in bursts [Woodman and Guillen, 1974; Rastogi and Bowhill , 1976; Harper and Woodman, 1977; Czechowsky et al., 1979].

5.3 Discussions

It is well known that neutral turbulence exists in the atmosphere up to about 100 km altitude. It has also been shown by Gallet [1955] and Villars and Weisskoff [1955] that, in the presence of gradients in the electron density, neutral turbulence can produce irregularities in the electron density. The physical mechanism is as follows. Turbulence produces a displacement of air parcels. In the atmosphere due to the vertical pressure gradient and density gradient, only the vertical displacement of an air parcel leads to fluctuations in the neutral density. Fluctuations in the neutral density due to horizontal displacement of air parcels would be of second order and hence unimportant. The vertical
displacement of neutrals produces irregularities in plasma as shown by Thrane and Grandal [1981], the plasma density at a given altitude is proportional to the neutral density. The intensity of the plasma irregularities thus produced depends upon the density of neutral gas as well as plasma density gradients [Gallet, 1955; Cunnold, 1975].

Detailed relationships between the fluctuations in the neutral density and the corresponding fluctuations in the plasma density have been discussed by Thrane and Grandal [1981]. Although the turbulence is present up to 100 km, it can efficiently produce plasma irregularities only in those regions where the collisions with neutrals dominate over the magnetic field effects on the plasma. Using a spherical ion probe, Chakrabarty et al. [1989] detected irregularities in the ion density, in more or less similar scale size ranges as ours, at 70-78 and 85-100 km altitude regions and attributed these to the neutral turbulence. The region of 85-100 km is one where theoretically the CFI-generated irregularities are expected to be present in their full strength and neutral turbulence generated plasma irregularities, if at all present, will be very weak.
Mesospheric turbulence studies over Jicamarca (11.95°S, 76.87°W) using VHF radar by Rastogi and Bowhill [1976] also indicate that the inner scale of turbulence in the 85 km region is of the order of a few tens of meters. The works of Hocking [1985a, b] and Blix et al. [1985] also indicate that $l_o$ is of the order of a few tens of meters around 80 km. We do not know the cause of the 1-15 m irregularities observed during these two occasions but we feel that these are related to the wind system which modifies the nature of the local turbulence. Radar echoes and atmospheric turbulence were observed in the same altitude domain, consistent with the anticipated need for adequate free thermal electron gradients to make such phenomena visible on the radar.

These echoes have been attributed to local turbulence within the region arising from the saturation of upward propagating gravity wave [Balsley et al., 1983]. Turbulence in the middle atmosphere is thought to occur as a result of instabilities within the atmospheric wave field caused by the growth of wave amplitudes with increasing height [Fritts, 1984]. This amplitude growth leads ultimately to local convective or dynamical instabilities at particular locations within the wave motions or to wave-wave interactions that act to saturate, or limit the further growth of, the wave spectrum [Fritts and Rastogi, 1985; Yeh and Liu,
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1985. The resulting turbulence appears to increase in scale and intensity with increasing height, with an outer scale varying from a few tens of meters in the stratosphere, to ~ 1 km in the mesosphere and lower thermosphere [Hocking, 1985]. The inner scale of inertial range turbulence likewise increases with height to tens of meters in the mesosphere and lower thermosphere. This turbulence becomes visible to the radar when there is sufficient turbulence intensity and also sufficient gradient of electron density to enhance radar reflections at a scale equal to half the Radar wavelength.

Radar echoes obtained in the mesosphere at Poker Flat on 29 March and 1 April 1985 revealed maxima in S/N at several heights between about 65 and 75 km, where it was possible to infer radial velocities with good temporal resolution. In order to infer the wave structure throughout a continuous height range however, it was necessary to average the observed Doppler power spectra at each height for a longer time. This suggests that these motions may have contributed preferentially to wave field saturation and turbulence production.

Our observations indicate clearly that solar radiation by itself is inadequate to provide a sufficiently large electron gradient to permit the
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radar to sense mean turbulence intensities at 3 m scales in the equatorial mesosphere. At a height range corresponding closely to that in which the radar obtained maximum echo intensities, where the energy deposition and gradients became more, the radar S/N likewise increased, despite the obvious wave activity and implied turbulence generation at other heights. Thus, it is apparent from our observations that the summer mesospheric echoes required a combination of sufficiently energetic turbulence at 3 m scales and sufficient electron densities to catch these turbulent structures and make them visible to the radar.

