THEORETICAL RANGE RESOLUTION STUDIES OF ST RADAR SYSTEMS HAVING INSTRUMENTAL IMPERFECTIONS

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THIS PAPER IS PRESENTED AS A MEMORIAL

TO MY LATE MOTHER

W/O WELTEYOHANNES ALEMU

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ABSTRACT

The range resolution of a radar system depends on a number of factors, such as the duration and shape of the transmitted radar pulse, the impulse response of the receiver matched filter, the antenna system, characteristics of some transmitting and receiving equipment, etc. In this study, the theoretical range resolution of the stratosphere-troposphere (ST) radar system having instrumental imperfections is considered. The imperfections considered are the width and shape of the transmitted pulse and the associated impulse response of the receiver matched filter which is assumed to be always matched to the transmitted pulse. All other parameters that influence range resolution are assumed to be ideal. A simplified model of an ST radar system suitable for resolution studies is presented and this is used to simulate atmospheric profiles.

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INTRODUCTION

The word radar, formed from the initialized letters in radio detection and ranging, signifies a means of employing radio waves to detect and locate material objects [1]. It detects the presence of targets and locate their position in space by transmitting electromagnetic energy and observing the returned echo.

During the last decade, radars capable of measuring atmospheric parameters such as wind, turbulence & stability in free atmosphere have been developed [2]. These radars can perform atmospheric observations for altitude ranges starting from 1 km to several kilometers above the ground level. Radars that can observe the troposphere (that part of the atmosphere below about 15 km.) and the stratosphere (the atmosphere above the troposphere & below about 50 km.)are called stratos- phere -troposphere (ST) radar systems[3]. Several of these radars operate in the lower VHF (30-300 MHz)band notably at about 50 MHz but also operate in the UHF (300-3000MHz) band. The same antenna is used for both transmitting and receiving, the technique to achie ve this is described in section 2.1.

The technique developed to study the atmosphere at all heights from near the ground upto 100 km, has been named the mesosphere-stratosphere -t roposphere (MST) radar technique [2], involves the use of large coherent monostatic radar systems operating in the VHF range to obtain echoes from the optically clear atmosphere. Note that ST radars use MST radar technique.

In the ST & MST radar systems, atmospheric parameters are indirectly studied from the radar returns, which come from the refractive index structure in the air that have length scales of the order of half the radar wave length, 3-4 m for VHF radars in use. The refractive index structures are primarily of two kinds: turbulent and laminar. The former results in turbulent scatter of the radar signal and the latter results in Fresnel (or partial) reflection [3].

During transmitting the signal and receiving an echo from a target, there is a signal distortion that comes from instrumental imperfections. Due to this imperfection, radar parameters like range, Doppler shift, intensity of the radar echo, etc, cannot be estimated accurately. Consequently, efforts must be made to minimize the effects of these imperfections. The present study considers the factors affecting the range resolution of ST radar systems, due to imperfections in the transmitting and receiving systems.

Before presenting the possible degradation effects on the range resolution & minimize these effects, descriptions are given on the basic principles of radar and ST radar systems.

2. BASIC PRINCIPLES OF RADAR

2.1 BASIC PRINCIPLES

Radar is an electromagnetic system, one that utilizes its own controlled illumination to detect the target and to probe the target characteristics[4].

The two basic operations performed by radar are

a. detection of the presence of reflecting target and

b. extraction of information from the received wave to obtain such target parameters as position, velocity and perhaps size [5].

The ability to detect a target at great distances and to locate its position with relatively high accuracy are the two chief attributes of radar [4]. Let us now consider an elementary form of a radar set[1], which is shown in figure 2.1, consisting of antenna, transmitter, receiver, T-R device and presentation unit or indicator.

The main tasks of a transmitter are modulation and amplification . Modulations is a process designed to match the transmitted signal to the properties of the channel through the use of a carrier wave.

The function of the receiver is to extract the desired signal from the channel. Since received signals are often very weak as a result of attenuation, the receiver may have several stages of amplification. In addition the receiver performs demodulation (or detection), which restores the signal to its original form [6].

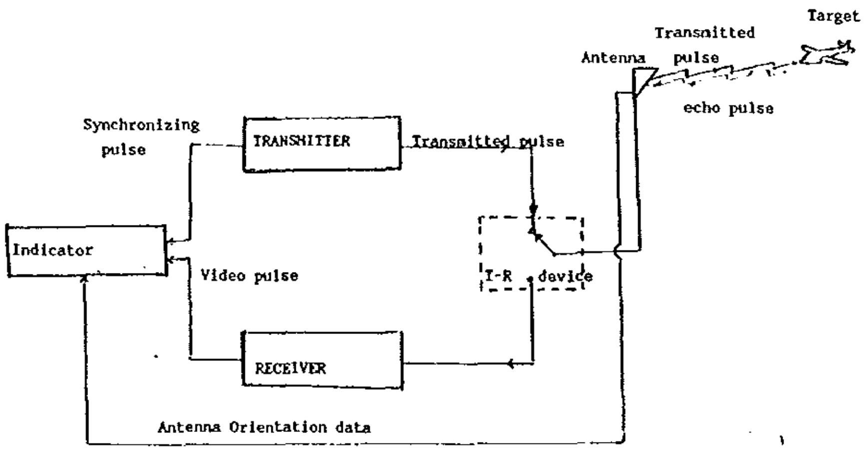


Fig. 2.1 An elementary form of a radar set.

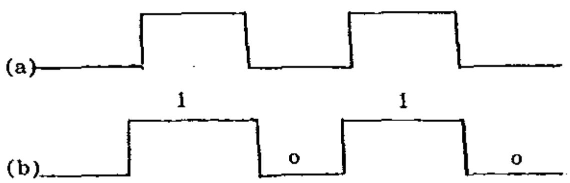


Fig. 2.2 (a) Transmitted signal,

(b) Operating modes of antenna as achieved by T-R device; the antenna is connected to the transmitter during 1 and to the receiver during 0.

The function of the antenna during transmission mode is to concentrate the radiated energy into a narrow beam which points in the desired direction in space. In the reception mode it collects the energy contained in the echo signal, and delivers it to the receiver. The received signal is then processed to detect the target and estimate its parameter.

The use of a single antenna for both transmission and reception in nearly all radar sets is made possible by a transmit - receive device (abbreviated T-R device) connected as shown in figure 2.1 [1]. The T-R device functions as a switch to connect the antenna to the transmitter during transmission, and to the receiver during the remainder of the interpulse period as shown in figure 2.2. The T-R device is also called a duplexer and a receiver protective device.

The indicator or presentation unit generally contains a cathode ray tube (CRT). It displays the received signals in such a manner that the operator can interpret the information that is displayed. It also displays synchronizing pulse from the transmitter [7].

2.2 MEASURED PARAMETERS

Parameters that can be measured by a radar at its indicator are

a. The time delay between transmitted signal and echo.

b. Intensity of the returned signal or echo.

c. Spectral parameters of returned signal.

2.3 ESTIMATED PARAMETERS

Having the above measured quantities, the following parameters are estimated.

a. The range of the target,

b. The velocity of the target,

c. The position of the target,

d. The cross-section of the target

and also other parameters are estimated. The estimated parameters are described in the following sections.

2.3.1 RANGE OF THE TARGET

Range of the target is a direct distance from the antenna to the target,and the maximum range is the range beyond which a target can-not be detected because signals are obscured by noise.

The radar range equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target and environment. It is useful not just as a means for determining the maximum range, but it can serve both as a tool for understanding radar operation and as a basis for radar design [5].

To formulate the radar range equation, consider the radar set and target to be isolated bodies in space, as shown in figure 2.3, provided that propagation effects are neglected [1].

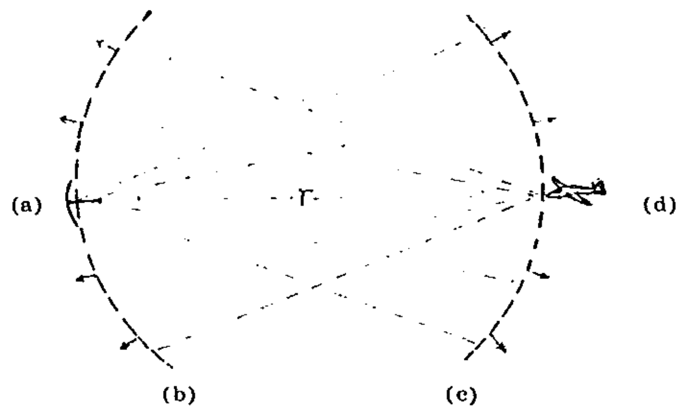


Fig. 2.3 Transmitted and reflected waves for radar set and object considered as isolated bodies in space.

Where (a) radar antenna,

(b) reflected and

(c) transmitted spherical wavefronts.

(d) target to be detected.

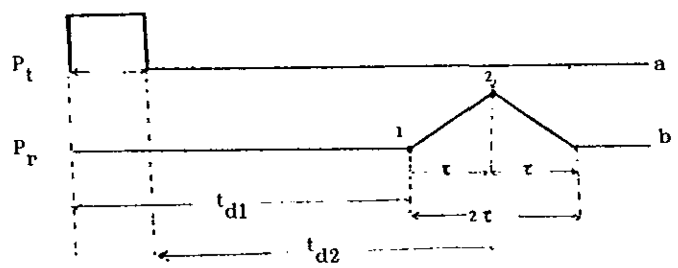


Fig. 2.4 Transmitted pulse and the out-put of matched filter receiver for received signal.

a) Transmitted pulse.

b) received pulse passed through a matched filter .

As shown in figure 2.3,we can relate the transmitted, reflected power and the range of the target.

Power density of the transmitted wave at the target =

$$\frac{P_t}{4\pi r^2} \times G_t \qquad (2.1)$$

Where P_t is the peak power (in watts) transmitted from the antenna,

r is the range of the target & G_t is the power gain of the transmitting antenna relative to an isotropic antenna.

(an isotropic antenna is a ficitious antenna that radiates uniformly in all directions). G_t is a factor greater than one, to take account of the concentration of the radiation in the direction of the target [5].

$$G_t = \frac{\text{The actual power density at the target}}{\text{power density that would be produced by an isotropic antenna}} \qquad (2.2)$$

The target intercepts a portion of the incident power and reradiates it in various directions. The measure of the amount of incident power intercepted by the target and reradiated back in the direction of the radar is denoted as the radar cross-section A_o . The radar cross-section A_o has units of area. It is a characteristic of the particular target and is a measure of its size as seen by the radar [5].

$$\text{The power density of echo signal at the radar site} = \frac{P_t G_t}{4\pi r^2} \times \frac{A_o}{4\pi r^2} \qquad (2.3)$$

The radar antenna captures a portion of the echo power. If the effective area of the receiving antenna is denoted by Ae, the power P_r received by the radar is,

$$P_r = \frac{P_t G_t}{4\pi r^2} \times G_t \times \frac{A_o}{4\pi r^2} \times A_e \qquad (2.4)$$

From equation 2.4, the free-space maximum range can be obtained if P_r represents the power of the weakest discernible echo pulse. Because the discernibility of a pulse depends upon its energy, the appropriate value for P_r is $\frac{W_{r\,min}}{\tau}$ where $W_{r\,min}$ is the energy of the minimum discernible pulse and τ is the pulse duration.

If P_r in equation 2.4 is replaced by $\frac{W_{r\,min}}{\tau}$, r becomes the maximum range r_{max}, and the resulting equation solved for r_{max} is the radar range equation.

$$r_{max} = \frac{1}{2(\pi)^{\frac{1}{2}}} \left([P_t\tau] \times \left[\frac{1}{W_{r\,min}}\right] \times [G_t A_e] \times [A_o] \right)^{1/4} \qquad (2.5)$$

(a) (b) (c) (d)

The bracketed factors in equation 2.5, show the effect of radar set characteristics and the target at maximum range [1].

In equation 2.5 (a) is the energy content of the transmitted pulse.

(b) is the minmum detectable echo-pulse energy.

(c) is the characteristics of antenna.

(d) is the reflecting effectiveness of target.

If the same antenna is used for transmission and reception, the power gain G and effective area A are related by equation (dropping subscripts)

$$G = \frac{4\pi A}{\lambda^2} \qquad (2.6)$$

Therefore the factor GA is proportional to $\frac{A^2}{\lambda^2}$, and at fixed wavelength the maximum range is proportional to the square root of effective antenna area.

The radar equation 2.5 is useful for rough computation of range performance, but it is simplified and doesnot give realistic values. The predicted ranges are generally optimistic. There are at least two major reasons why the simple form of the radar equation doesn't predict with any accurancy the range of actual radars [5] :

a) It doesn't include various losses that can occur in a radar,

b) The minimum detectable signal is statistical in nature, since it is determined by noise. Thus the specification of the range must be made in statistical terms.