Studies from Poker Flat have concluded that the wave motion was more dominant in generating turbulence within the middle atmosphere because of its close correlation with the modulation observed in the S/N profiles. This is to be expected since the MST Radar could only observe in regions where the electron density gradient exceeded a basic threshold. Since the radar echoes occurred only in the height interval where the measurements implied large electron density gradients, our observations support the view that Summer echoes in the mesosphere obtained using MST radars require both local, intense turbulence arising from wave saturation processes and a sufficient electron density gradient to make the structure at 3 meter scales detectable. In this case it has been
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possible to verify earlier concepts regarding the ability of the radar to investigate the wave and turbulent nature of the neutral atmosphere. Small scale turbulence in the high latitude middle atmosphere during equinox, was studied by Blood et al., 1988 using the data obtained from rocket probes and MST radar measurements of plasma density irregularities. Additional information pertaining to the background ionospheric and auroral conditions, other rocket measurements and ground based MST radar observations are reported by Goldberg et al. [1988]. From these studies it is evident that the smaller waves are evident as velocity fluctuations of about 3 m s\(^{-1}\), have an apparent wave-length of 1-3 km. Despite their smaller wave energy, they are believed to play a significant role in the vertical transport of momentum and energy and in the production of turbulence [Manson et al. 1981; Vincent 1984].

Rocket probe measurements have been presented to demonstrate small scale plasma density irregularities and their indication of turbulence in the inertial subrange. The extent and size of these turbulence features are considered, along with signal to noise (S/N) measurements by the MST radar. The altitude region where particularly good fit to the -5/3 value occurs is between approximately 74 and 79 km, which was partly where the largest variations (1-2%) in electron density
Radar reflectivity measurements were measured. Regions of enhanced variance are observed at 68 and 75 km, resulting from the electron density fluctuations at these altitudes. If the density profile is compared with the MST radar’s density values near the time of the launch the regions of largest variance occur where the most extreme S/N values were obtained, supporting the measurement agreement of electron density fluctuations by both the radar and rocket probe. Some differences would be expected, however, since the electron density calculations used probe data obtained during a relatively short time at spatial scales of 200 m, while the MST radar’s S/N values involved 2.4 km height averaging of echoes from ~ 3 m structures at not precisely the same location.

A comparison between measurements of positive ion density fluctuations and the associated MST radar data for equinox were presented in detail by Goldberg et al. [1988] shows that there is a relatively good correspondence between the regions of enhanced S/N ratio and the regions where the ion probe detects the largest fluctuations. Especially, the S/N ratio is reduced above 71 km, which corresponds well with the probe measurements. The MST radar, however was unable to detect turbulence below and above the main scattering region, while the ion probe measured an enhanced level of fluctuations down to about 60
km. A similar comparison between electron density fluctuations are strong up to 85 km. It is important to note that the spatial scale to which the MST radar is most sensitive has less energy at higher altitudes thereby causing the drop in the radar S/N measurements. It is therefore concluded that there is a correspondence between ion and electron density fluctuations and the MST radar observations, although not a one-to-one relation. It is thought that the occurrence of large amplitude wave motions at these altitudes has resulted in neutral and charge density fluctuations which offset the mean gradient of electron density.

In the high latitudes, a cooperative field program involving ground based and rocket instrumentation has led to correlative measurements of small scale turbulence and wave structure in the high latitude mesosphere during equinox. The occurrence of moderate auroral ionization enabled both the MST radar and the nose tip probe to measure electron density irregularities down to an altitude of about 62 km. The ion probe measured fluctuations in positive ion density in the altitude region from 50-90 km are consistent with MST radar measurements. Turbulence in the inertial subrange was observed at heights where the fluctuations generally were the largest.
5.4 Conclusions:

The 1-3 km structure is believed to play an important role in the transport of energy and momentum and in the production of turbulence. Its smaller wave length provides for the more efficient deposition of energy in the lower mesosphere where small scale turbulence was detected by the probes. These irregularities are distinctly different, in their appearance and extent, from the irregularities produced by plasma instabilities such as cross-field and two-stream instabilities. A coordinated program involving the MST Radar and rockets was conducted in the month of March to learn more about mesospheric dynamics.

The MST radar and rocket measurements demonstrated consistent measurements of electron density fluctuations. The rocket measurements of background electron density exhibited gradients relative to the monotonically increasing density profile which may indicate the presence of large amplitude wave motions that act to transport the plasma by mixing.

The radar reflectivity varies from $10^{-17}$ to $10^{-19}$/m in all the seasons with a seasonal variation. The electron density fluctuations also vary from season to season corresponding to the previous rocket observations.
Appendix – I

Before discussing the scattering from the fluctuations in the radio refractive index, let us first examine a simpler case of scattering from an isolated hard target located in free space. Suppose we transmit a radio wave of power $P_t$ from an omni directional antenna, the density of power $P_t$ passing through a unit area located at a point sufficiently far from the antenna and perpendicular to the direction of propagation is given by

$$P_i = \frac{P_t}{4\pi r^2} \quad (1)$$

where $r$ is the distance of the point from the antenna. The antenna used for a radar usually has a string directivity with which a narrow region can be illuminated selectively. The above equation is thus modified as

$$P_i = \frac{P_t G_t}{4\pi r^2} \quad (2)$$

where $G_t$ is the directional gain of the antenna, which is a function of the azimuth and vertical angles.

We now consider a target located at this point which intercepts the power and scatters into various directions. The density of the scattered power $P_s$ per unit area at a distance $r$ from the target is expressed in terms of the scattering cross section $\sigma$ of the target as
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\[ P_s = \frac{P}{4\pi r^2} \]

\( \sigma \) is defined as an effective area of the scatterer, the power illuminating in which area is scattered isotropically.

If we increase the scattered power with an antenna, which has a capability of collecting all power passing through an effective area \( A_e \), the received power \( P_r \) is expressed as

\[ P_r = P_s A_e L \]

where \( L \) is the loss factor which represents various attenuations of the received signal due to antenna, transmission line, connectors etc.

By combining equations 2, 3 and 4, we obtain

\[ P_r = \frac{P_s G_t A_e L}{4\pi^2 r^2} \sigma \]

This equation gives the received echo power from a given target by radar and hence is known as the radar equation. The two parameters \( G_t \) and \( A_e \) are related by a universal relation, which is

\[ G_t = \frac{4\pi}{\lambda^2} A_e \]

where \( \lambda \) is the radar wavelength.
It is assumed that Gt and Ae take maximum value and the antenna beam is pointed to the direction of the target. Therefore for monostatic radar, the radar equation thereby reduces to

\[ P_r = \frac{P_t A_e^2 L}{4\pi \lambda^2 r^4} \sigma \]  

(7)

This equation gives the basis of the radar system design for choosing appropriate transmitter power and the effective antenna area for a given target with a scattering cross section at a range r. The minimum detectable signal is contaminated by \( P_n \), the noise power. The power of noise produced by a resistor at a temperature T for a given bandwidth B is

\[ P_n = kTB \]  

(8)

where \( k = 1.38 \times 10^{-23} \text{WSK}^{-1} \). The above equation for \( P_n \) applied to a single target.

If there are more than one target in the sample volume \( V \) of the air, observed in terms of the sum of the echo power from individual scatterers, for a situation where they are random and have no correlation between each other, the total received echo power becomes the sum of

\[ P_r = \frac{P_t A_e^2 L}{4\pi \lambda^2 r^4} \sigma \sum \sigma \]  

where \( \sum \sigma \) is the sum of the scattering cross sections of all targets.
the individual scatterers. In this case, the scattering cross section $\sigma$ can be replaced by $\Sigma \sigma$. If the number of scatterers is very large and if the scatterers are uniformly distributed in space, $\sigma$ increases linearly as $V$ increases. It is thereby suitable to define the volume reflectivity $\eta$ the scattering cross section per unit volume as

$$\eta = \frac{d\sigma}{dV}$$

and $\eta$ has dimensions of m$^{-1}$.