The range of a target is determined from the delay time. The echo received from the target not only indicates that a target is present, but the time that is elapsed between the transmission of the pulse and the recept of the echo is a measure of the distance to the target, as shown in figure 2.4. Separation of the echo signal and the transmitted signal is made on the basis of difference in time.

Where t_{d1} and t_{d2} are the time delays, measured from the first (leading) edge and the second edge of the transmitted signal to point 1 and 2 of the received signal respectively.

As shown in figure 2.4, a rectangular radar pulse of duration τ is transmitted from the radar. When this pulse is reflected from the target and received by the radar, which have a matched filter receiver (sec. 2.6), the out-put from this receiver is a triangle as shown.

The leading edge of the transmitted signal returns first and the point that corresponds to this is, point 1 at receiver out-put signal. It is difficult to locate point 1 due to the noise that masks it. Therefore t_{d1} does not indicate the correct time delay.

A better way of measuring time delay is using t_{d2}, we have to shift τ in both P_t & P_r as indicated in fig. 2.4, and we can measure starting from the second edge of the transmitted signal up to point 2, that is the peak point of the output signal of the receiver.

The range of a target can be found from delay time $t_{d2}=t_d$,

$$r = \frac{ct_d}{2} \qquad (2.7)$$

The factor 2 appears in the denominator because of the two way propagation of radar pulse. Where c is the speed of light.

Remark

1. Until this point we have considered only propagation delay, but there is a delay at transmitter t_t , at antenna t_a during transmission and reception, and also delay at the receiver t_r.

Therefore to measure the range from a radar antenna site, t_t, t_a & t_r must be subtracted from t_d .

2. The above ideal case, that is a perfect rectangular radar pulse doesnot exist in practice. The actual practical pulse is distorted due to instrumental imperfections.

2.3.2 POSITION OF THE TARGET

Position or location of a target is accomplished by determining the distance and direction of a target from the radar equipment and requires, in general, the measurement of three coordinates usually range, angle of azimuth and elevation as shown in fig. 2.5, [7].

2.3.3 VELOCITY OF THE TARGET

A feasible technique for separating the received signal from the transmitted signal, when there is relative motion between radar and target is based on recognizing the change in the echo-signal frequency caused by Doppler effect.

An apparent change in frequency (Doppler effect) will be result if either the source of oscillation or an observer is in motion, and this is a basis of continuous wave (CW) radar [5]. The change in frequency observed by a radar is used to indicate the presence of the moving target & its radial velocity and also indicate whether an object is approaching or receding [7].

Let us now, consider a target moving with velocity v towards an observer, and unmodulated continuous wave (CW) is emitted from the radar.

The emitted wave

$$Ye = \sin \omega t \qquad (2.8)$$

The received waveform is

$$Yr = \sin (\omega t - \phi (t) \qquad (2.9)$$

If r is the range of the target, the total number of wavelength contained in the two-way path between the radar and the target is $2r/\lambda$ Since one wavelength corresponds to an angular excursion of 2π radians, the total angular excursion ϕ made by the electromagnetic wave during its transit to and from the target is $\frac{4\pi r}{\lambda}$ radians.

Therefore $$\phi (t) = \frac{4 \pi r}{\lambda} \qquad (2.10)$$

The received wave then has a radian frequency

$$\omega_r = \omega - \frac{d\phi}{dt} \qquad (2.11)$$

$$= \omega - \frac{4\pi}{\lambda} \frac{dr}{dt}$$

Where $\frac{dr}{dt} = -v$ (radial velocity)

Therefore, $$\omega_r = \omega + \frac{4\pi v}{\lambda} \qquad (2.12)$$

and $$f_r = f_e + \frac{2v}{\lambda} \qquad (2.13)$$

The shift in frequency suffered by the emitted signal after being scattered (refelcted) by the moving target is the Doppler shift, f_d.

$$f_d = f_r - f_e = \frac{2v}{\lambda} \qquad (2.14)$$

The received echo signal is compared in phase to the transmitted signal, so that the radial velocities of the echoing region may be determined by means of Doppler shift.

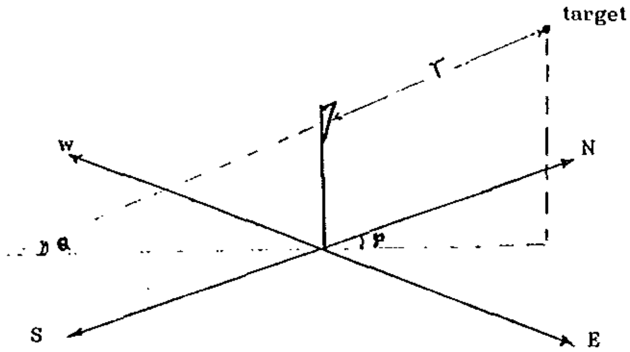


Fig. 2.5 , Radar set up to locate a target. Where r is the range of the target,

Q is the angle of elevation

ψ is the angle of azimuth angle of bearing of the target.

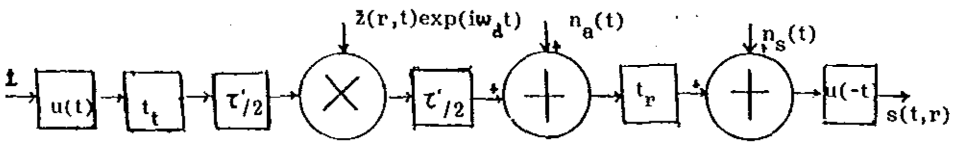


Fig. 2.6, System set up.

Where $n_a(t)$ is atmospheric noise.

$n_s(t)$ is system noise.

$\tau'/2$ is propagation delay.

t_t is delay at the transmitter.

t_r is delay at the receiver.

2.4 ANALYSIS OF THE TRANSMITTED RADAR SIGNAL

The transmitter modulates a rectangular pulse by a carrier wave of frequency f_c and emits a signal of the form

$$s(t) = s_1(t)\, s_2(t) \qquad (2.15)$$

Where $s_1(t) = A\cos 2\pi f_c t$ (2.16)

is the carrier signal and

$$s_2(t) = \prod\left(\frac{t}{\tau}\right) \qquad (2.17)$$

is a periodic train of rectangular pulse of width τ and pulse repetition frequency F_r .

The spectrum of s(t) is the Convolution of the spectrum of the signals of equations 2.16 and 2.17.

$$\mathcal{F}[s(t)] = \mathcal{F}[s_1(t)] * \mathcal{F}[s_2(t)] \qquad (2.18)$$

The spectrum of each signal in equation 2.16 and 2.17 is

$$\mathcal{F}[s_1(t)] = \frac{A}{2}[\delta(f-f_c) + \delta(f+f_c)] \qquad (2.19)$$

$$\mathcal{F}[s_2(t)] = \sum_{n=-\infty}^{\infty} \delta(f-nF_r)\frac{\tau F_r}{2} \sin \frac{\pi f\tau}{\pi f\tau} \qquad (2.20)$$

The magnitude of the transmitted signal taking the positive frequency part.

$$|S_+(f)| = \frac{\tau A F_r}{2}\left|\frac{\sin \pi(f-f_c)\tau}{\pi(f-f_c)\tau}\right| \sum_{n=-\infty}^{\infty}\delta(f - f_c - nF_r) \qquad (2.21)$$

The time domain and frequency domain representation of the transmitted signal is shown in fig. 2.7.

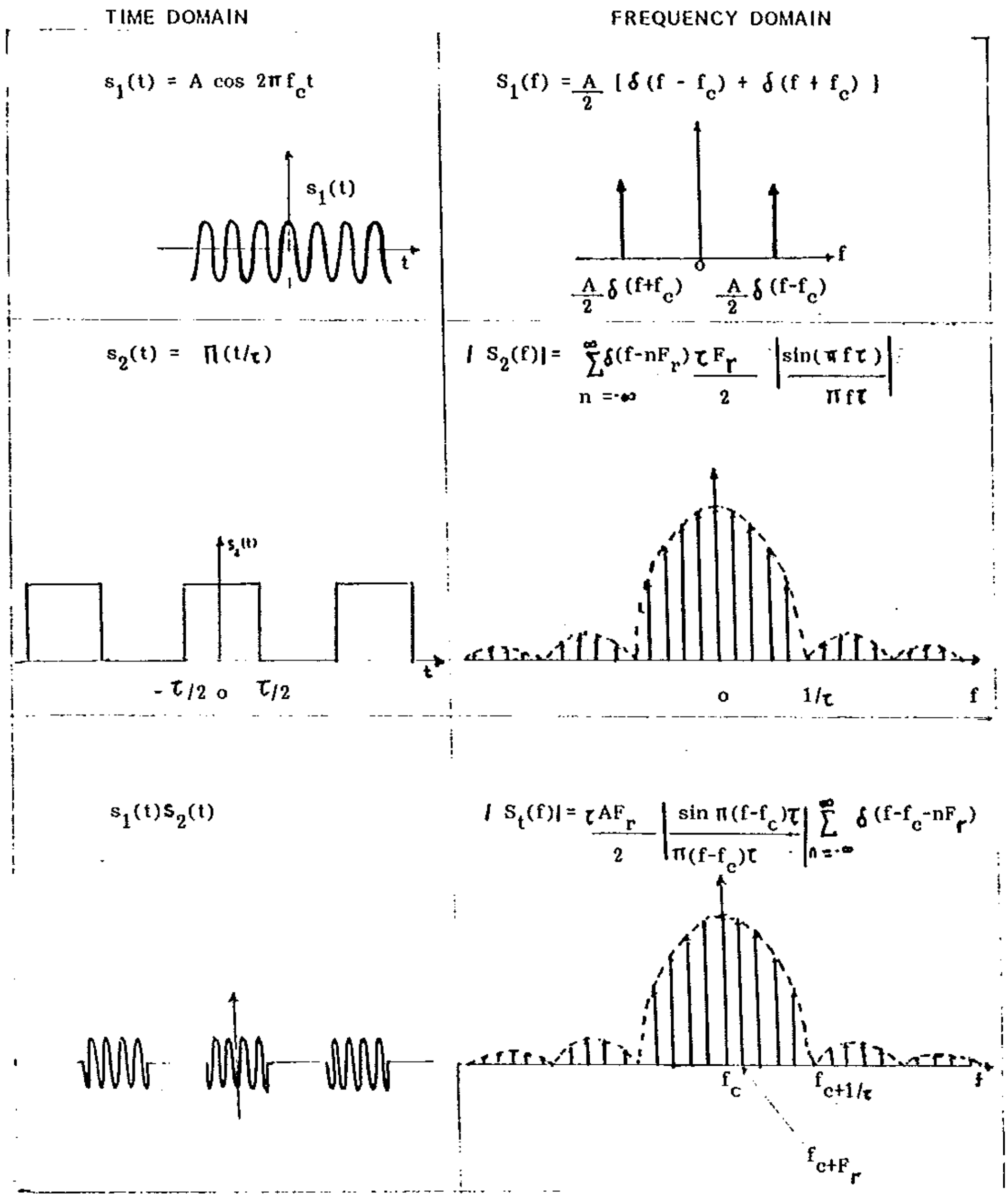


Fig 2.1 Time & frequency domain representation of transmitted signal.

2.5 ANALYSIS OF THE RECEIVED RADAR SIGNAL

For a target at a distance r from the radar the spectrum of the received signal is

$$S(f,r) = S(f) * S_d(f,r) \qquad (2.22)$$

Where S(f) is the spectrum of the signal $S_d(f,r)$ is the Doppler spectrum of the target. At the receiver, the signal is demodulated and passed through a matched filter (sec. 2.6).

Consider the simplified model of a radar system shown in figure 2.6.

Suppose an impulse $\delta(t)$ is input at the left side of a system as shown in fig.2.6 , whose impulse response h(t) = u(t) which is a rectangle. The out put from this system is,

$$\delta(t) * u(t) = u(t) \qquad (2.23)$$

Then this rectangular pulse is delayed at different stages as indicated in fig.2.6. It is modulated by a target and atmospheric noise is added to it. When this is received, system noise is also added. To get the desired signal at the output of the receiver, we may use a matched filter receiver whose impulse response h(t) = u(-t).

2.6 MATCHED FILTER RECEIVER

The requirement for optimum detection of a signal of known characteristics in white gaussian noise give rise to the concept of the matched filter. The matched filter receiver, requires a particular relationship between the spectrum of the transmitted signal and the frequency response of the receiver system, which maximizes the output peak signal to mean noise (power) ratio for a known signal in additive white noise, and is also optimum for a number of other detection strategies [8]. This criterion or its equivalent, is used for the design of almost all radar receivers. A matched filter for a radar transmitting a rectangular shaped pulse is usually characterized by a bandwidth B approximately the reciprocal of the pulse width or $B \approx \frac{1}{\tau}$ [5].

To confirm the above discussion, let's consider the linear time invariant system shown in fig 2.8.

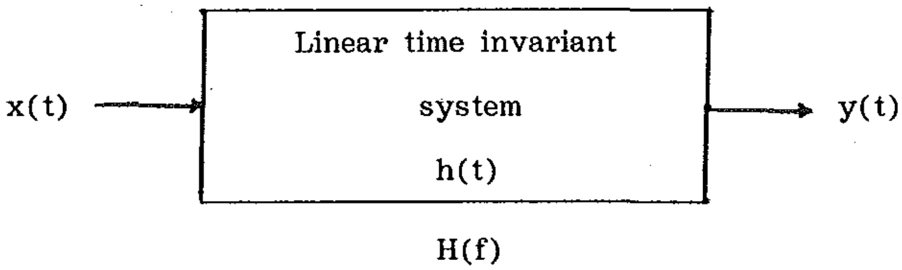


Fig. 2.8 Matched filter receiver

Where x(t) is the input to the system.

y(t) is the output of the system

h(t) is impulse response of the system.

H(f) is the transfer function. of the system.

The input to the system, x(t) is a linear combination of the signal and noise,

$$x(t) = s(t) + n(t) \tag{2.24}$$

and the corresponding out put is

$$y(t) = s_o(t) + n_o(t) \tag{2.25}$$

Where s(t) is the input signal

$s_o(t)$ is the output signal

n(t) is the input noise and

$n_o(t)$ is the output noise

To get the frequency response of such system, consider the output signal of the system shown in figure 2.8. The output signal of the system is

$$s_o(t) = s(t) * h(t) \qquad (2.26)$$

Which is equivalent to

$$s_o(t) = \int_{-\infty}^{\infty} S(f)\, H(f) \exp(i2\pi ft)df \qquad (2.27)$$

The peak signal power, P_s, of the output signal at some time t_o is,

$$P_s = [s_o(t_o)]^2 = [\int_{-\infty}^{\infty} S(f)H(f) \exp(i2\pi ft_o)\, df\,]^2 \qquad (2.28)$$

The average output noise power, P_n, is equal to the spectral density of the input noise G(f) times the squared magnitude of the transfer function H(f) (see appendix A).

$$P_n = \int_{-\infty}^{\infty} G(f)\, [\, H(f)]^2\, df \qquad (2.29)$$

Where G(f) is the input noise power density spectrum. The ratio of powers to be maximized becomes,

$$\text{SNR or } \frac{P_s}{P_n} = \frac{[\int_{-\infty}^{\infty} S(f)\, H(f)\, \exp(i2\pi ft_o)df]^2}{\int_{-\infty}^{\infty} G(f)\, [\, H(f)]^2\, df} \qquad (2.30)$$

Where SNR is the signal to noise ratio.

To maximize equation 2.30, we may apply the Schwarz inequality. If A(f) and B(f) are in general complex functions of the real variable f, the inequality states that [9],

$$\left[\int_{-\infty}^{\infty} A(f)\, B(f)\, df \right]^2 \leq \int_{-\infty}^{\infty} [A(f)]^2\, df \int_{-\infty}^{\infty} [B(f)]^2\, df \qquad (2.31)$$

The equality of equation 2.31 holds when B(f) is proportional to A(f), that is,

$$A(f) = C\, B^*(f) \qquad (2.32)$$

Where C is an arbitrary real constant. If we make the substitutions,

$$A(f) = (\, G(f)\,)^{\frac{1}{2}}\, H(f) \qquad (2.33)$$

$$B(f) = \frac{S(f)\, \exp\, (i2\pi f t_o\,)}{(\, G(f)\,)^{\frac{1}{2}}} \qquad (2.34)$$

in the schwartz inequality we obtain

$$(SNR) \leq \int_{-\infty}^{\infty} \frac{[\, S(f)\,]^2}{G(f)}\, df \qquad (2.35)$$

The maximum ratio occurs when the equality holds, that is when equation 2.32 is true. Substituting equation, 2.33 and equation 2.34 into equation 2.32 we get,

$$H_{opt}\,(f) = \frac{1}{C}\, \frac{S^*(f)}{G(f)}\, \exp\, (\, -i2\pi f t_o) \qquad (2.36)$$

Where $H_{opt}(f)$ is the optimum or matched filters transfer function.

If a signal having a spectrum S(f) and noise having a power density spectrum G(f) are passed through a filter which maximizes the ratio of peak out put signal power to average out-put noise power, the filter must have the frequency response defined in equation 2.36. Since C is arbitrary and the exponential factor represents a delay (which controls the time of occurrence of the out-put maximum), the important information in equation 2.36 is the factor $\frac{S^*(f)}{G(f)}$ [9].

2.6.1 FILTER FOR WHITE NOISE

White noise is an idealized form of noise, whose spectral density is independent of the operating frequency. The spectral density of white noise is [10],

$$G(f) = \frac{N_o}{2} \qquad (2.37)$$

where the factor half has been included to indicate that half the power is associated with positive frequency and half with negative frequency as shown in figure 2.9 Alternately, N_o is the positive frequency power density [6].

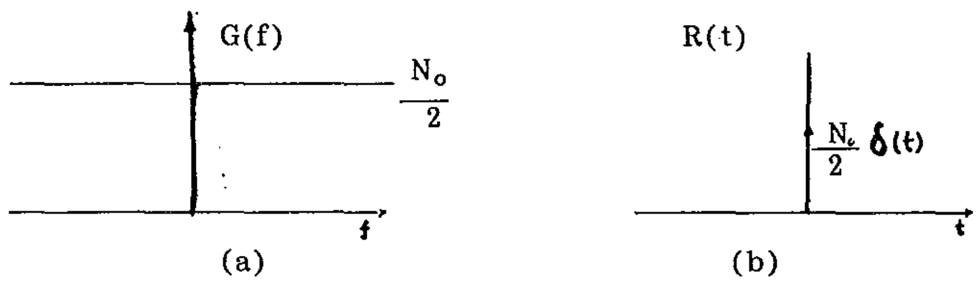


Fig. 2.9 characteristics of white noise

a) Spectral density

b) Autocorrelation function

The autocorrelation function of the white noise is

$$R(t) = \frac{N_o}{2} \delta(t) \qquad (2.38)$$

From equation 2.38, we can understand that R(t) is zero for $t \neq 0$. This shows that any two different samples of white noise are uncorrelated; if the white noise is also Gaussian, then the two samples are statistically independent [10].

Strictly speaking, white noise has infinite mean power and, as such, it is not physically realizable. Nevertheless, white noise has convenient mathematical properties and therefore is useful in system analysis.

If we consider a Gaussian noise process that has a spectrum much wider than the bandwidth of the system which operates on it, and if it has a spectral density that is essentially constant over that band, we may model it as white Gaussian noise [10].

Having aquired the above ideas about white noise, Let us return to our matched filter transfer function, equation 2.36. Substituting G(f) for a white noise in equation 2.36 we can get,

$$H_{opt}(f) = \frac{N_o}{2C} S^*(f) \exp(-i2\pi f t_o) \qquad (2.39)$$

$$= K S^*(f) \exp(-i2\pi f t_o)$$

where K is an arbitrary real constant (generally taken to be unity).

The matched filter may also be specified by its impulse response h(t), which is the inverse Fourier transform of the frequency response function.

$$h_{opt}(t) = \int_{-\infty}^{\infty} H_{opt}(f) \exp (i2\pi ft) \, df \qquad (2.40)$$

Physically the impulse response is the out-put of the filter as a function of time, when the input is an impulse (delta function). Substituting equation 2.39 into equation 2.40 gives,

$$h_{opt}(f) = \int_{-\infty}^{\infty} S^*(f) \exp [-i2\pi f(t_o - t)] \, df \qquad (2.41)$$

for a real - valued signal s(t), we have $S^*(f) = S(-f)$,

$$h_{opt}(t) = \int_{-\infty}^{\infty} S(-f) \exp [-i2\pi f(t_o - t)] \, df \qquad (2.42)$$

$$= s(t_o - t)$$

The result obtained is that, the impulse response of the matched filter is a time reversed and delayed version of the input signal, that is matched to the input signal hence the name matched filter.

Note that, the only assumption we have made about the statistics of the input noise is that it is stationary and white with spectral density $\frac{N_o}{2}$ [12].

The impulse response of the filter, if it is to be realized, it is not defined for t less than zero. (one can not have any response before the impulse is applied). Therefore we must always have t less than t_o. However, for the sake of convenience the impulse response of the matched filter is sometimes written as s(-t) [5]. For such cases if the noise is assumed to be negligible, the output would be the auto-correlation function of a rectangular pulse of width τ is a triangle, which has a base width of 2τ .

The optimum receiver for detecting the presence of signal s(t) in the received wave-form is shown in figure 2.10)

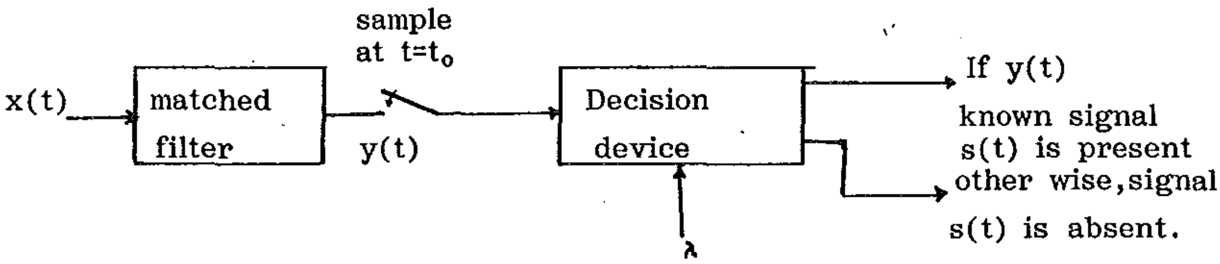


Fig 2.10. The receiver

The receiver consists of a. Filter matched to s(t)

b. Sampler

C. Decision - device

At $t = t_o$, the matched filter output is sampled, and the amplitude of this sample is compared with a preset decision level λ . If this level is exceeded, the receiver decides that the signal s(t) is present; otherwise, it will decide that it is absent. [10].

3. ST RADAR SYSTEM AND IT'S PRINCIPLES OF OPERATION

3.1 THE ST RADAR SYSTEM

Stratosphere - troposphere (ST) radars can observe the troposphere and the lower stratosphere of the atmosphere. Several of these radars operate in the lower VHF band notably at about 50 MHz , but there are also radars that operate in the UHF band.

In ST radar systems, atmospheric parameters, such as wind velocity, degree of turbulence and atmospheric stability are indirectly studied from radar returns (or atmospheric echoes). The two primary mechanisms for radar returns observed by VHF ST radars are [11] :-

a) Scattering that arises from randomly distributed fluctuations in the refractive index of the atmosphere having dimensions comparable to one half the radar wavelength.

b) Partial reflections from horizontally stratified stable layers, applicable to radars operating in the lower VHF band.

3.1.1 COMPONENTS OF ST RADAR SYSTEM AND PRINCIPLES OF OPERATION

From the block diagram shown in figure 3.2 the control box includes the oscillator, the synchronizer, & the modulator. The oscillator generates the signal, the synchronizer controls the pulsed transmission by determining the pulse width and interpulse period (and therefore, pulse repetition frequency), while modulator matches the signal (pulse to the transmission medium) through the use of a carrier frequency. The structure of the wave or shape of the pulse is, therefore determined by the control box and is delivered to the transmitter.

Since the same antenna is used for transmission and reception, there exists a switch that connects the antenna alternately to the transmitter and receiver. The switch prevents the high power transmitted pulse from damaging the sensitive receiver. The antennas shown in figure 3.1 are sequentially accessed by two switches; One which indicates the network will be in operation (network # 1 - antennas # 1,3; network #2 - antenna # 2), while the other switch will change the zenith angle from 0^{o} to β.

The number of sampling gates, their spacing, and the delay are also designated with the control box. This information is sent to the receiver along with a sample of the transmitted signal. The data generated from the fixed ranges are sent to the computer for signal processing, data display and recorded for future use.

3.2 ATMOSPHERIC PARAMETERS MEASURED BY ST RADAR

The atmospheric parameters that can be measured are mainly derived from the Doppler power spectrum (relative echo power density as a function of frequency shift from the transmitter frequency) of the signal return from a given height [12].