This situation applies, for example to the incoherent scattering due to free electrons in the ionosphere observed with a sufficiently high frequency of above about 1 GHz for which the volume reflectivity is given by

$$\eta = N_e \sigma_e$$

where $\sigma_e$ is the scattering cross section of an electron, which is given by

$$\sigma_e = \frac{e^4}{4\pi \varepsilon_0^2 m_e c} = 9.98 \times 10^{-29} \text{m}^2$$

For sufficiently low frequencies in VHF and UHF bands, an extra coefficient of $\frac{1}{2}$ is multiplied to the right hand side of equation 10.
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Now we treat the above equation from a more macroscopic way of the scattering due to fluctuations in refractive index n in order to discuss the cross section of the neutral atmosphere.

Radar equation for turbulent scatter:

Let $P_t$ be the power transmitted by the antenna, which is having an effective aperture, $A_e$ and a directional gain $G$. The power transmitted by the radar is intercepted by the target with a cross section $\sigma$. The intercepted power is radiated by the target. The power radiated by the target is, (Skolnik, 1990),

$$\frac{P_t \alpha_r G}{4\pi^2 \sigma}$$

(12)

The intercepted power by the target is then scattered isotropically. The power received by the antenna is

$$P_r = \frac{P_t \alpha_r G}{4\pi^2 \sigma} \cdot \frac{A_e \alpha_r}{4\pi^2} = \frac{P_t G A_e \alpha_r \sigma}{16\pi^4}$$

(13)

The gain $G$ is $4\pi A_e/\lambda^2$.

The power received by the antenna can be expressed as

$$P_t = \frac{P_r \alpha_r A_e^2}{4\pi^2 \lambda^2 r^4}$$

(14)
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The cross section of the distributed targets can be expressed in terms of the volume reflectivity ($\eta$), the parameter which gives the total contributions from the number if scatterers within the probing volume $V$.

$$\sigma = \eta V, \quad \therefore \quad \sigma = \frac{P \alpha \alpha_c A_t^2}{4\pi^2 R^4} \eta V \quad \text{----------------------------------- (15)}$$

Let $\theta$ be the width of the radar beam transmitted by an antenna array of square matrix. Then the probing volume of the target by the radar beam at any given range is $r^2 \theta^2 \Delta r$.

$$P_r = \frac{P \alpha \alpha_c A_t^2 \Delta r \theta^2}{4\pi^2 r^4} \eta \quad \text{----------------------------------- (16)}$$

For a Gaussian beam, the gain of the antenna can be expressed in terms of beam width ($\theta$) as [Probert-Jones, 1962].

$$G = \frac{K^2 \pi^2}{\theta^2} \quad \text{----------------------------------- (17)}$$

where $K$ is a dimensionless constant and nearly unity.

$$\frac{4\pi A_s}{\lambda^2} = \frac{\pi^2}{\theta^2} \quad \text{----------------------------------- (18)}$$

$$\frac{\theta^2}{2} = \frac{4A_t}{\pi\lambda^2} \quad \text{----------------------------------- (19)}$$

Therefore, $P_r$ now can be written as
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\[ P_r = \frac{P_t \alpha, \alpha, A_e \Delta r}{16 r^2} \eta \] \hspace{1cm} (19)

The two way transmission reduces the received power by a factor of \(2 \ln 2\) [Probert-Jones, 1962].

\[ P_r = \frac{P_t \alpha, \alpha, A_e \Delta r}{16 (2 \ln 2) r^2} \eta \] \hspace{1cm} (20)

The noise power \(P_N\) is expressed in terms of sky noise temperature \((T_c)\) and system temperature \((T_r)\) and effective receiver bandwidth \((B_N)\) as

\[ P_N = k B_N (\alpha, T_c + T_r) \] \hspace{1cm} (21)

where \(k\) is the Boltzman’s constant. Now the radar signal-to-noise ratio (SNR), for clear air turbulence, \((S/N)_c\) can be written as

\[ \left( \frac{S}{N} \right)_c = \frac{P_r}{P_N} = \frac{P_t \alpha, \alpha, A_e \Delta r}{(32 \ln 2) r^2 k B_N (\alpha, T_c + T_r)} \eta \] \hspace{1cm} (22)