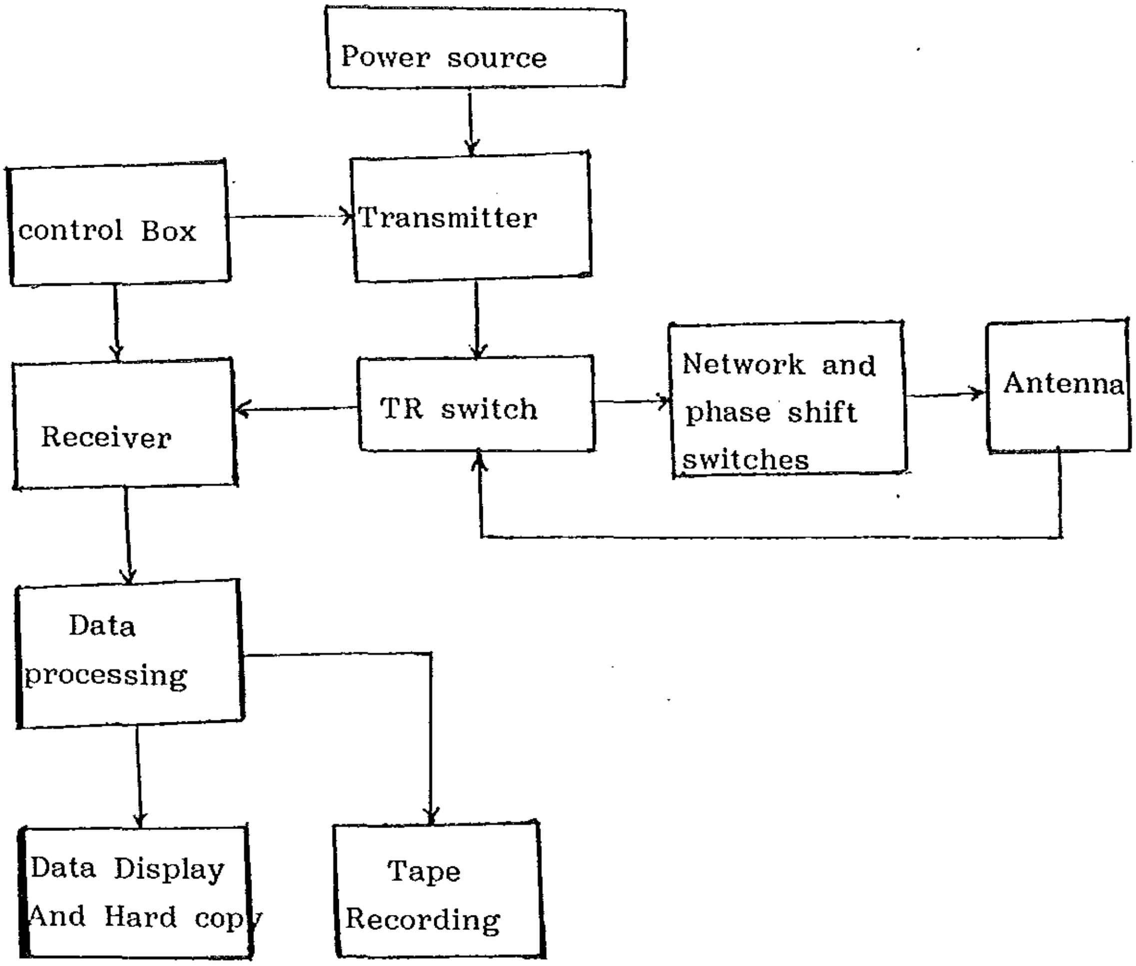


Fig. 3.2 Block diagram of typical ST radar.

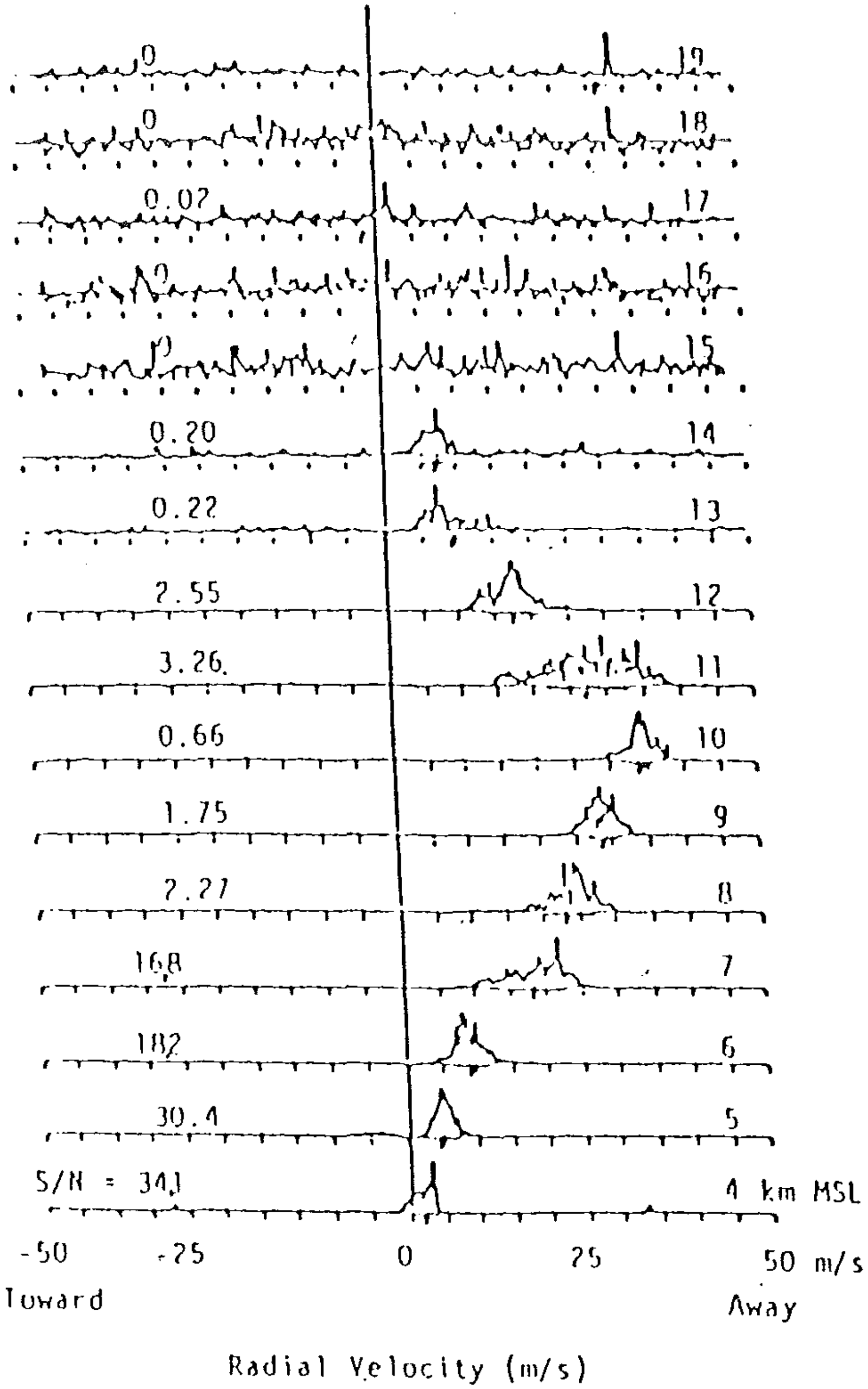


Fig. 3.3 Radial velocity versus altitude, the left side shows signal to noise ratio.(after K.S Gage & B.B Balsley [12]).

The mean Doppler shift is a measure of the mean radial component of motion of the scattering element. The ST radars use a coherent receiving system (that is, the received echo signal is compared in phase to the transmitted signal), so that the radial velocities of the echoing region may be determined by means of their Doppler shift (see figure 3.3) The magnitude of the echo spectrum and the width of the Doppler spectrum contain additional information on turbulence parameter.

Strong echoes that are obtained at vertical incidence from stable regions of the atmosphere via partial reflections. The intensity of these echoes yields a measure of atmospheric stability. As we have seen the antenna orientation of ST radar in figure 3.2, the signal received on the vertical antenna is considerably enchanced in comparison with the signal received on antennas pointed β of zenith. This enhancement has been attributed to partial reflection from stable regions of the atmosphere.

3.3 THE ST RADAR EQUATIONS

The radar equation relates the received signal strength P_r to the radar parameters appropriate to any particular system and the volume reflectivity η , or reflection coefficient $/\rho/$, for any particular atmospheric process being studied.

For the power received by a radar at vertical incidence from a horizontal reflecting region (partial reflection) at range r is derived by FRIEND [13] .

$$P_r = \frac{\alpha^2 P_t A_e^{\,2}}{4\,\lambda_R^2\; r^2} \quad |\rho|^2 \qquad (3.1)$$

where α is the efficiency of the antenna and transmission,

P_t is the peak transmitter power,

A_e is the effective antenna area,

λ_R is radar wave-length,

r is the range and

$|\rho|^2$ is the power reflection coefficient.

Atmospheric turblence is intermittent in space and time, it is some what different radar equation is obtained for this case. It is convenient to treat the radar volume defined by the antenna beam and the radar range resolution ($r = \frac{c\tau}{2}$, where τ is the pulse width). Having this, the radar equation for turbulent scattering from distributed (beam-filling) targets is :-

$$P_r = \frac{P_t\ \alpha^2\ c\ \tau_e\ A_e}{8\,\pi\, r^2}\,\eta \qquad (3.2)$$

where c is the velocity of light and τ_e is the effective duration of the radar pulse [14], [15].

For a radar receiver with a Gaussian response matched to the transmitted waveform of duration τ , $\tau_e \approx 0.6\tau$ [16]. For a rectangular uniformly illuminated array [17], [18], $A_e = (\frac{4}{9})\ A \cos\beta$, where A is the geometrical area of the array and β is the zenith angle [19].

The noise power that competes with the received power P_r is [20].

$$P_n = (\alpha T_c + T_r)\, KB_N \tag{3.3}$$

Where T_c is the cosmic noise temperature,

T_r is the receiver noise temperature,

K is Boltzmann's constant and

B_N is the bandwidth of the receiver.

The signal to noise ratio (SNR) for the case of turbulent scattering can be calculated dividing equation 3.2 by equation 3.3

$$\text{SNR or } \frac{P_r}{P_N} = \frac{P_t\, \alpha^2\, c\, \tau_e A_e\, \eta}{8\pi r^2\, (\alpha T_c + T_r)\, KB_N} \tag{3.4}$$

3.4 ECHOES OBSERVED BY MST RADARS

Mesosphere- stratosphere - troposphere (MST) radar, observes in all these three regions of atmosphere as indicated by its name. The technique used by MST radars also applied to ST radar system, and the primary mechanisms for the echoes observed by MST is the same as ST radar, but at a height above 50 km (above observation level of ST radar) the echoes are enhanced by free electrons during the day time for MST radars [20] , [21].

Referring figure 3.4a, the refractive index fluctuation that influences scattering and partial reflection, varies with humidity for the first few kilometers, then upto 50 kilometers with temperature and finally during the day time it varies with free electrons contribution above 50 kilometers [11].

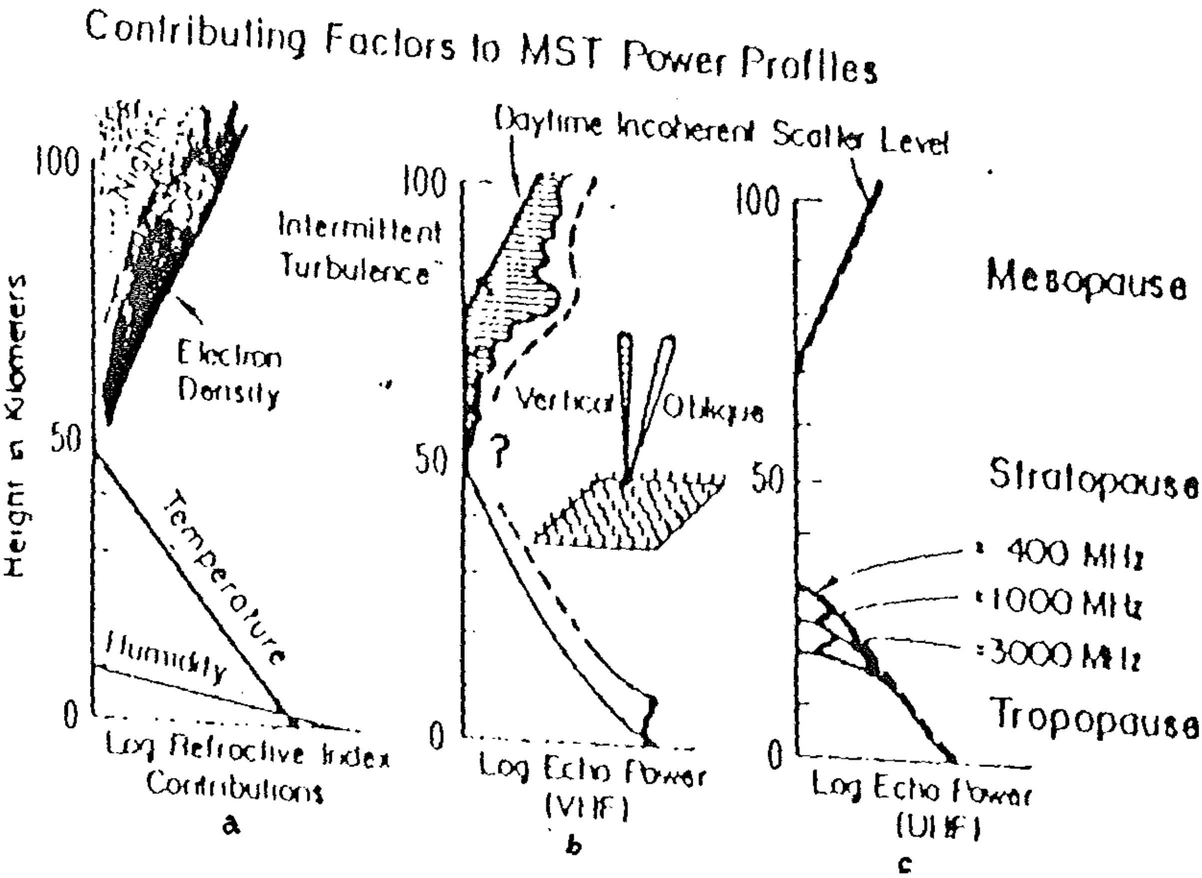


Fig. 3.4 Artists conception of some contributing factors to MST power profiles (after K.S Gage & B.B.Balsey [11]).

Depending upon contributing factors to the index of refraction as shown in figure 3.4b, scattering process at VHF roughly decrease exponentially with increasing height below 50 km (solid curve) is due to the corresponding decrease in turbulent fluctuation level and decrease in atmospheric density. Above 50 km the minimum echo level (labelled day time incoherent scatter level) is set by thermal scatter from free electrons [11].

More-over, when the antenna is directed vertically, additional echo enhancements are possible over the entire height range (dashed curve) from Fresnel reflection, from horizontally stratified structure. [11].

Note that The most difficult region to observe by the MST technique is the region near the stratopause because of the combined effect of exponentially decreasing atmospheric density and lack of sufficient free electrons [21].

Referring figure 3.4 c, we can see that the maximum observable height of turbulent scatter is frequency dependent, and depends upon viscous damping of the pertinent turbulent scale size. This is roughly indicated by the three separate curves in stratosphere labelled 400, 1000, and 3000 MHz [11].

The longer wave length radars are more effective in measuring turbulence in the mesosphere, where both the increased (kinematic) viscosity and the dispersive refractive index favor longer wavelengths [21]. For this reasons, only a VHF radar can be an MST radar.

4. RANGE RESOLUTION STDUIES

4.1 INTRODUCTION

The received signal in an ST radar system is sampled at different time instants, corresponding to different ranges during the receive phase of the transmit / receive cycle of the system.

The questions that are asked here are, where is the signal sampled at a particular time instant coming from ? To what extent can the source of the signal be resolved in range ? What are the factors affecting range resolution ? What is the range resolution requirement of ST radar systems? An attempt is made to answer these questions in this section.

4.2 MODELS FOR RESOLUTION STUDIES

A simplified model of the transmit / receive channel of an ST radar system is shown in Fig. 4.1 . In this case , the medium to be observed is modeled as a linear time invariant system. For range reolution studies, knowledge of the amplitude of the base band signal is sufficient. Consequently, the model contains only components that affect these signals.

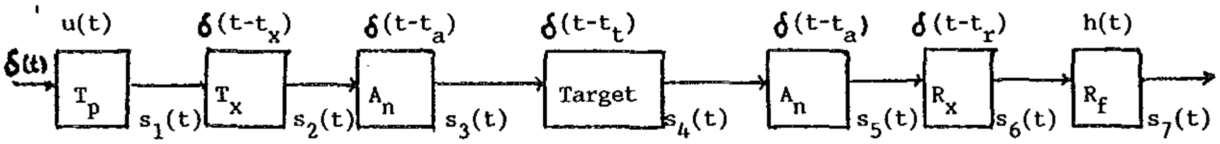


Fig. 4.1 system model

For the purpose of this study, the antenna beam width is assumed to be very narrow with no side lobes, so that no range ambiguities are introduced due to this. To simplify the presentation the noise component is left out. Note also that the effect of a noise is minimized through coherently summing it and taking the average as described in appendix B.

4.2.1 GENERAL CONSIDERATION TO THE SYSTEM MODEL

From the system model shown in figure 4.1, t_x, t_a, t_t & t_r are the time delays corresponding to transmitter, antenna, target and receiver respectively. Where s_i indicate the output from the i^{th} component in the model.

Referring to the system model shown in figure 4.1, an impulse is applied from the left side to trigger a pulse generator having an impulse response u(t) of a rectangular shape. The output from this system would be.

$$s_1(t) = \delta(t) * u(t) = u(t) \qquad (4.1)$$

The output is the same as the impulse response of the system for this case and a rectangular pulse is generated.

The pulse generated passes through the components having a unit impulse responses delayed to the corresponding component. To find the output from the receiver filter at the right end, we have to find s_i's sequentially.

Therefore

$$s_2(t) = s_1(t) * \delta(t-t_x)$$
$$= s_1(t-t_x) \qquad (4.2)$$

$$s_3(t) = s_2(t) * \delta(t-t_a)$$
$$= s_1(t-t_x) * \delta(t-t_a) \qquad (4.3)$$
$$= s_1(t-t_x-t_a)$$

$$s_4(t) = s_3(t) * \delta(t-t_t)$$
$$= s_1(t-t_x-t_a) * \delta(t-t_t) \qquad (4.4)$$
$$= s_1(t-t_x-t_a-t_t)$$

$$s_5(t) = s_4(t) * \delta(t-t_a)$$
$$= s_1(t-t_x-t_a-t_t) * \delta(t-t_a) \qquad (4.5)$$
$$= s_1(t-t_x-t_a-t_t-t_a)$$

$$s_6(t) = s_5(t) * \delta(t-t_r)$$
$$= s_1(t-t_x-t_t-2t_a) * \delta(t-t_r) \qquad (4.6)$$
$$= s_1(t-t_x-t_t-2t_a-t_r)$$

$$s_7(t) = s_6(t) * h(t)$$
$$= s_1(t-t_x-t_t-2t_a-t_r) * h(t) \qquad (4.7)$$

Let T' be the total time delay , $T'=t_x+ t_t + 2t_a + t_r$
Therefore, $s_7(t) = s_1(t-T') * h(t)$, let $s_o(t) = s_7(t)$ and $s_{in}(t-T') = s_1(t-T')$

$$s_o(t) = s_{in}(t-T') * h(t) \qquad (4.8)$$

Which is the output of the system model shown in figure 4.1

We can also put the system model in the following way.

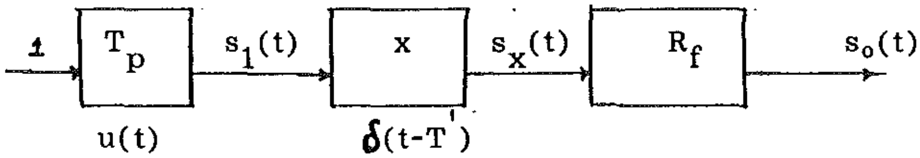


Fig. 4.2 simplified system model

The output from the pulse generator from equation 4.1 is $s_1(t) = \delta(t) * u(t) = u(t)$ and the output from the system x, which has a unit impulse response & delayed T', is

$$s_x(t) = s_1(t) * \delta(t-T')$$
$$= s_1(t-T') = s_{in}(t-T') \qquad (4.9)$$

The output from the receiver filter will be,

$s_o(t) = s_{in}(t-T') * h(t)$ which is the same as equation 4.8.

4.2.2 IDEAL SYSTEM

For an ideal system all the delays indicated on system model are zero except delay at the target, and the receiver filter is matched to the signal input to it perfectly.

Having equation 4.8 from the system model,

$s_o(t) = s_{in}(t-T') * h(t)$, $T' = t_t$ delay at the target and $h(t) = s(-t)$ for an ideal system

$$s_o(t) = s_{in}(t-t_t) * s(-t) \qquad (4.10)$$

Doing this convolution, we can get a triangle at the receiver output as shown in figure 4.3b.

To achieve this result, let's perform a discrete convolution for data values found in table 1. let t=k for discrete time, & the discrete convolution can be written as,

$$S_o(k) = \sum_{I=0}^{N-k} S(I)S(I+k), \text{ for } 0 \leq k < N \qquad (4.11)$$

and the symmetry condition is imposed to the negative part.

The response function that is shown in figure 4.3b is from a single point target. Let us now consider uniform targets viewed by a rectangular pulse of width τ taken as a window of observation as shown in figure 4.4a

Referring to figure 4,4a the voltage sampled at OE comes from different targets within the limit of 2τ as shown. Targets at the left of A & from the right side of I including A&I don't have any contribution to the sampling instant. All other targets within the width of 2τ contributes to the sampling instant, however, their contribution decreases with distance from it for uniform targets.

As we can see from figure 4.4b, whether the intensity of the target is small or large it doesn't contribute to the sampled value at a point 2τ & beyond it. However depending upon the intensity it contributes more, or less to the sampling value as shown.

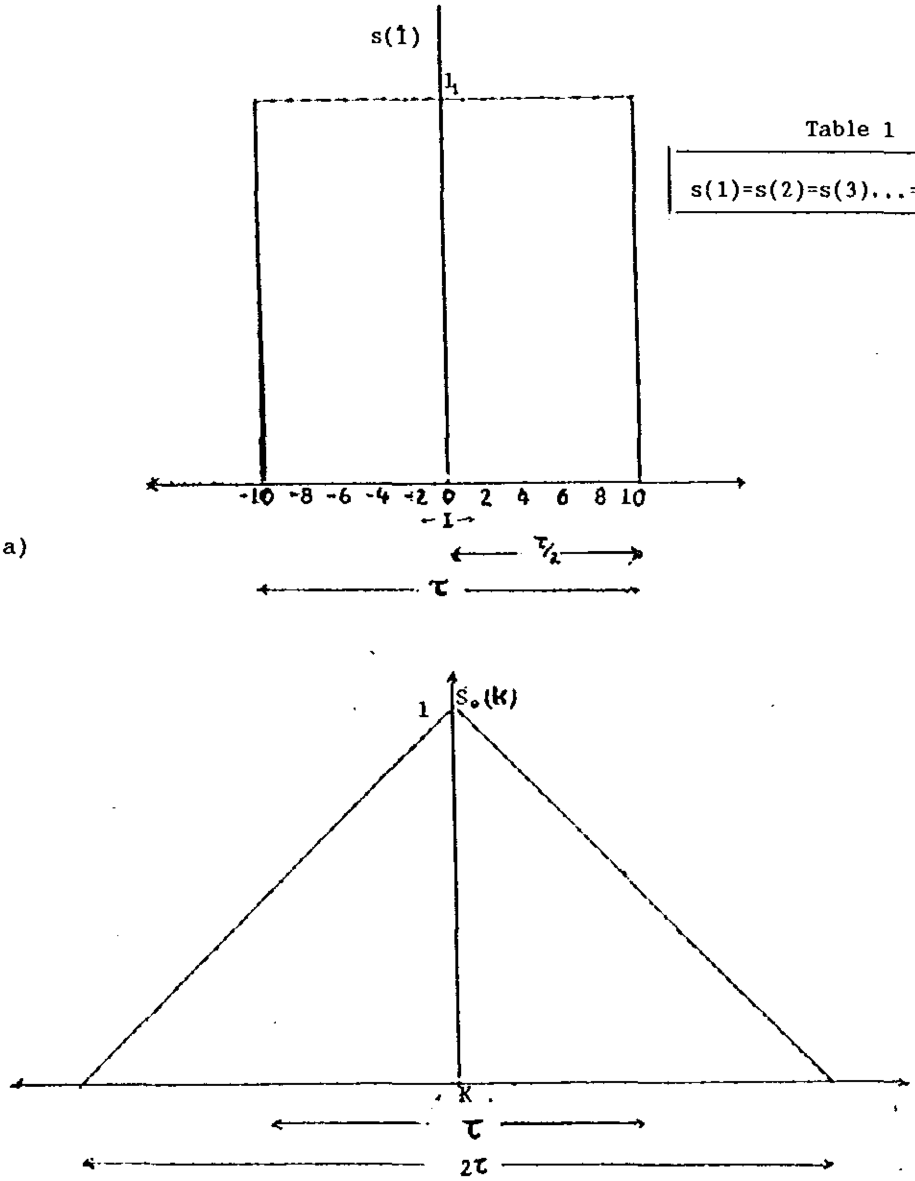


Table 1

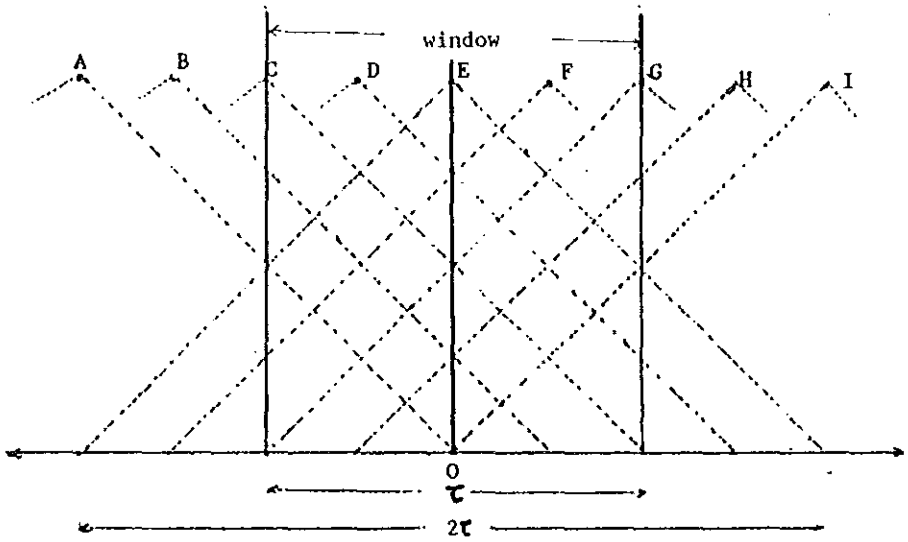
s(1)=s(2)=s(3)...=s(10) = 1

(a)