Let \(N\) be the number of coherent integrations, then the gain due to coherent integrations is \(F_r/2B_f\) where \(F_r\) is the pulse repetition frequency (PRF) and \(B_f\) is the coherent bandwidth.
\[
\left( \frac{S}{N} \right)_c = \frac{P_t \alpha, \alpha, A_e}{32 \ln 2 k B_N (\alpha r T_c + T_r)} \frac{\Delta r}{r^2} \frac{F_r}{2 B_f} \eta
\]  

(23)

For coded transmitted pulse, let \( N_B \) be the number of bauds in the coded transmitted radar pulse, then

\[
\left( \frac{S}{N} \right)_c = \frac{P_t N_B \alpha, \alpha, A_e}{32 \ln 2 k B_N (\alpha r T_c + T_r)} \frac{\Delta r}{r^2} \frac{F_r}{2 B_f} \eta
\]  

(24)

Finally the equation for \( \eta \) can be written as

\[
\eta = \frac{64 \ln 2 B_f \Delta r}{P_t \alpha, \alpha, A_e F_r \cos \chi} \left( \frac{S}{N} \right)_c
\]  

(25)

where

- \( B_f \) is the Band width of the integrating filter
- \( K \) is the Boltzmann’s constant,
- \( B_r \) is the receiver bandwidth,
- \( T_r \) is the receiver noise temperature,
- \( T_c \) is the cosmic noise temperature,
- \( P_t \) is the average Transmitted power,
- \( \alpha_r \) is the receiver Loss,
- \( \alpha_t \) is the transmitter Loss,
F_r is the Pulse Repetition Frequency,

Δr is the range resolution,

A_e is the effective antenna area,

N_B is the number of Bauds.

χ Off Zenith angle

By substituting all the radar constants in the above equation, we finally arrive at

\[
10 \log(\eta) = 10 \log(S/N) + 10 \log(\chi^2) - 272.6278 \\
10 \log(\eta) = 10 \log(S/N) + 20 \log(\Delta r) - 272.6278 \\
= (S/N) + 20 \log(\Delta r \times 1000) - 272.6278 \tag{26}
\]
Table 5.1 Indian MST Radar parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar wavelength</td>
<td>5.66 m</td>
</tr>
<tr>
<td>Peak transmitted power</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Range resolution (Δr)</td>
<td>2.4 Km</td>
</tr>
<tr>
<td>Pulse Repetition Frequency (F_r)</td>
<td>1 KHz</td>
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<tr>
<td>Number of bauds for uncoded pulse (N_b)</td>
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<tr>
<td>Receiver bandwidth (B_r)</td>
<td>1.7 MHz</td>
</tr>
<tr>
<td>Receiver Noise temperature (T_r)</td>
<td>607°K</td>
</tr>
<tr>
<td>Cosmic Noise Temperature (T_c)</td>
<td>6000°K</td>
</tr>
<tr>
<td>Insertion loss in transmission path (α_t)</td>
<td>2.65 dB</td>
</tr>
<tr>
<td>Insertion loss in receiver path (α_r)</td>
<td>4.4 dB</td>
</tr>
<tr>
<td>Effective Antenna area (A_e)</td>
<td>1.2×10^6 m^2</td>
</tr>
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</table>
Table 5.2 Specifications of the experiment carried out to study the mesosphere

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of observation</td>
<td>1998 - 2001</td>
</tr>
<tr>
<td>Pulse width</td>
<td>16 µs</td>
</tr>
<tr>
<td>Range resolution</td>
<td>2.4 Km</td>
</tr>
<tr>
<td>Inter Pulse Period</td>
<td>1000µs</td>
</tr>
<tr>
<td>No of Beams</td>
<td>5 (E10y, W10y, Zy, N10x, S10x)*</td>
</tr>
<tr>
<td>No of FFT Points</td>
<td>256</td>
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<tr>
<td>No of incoherent integrations</td>
<td>1</td>
</tr>
<tr>
<td>Maximum Doppler Frequency</td>
<td>3.9 Hz</td>
</tr>
<tr>
<td>Maximum Doppler Velocity</td>
<td>10.94 m/s</td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>0.061 Hz</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>0.176 m/s</td>
</tr>
</tbody>
</table>

- E10y = East west polarization with off zenith angle of 10°
- W10y = East west polarization with off zenith angle of 10°
- N10x = North South polarization with off zenith angle of 10°
- S10x = North south polarization with off zenith angle of 10°