(b)

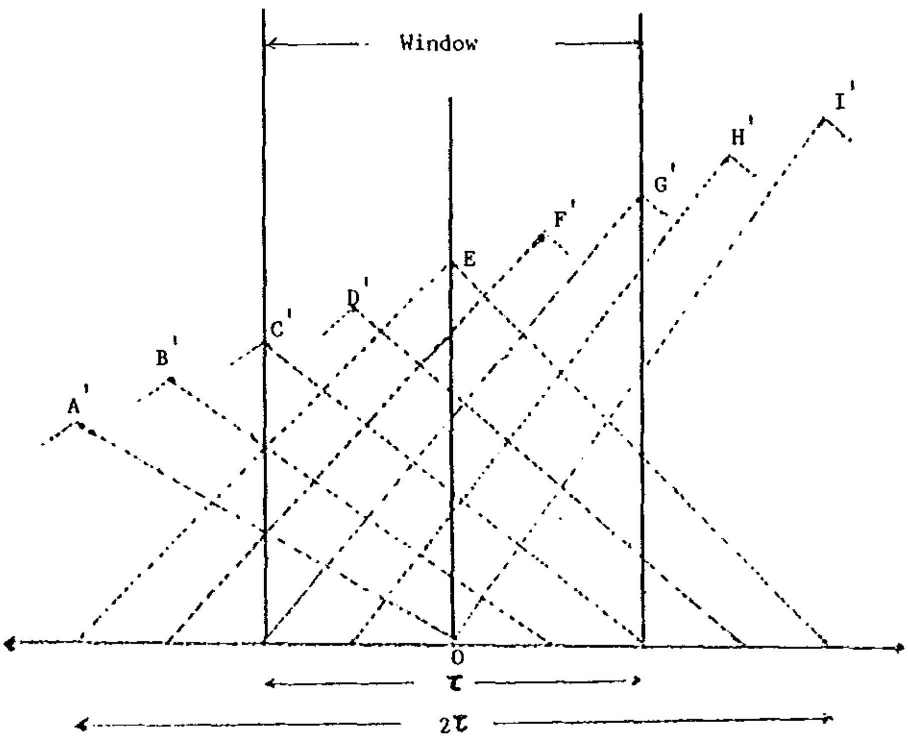
Fig. 4.3 (a) transmitted & received pulse.

(b) matched filter receiver output.



O E is the sampling instant.

(a)



(b)

Fig. 4.4 (a) uniform targests when viewed by a rectangular pulse,

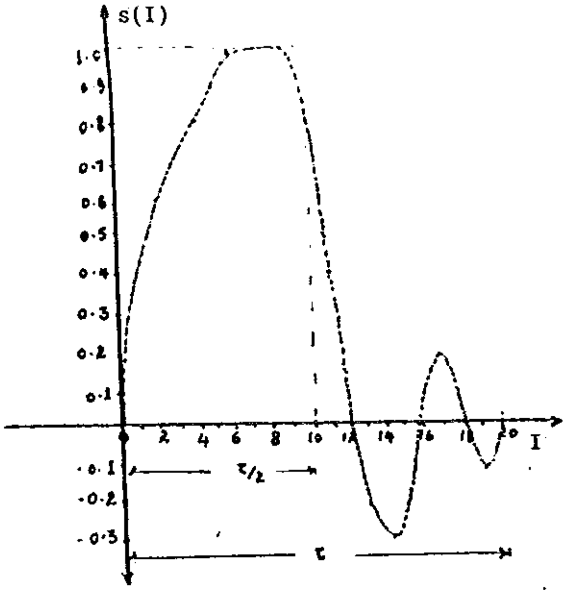
(b) non uniform targets when viewed by a rectangular pulse.

4.2.3 SYSTEM WITH IMPERFECTIONS

In the actual sense the pulse that is transmitted is not a perfect rectangle, it is distorted due to instrumental imperfections as one shown in figure 4.5a. The discrete convolution of this distorted pulse by itself gives almost a triangle with side lobes shown in figure 4.5b. The receiving system for this case is not perfect, that is, it doesn't have a matched filter with an impulse response identical to the ideal filter.

Figure 4.5b shows the recievers output (response function) from a single target. The response functions for uniform intensity & varying intensity targets are shown in figure 4.6.

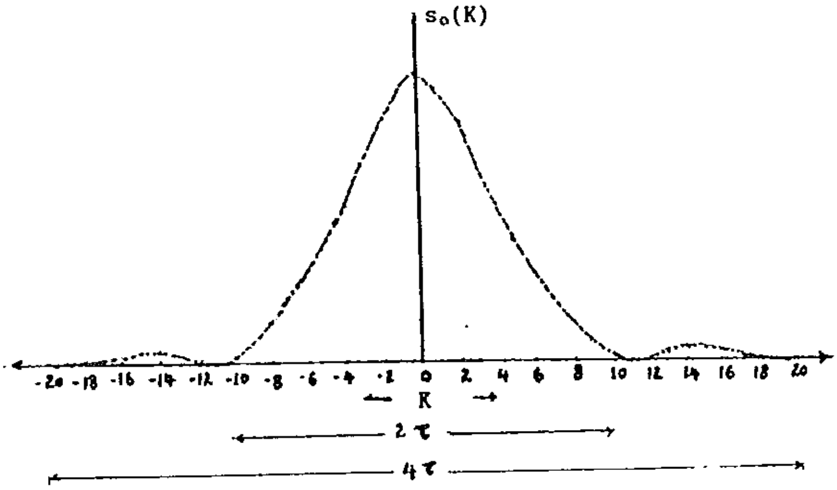
The main lobe that is shown in figure 4.5b is almost a triangle whose base is 2τ as in the case of the ideal system. But due to the distortion of the transmitted pulse, the side lobes are created as shown, which influences the resolution of the observation of the desired target.



(a)

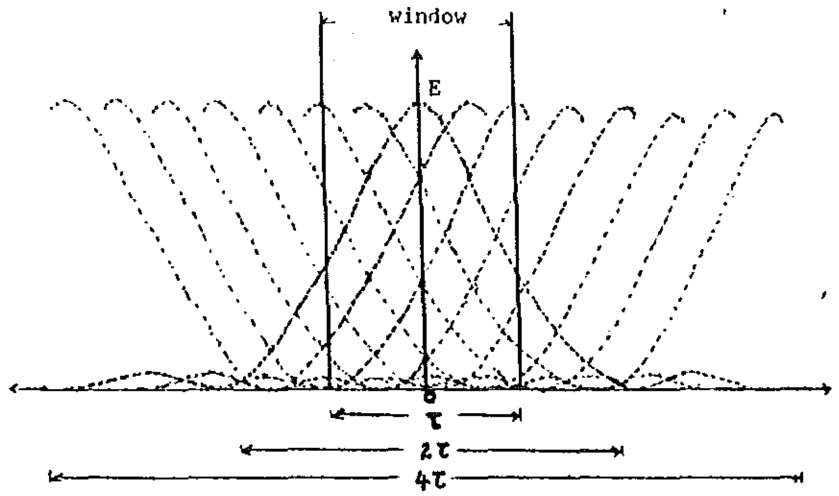
Table 2

I	s(I)
0.0	0.0
1	0.4
2	0.6
3	0.7
4	0.8
5	0.9
6	1.0
7	1.0
8	1.0
9	1.0
10	0.8
11	0.4
12	0.0
13	-0.2
14	-0.3
15	-0.1
16	0.1
17	0.2
18	0.0
19	-0.1
20	0.0

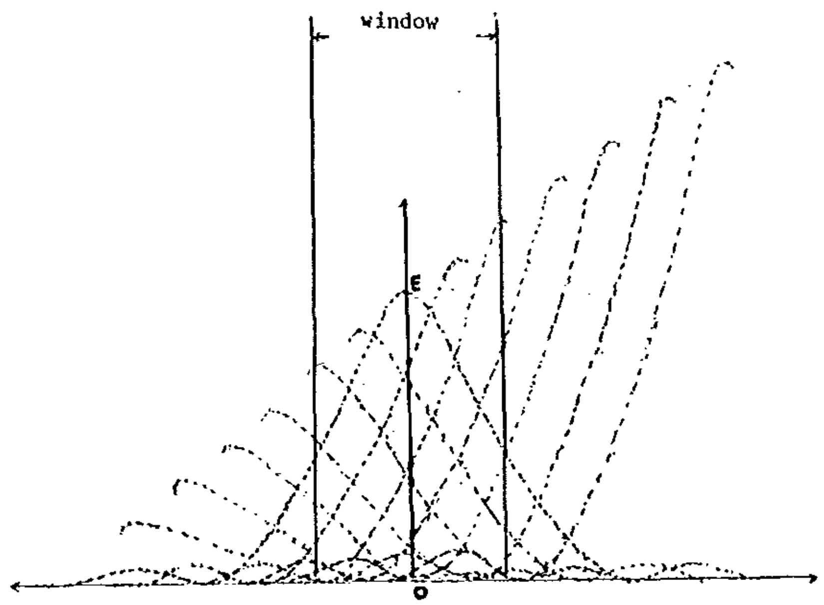


(b)

Fig. 4.5 (a) distorted radar pulse.
(b) receiver output (discrete convolution of the distorted radar pulse by it self; this is done using the computer as it's program is described in appendix c, taking the symmetry for the negative part).



(a)



(b)

Fig. 4.6 (a) uniform targets when viewed by a distorted radar pulse.
(b) non uniform targets when viewed by a distorted radar pulse.

4.3 CASE STUDIES FOR ATMOSPHERIC PROFILES

The actual radar response from a number of atmospheric layers can be calculated from convolution of the response function with the vertical profile of the atmosphere. The total power returned is extended in the range, and for the case of very closely spaced layers the returned signal cover, or nearly cover, the range between target layers depending upon the pulse width.

From observation it was found that turbulence in the troposphere and stratosphere occurs in this (about 200 m or less) horizontal layers separated in altitude by a few hundred meters or more, are responsible for an echo observed by ST radars. In order to discriminate such layers the radar must have a sufficient range resolution [24].

Having the general idea on atmospheric profiles, the model developed as atmospheric profiles and a radar response to these profiles with different pulse widths are shown in figures 4.7, 4.8 and 4.9. In all these three, the profile at the left is the echo intensity of target layers and the right side is its radar response.

Figure 4.10 shows a single target, when viewed by a receiver output that is obtained form distorted radar pulse.

In each of the models for vertical profile of the atmosphere shown in fig. 4.7,4.8&4.9 r'_is are assumed to be separated by 450 meters. Each r_i includes three turbulent layers separated by 150 meters, the width of the layer assumed very small & can be neglected. The pulse width τ ,covers the distance between two successive turbulent layers for fig.4.7, three for fig.4.8& four for fig.4.8. From range resolution equation $\Delta r = \frac{c\tau}{2}$, $\tau = \frac{2r}{c}$; the corresponding pulse widths for fig.4.7,4.8&4.9 are 2.0μs,& 3μs & 4μs respectively.

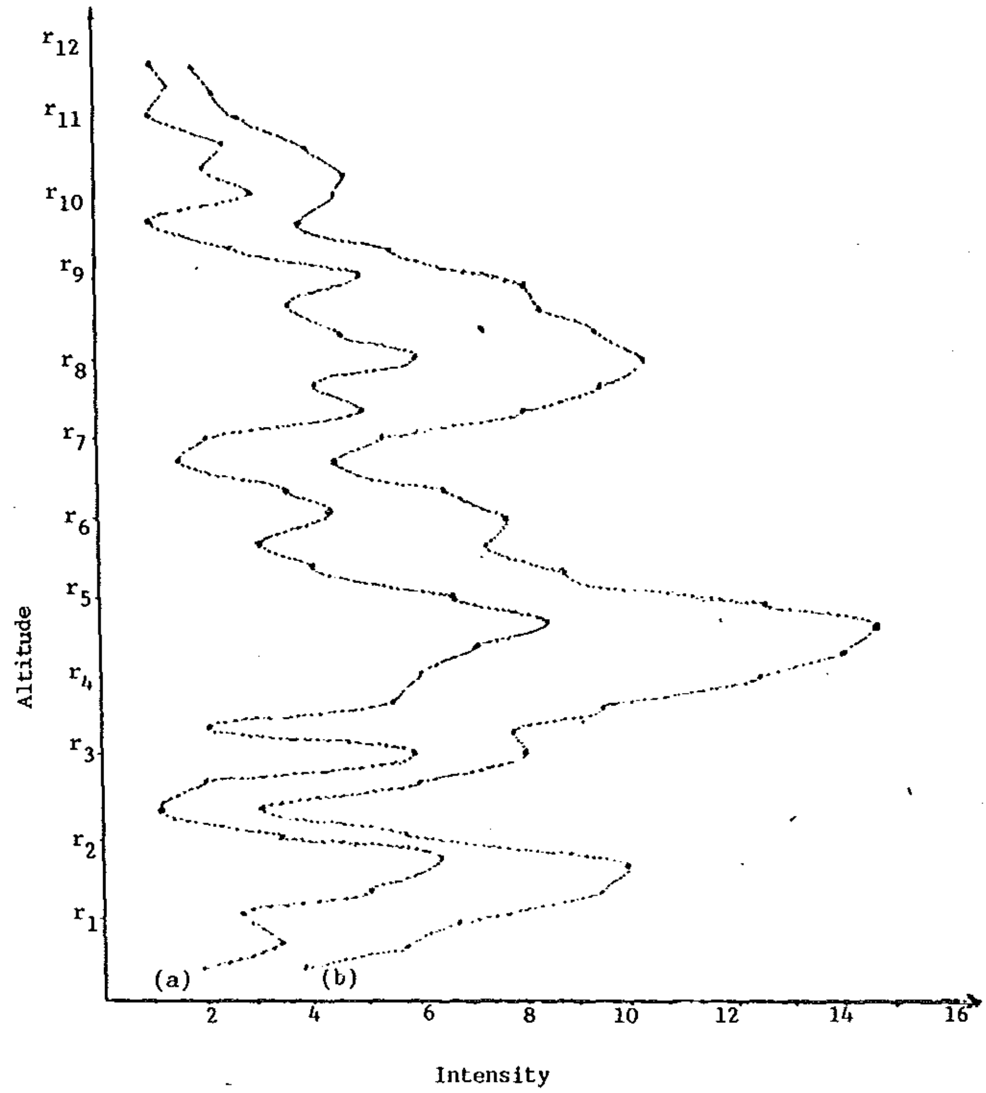


Fig. 4.7 model for vertical profile of the atmosphere.

(a) echo intensities, from turbulent layers.

(b) radar response (for τ = 2.0 μs).

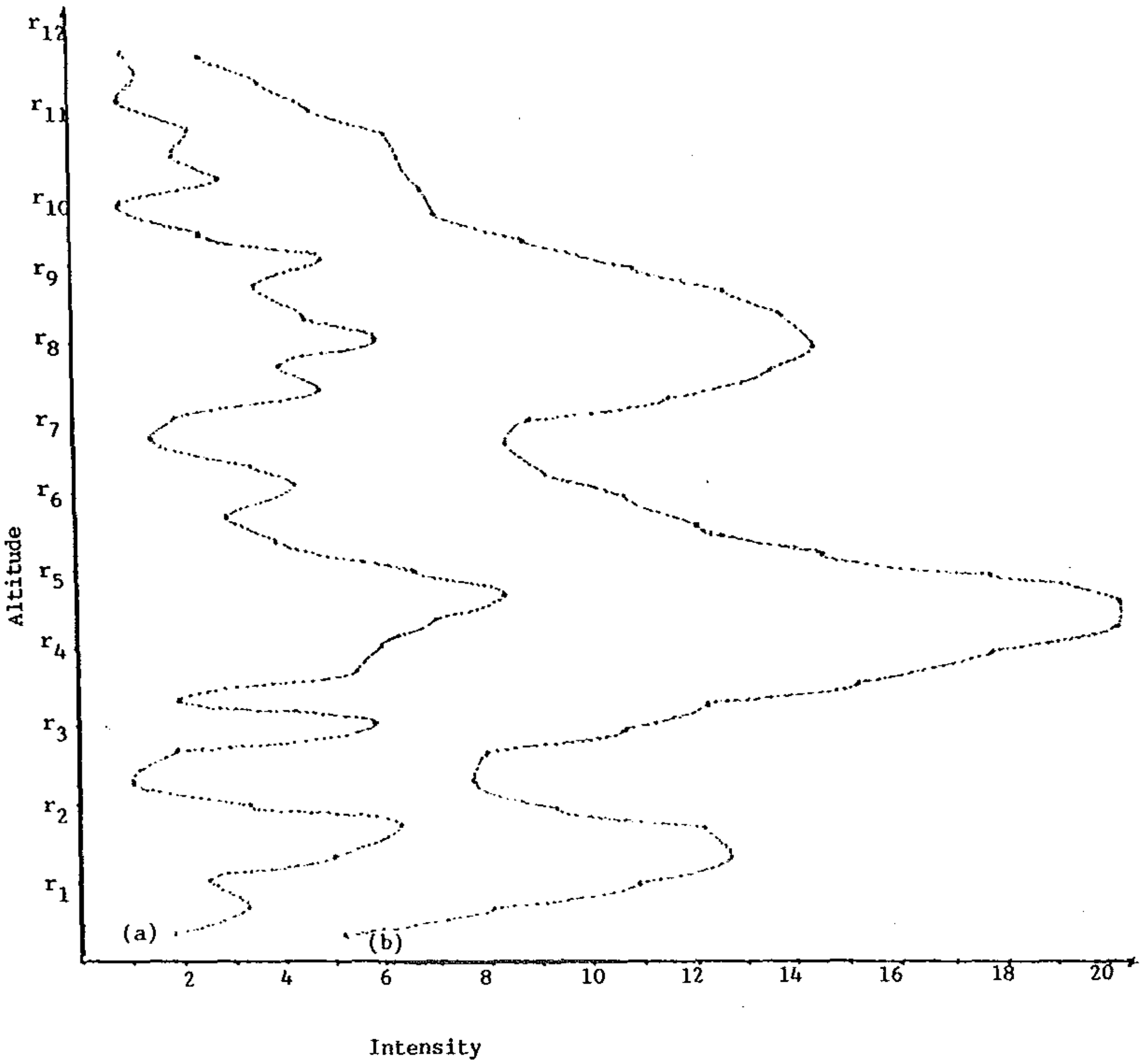


Fig. 4.8 model for, vertical profile of the atmosphere.

(a) echo intensities, from turbulent layers.

(b) radar response (for τ = 3.0 μ s).

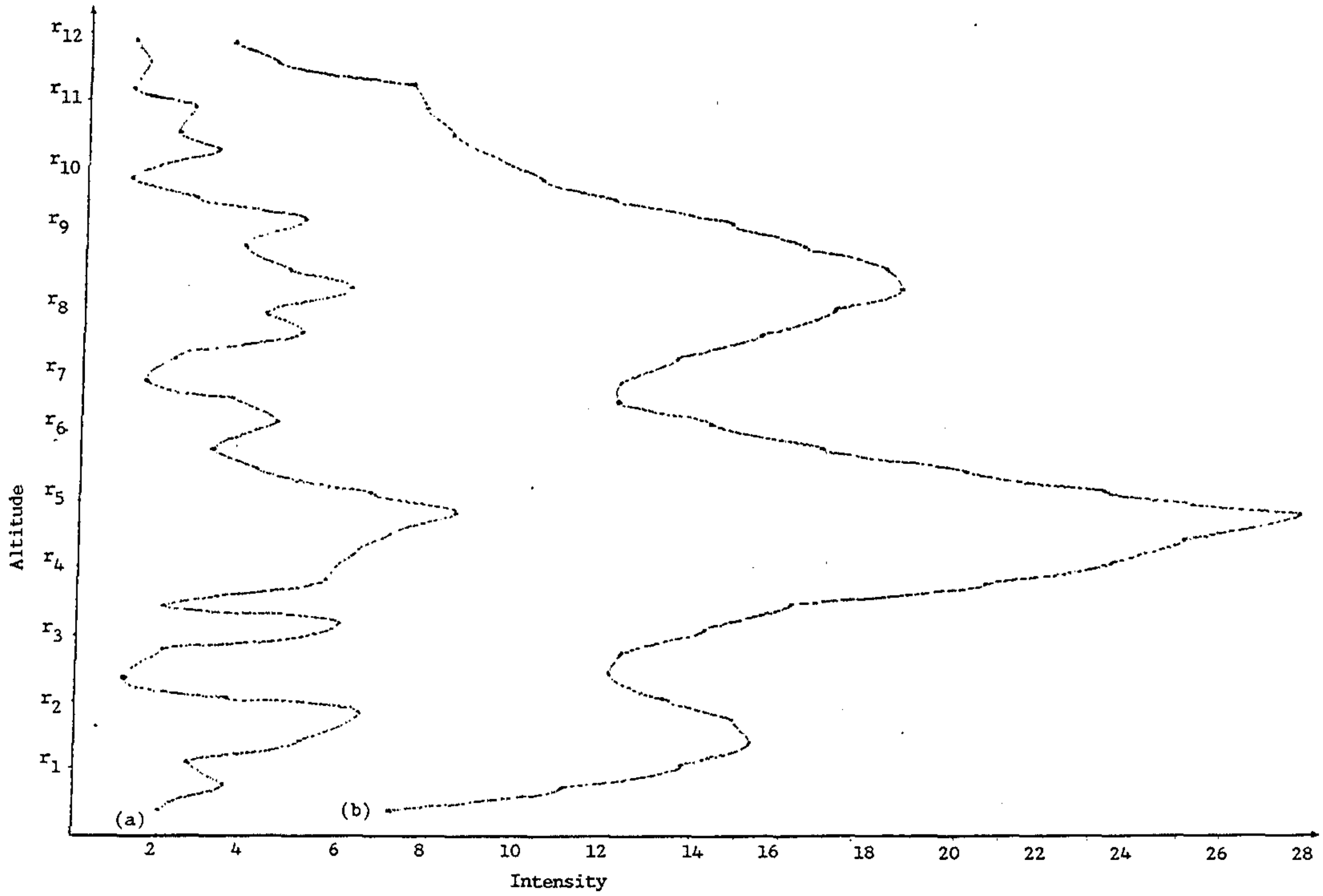


Fig. 4.9 model for, vertical profile of the atmosphere.

(a) echo intensities, from turbulent layers.

(b) radar response (for $\tau = 4.0\ \mu s$).

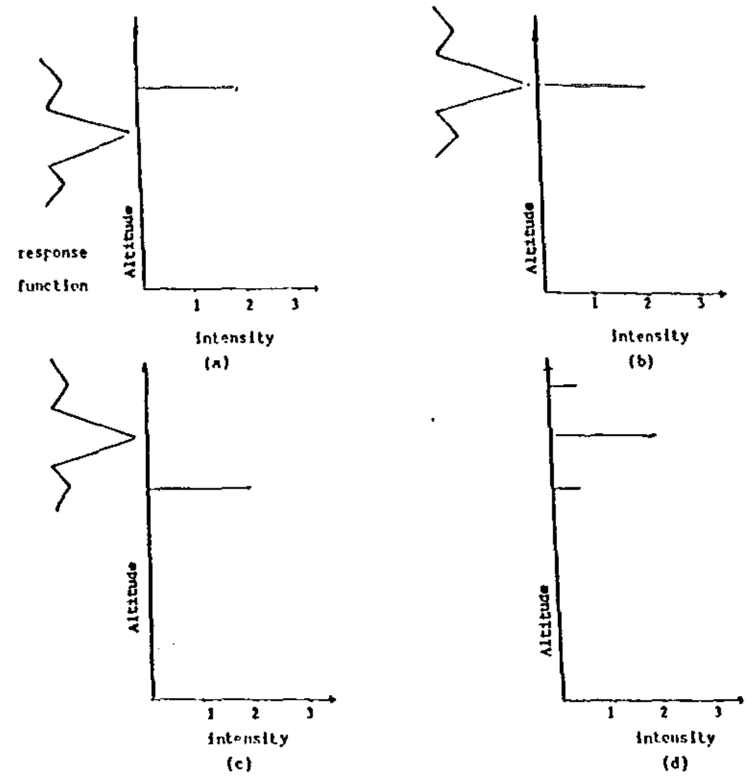


Fig. 4.10 (a),(b),&(c) indicate a single target when viewed by a destorted radar pulse. (d) shows the radar response to this single target (which is the convolution of the response function with the echo intensity of the target). A single target appear as if there are three targets as shown.

4.4 EXAMPLES OF ATMOSPHERIC PROFILES

The real atmospheric profiles that are measured by a radar are shown in fig. 4.11 and 4.12. Fig.4.11 shows the east ward component of wind as a function of altitude, we observe here the discrete layered structure of turbulence especially at higher altitudes. Turbulence is fairly continuous at tropospheric altitudes but in the stratosphere starting around 16 km, it breakes into layers. These are separated by a few hundred meters at the lower altitudes with increasing separation, reaching 1km. to few kilometers as we reach 24-30 km. altitude [22].

Fig. 4.12 shows the measurement taken by two different instruments, a scintillation detection and ranging (SCIDAR) and a radar, where simultaneously operated to retrieve profiles of the atmospheric turbulence. The agreement is good enough, over a large range of altitudes [23].

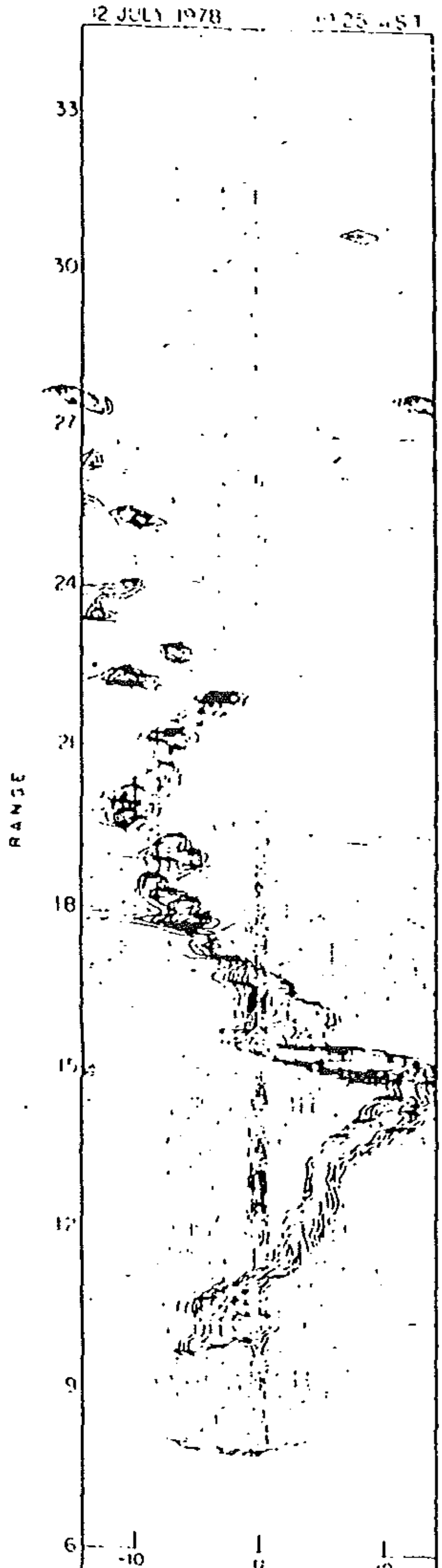


Fig. 4.11 contour plot as a function of frequency and altitude of power frequency spectra of stratospheric echo (after R.F.woodman [22]).

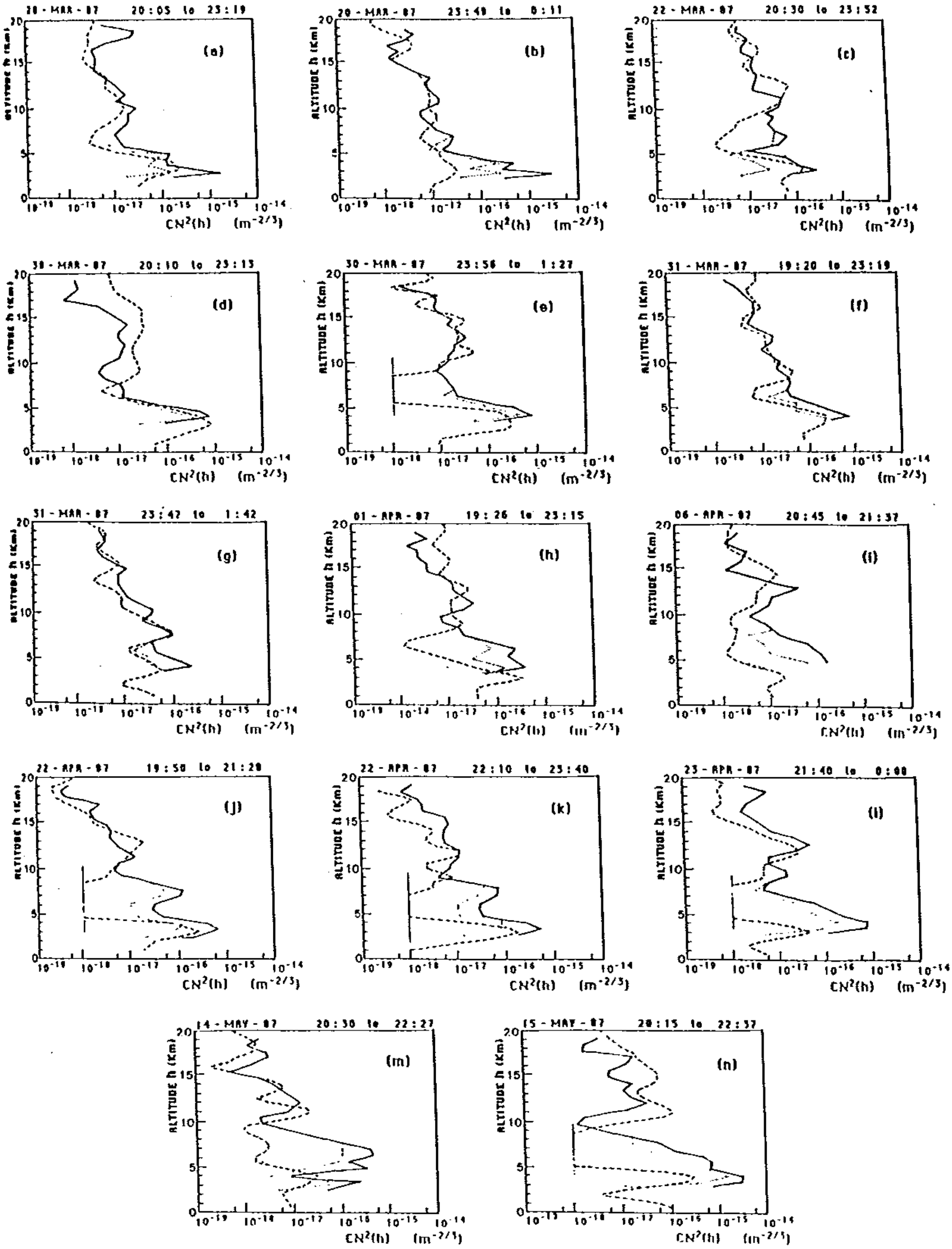


Fig. 4.12, comparison of time averaged refractivity turbulence structure constant $C_n^2(h)$ profiles deduced from oblique VHF radar (solid line), SCIDAR (dashed lines) & " de-enhanced" radar (dotted lines) by water vapor in the troposphere (after vernin etal [23]).

4.5 DISCUSSION

When viewing targets with a rectangular radar pulse of width τ as described in section 4.2.2, it is observed that targets within the width of 2τ will contribute to the sampling instant. However, their contribution decreases with distance from the center of observation for uniform targets. This is the case for an ideal system.

If we consider system with imperfection as described in section 4.2.3, the main lobe has a width of 2τ and this seems to have a behavior of an ideal system described above . However, the extended side lobes have an influence to the voltage sampling, that is targets beyond 2τ interfere with targets within this limit. For example very intense targets may induce very strong responses from side lobes and the false signal will be detected at other ranges rather than that was desired.

Based on descriptions above and the preceding sections, the range resolution is mainly influenced by the type of the transmitted & received pulse and also upon the nature of the receiver. Therefore to minimize the degradation in the range resolution the transmitted pulse should be a perfect rectangle and this has to be received with out distortion by a matched filter receiver. The width of a pulse also have an influence on range resolution. The larger the pulse width, the more is the target masked. As it is illustrated in figures 4.7, 4.8 & 4.9 the details of the targets were masked with increasing τ . Therefore to achieve the maximum range resolution the pulse width should be kept as small as possible.

Depending upon the above facts, to minimize the degradation in ST radar due to instrumental imperfections, the transmitted pulse should have a rectangular shape (eventhough, the reflecting targets are not hard, to reflect without distortion), the pulse width should be as small as possible & its receiving system should have a matched filter receiver.

Note that, the broad pulse (that have large τ) carries high energy & used for long range search, but narrow pulse (that have small τ) gives good discrimination or used for accurate position finding. Therefore the selection of long range search or accurate position finding is a compromise that depends upon how important it is during operation.

APPENDIX A

Consider a linear time invariant system and wide-sense stationary processes as illustrated in figure A.1

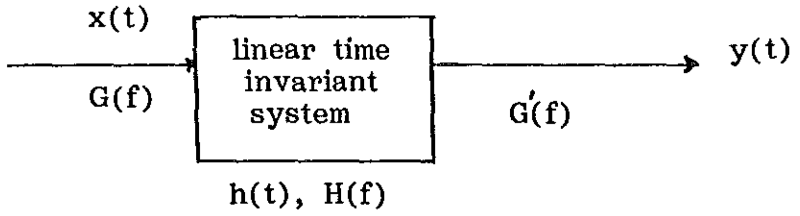


Fig A. 1 a system illustrating definition of input and output random processes.

When y(t) is the output, to system input x(t), the input process power density spectrum is G(f), while that of the response is G'(f), h(t) is the impulse response (assumed real) of the system and the filter transfer function is H(f). Note that h(t) and H(f) are not random processes.

The output y(t) can be written as ,

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x\,(t-u)h(u)du \qquad (1)$$

If the random process y(t) is ergodic, the output autocorrelation function becomes the expectation of the random process y(t).

$$R_y(t,t+\tau) = E[y(t)\; y(t+\tau)] = E[\int_{-\infty}^{\infty} x(t-u)h(u)du \int_{-\infty}^{\infty} x\,(t+\tau+v)h(v)dv$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E[x(t-u)x[t+\tau-v)]h(u)h(v)dudv \qquad (2)$$

Since $E\,[x(t-u)x(t+\tau-v)]=R_x\,(\tau+u-v)$,

$$R_y(\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R_x(\tau+u-v)\; h(u)h(v)dudv \qquad (3)$$

The output power density spectrum can easily be found by direct Fourier transformation of the autocorrelation function.

$$G'(f) = \int_{-\infty}^{\infty} R_y(\tau) \exp(-i2\pi f \tau) d\tau \quad (4)$$

Substituting equation 3 into equation 4,

$$G'(f) = \int_{-\infty}^{\infty} h(u) \int_{-\infty}^{\infty} h(v) \int_{-\infty}^{\infty} R_x(\tau + u - v) \exp(-i2\pi f\tau) d\tau \, dv du \quad (5)$$

By introducing the variable change $w = \tau + u - v$ we get

$$G'(f) = \int_{-\infty}^{\infty} h(u)\exp(i2\pi fu)du \int_{-\infty}^{\infty} h(v)\exp(-i2\pi fv)dv \int_{-\infty}^{\infty} R_x(w)\exp(-i2\pi fw)dw \quad (6)$$

These three integrals are recognized as $H^*(f)$, $H(f)$, and $G(f)$, respectively, owing to our assumption of real system impulse response. As a result, the output power density spectrum becomes

$$G'(f) = |H(f)|^2 G(f) \quad (7)$$

The average output noise P_n can be found from equation 7,

$$P_n = \int_{-\infty}^{\infty} G'(f) \, df$$

$$= \int_{-\infty}^{\infty} |H(f)|^2 G(f) \, df \quad (8)$$

Which is written in equation 2.29.

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