2. INTERPRETATION OF MST RADAR RETURNS FROM CLEAR AIR
(Keynote Paper)

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INTRODUCTION

The nature of the scattering and reflection mechanisms that give rise to the MST radar echoes from the clear air has been a subject of investigation for many years since the beginning of the experimental observation of tropospheric over-the-horizon propagation of radio waves. The understanding of these mechanisms is essential in the correct interpretation of the data which carry information about winds, waves, turbulence and stability in the atmosphere. There are two main aspects of the problem. The first concerns the nature of the targets the radar sees and their generation mechanisms. The second aspect is the signatures of the radar signals returned from the different targets. Volume scatterings from isotropic or anisotropic turbulence, and partial reflections from horizontally stratified, sharp refractive index gradients are believed to be the main contributors to the radar echoes. In general, it is most likely that combined effects from all these mechanisms produce the observed data. Therefore, it is important to study the signature of the echo signals for these different scatterers under realistic experimental conditions. Questions such as: how the pulse rate, width and coding will affect the returned signal; what are the different features of the complex signal statistics under different scattering and reflection conditions, etc., should be investigated. It is hoped that from these studies, the nature of the targets can be better understood. Then it may be possible to relate them to atmospheric dynamic processes (GAGE and BALSLEY, 1980).

BASIC THEORY

At the VHF and UHF frequency bands for the MST radars, the atmosphere is almost transparent. The changes of refractive index caused by the inhomogeneous structures are usually very small compared to the ambient values. Under these conditions, the single scattering Booker-Gordon equation for the scattered field can be applied:

$$\vec{E}_s(\vec{r}) = \frac{k^2}{2\pi} \int_{V'} \frac{e^{ik|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} N_1(\vec{r}') \, [\hat{a}_n \times (\vec{E}_0(\vec{r}') \times \hat{a}_n)] \, d\vec{r}' \qquad (1)$$

where the geometry is shown in Figure 1. $\vec{E}_s$ is the scattered field at the receiver, N_1 is the inhomogeneous part of the refractive index, $\vec{E}_0$ is the incident field and $\hat{a}_n$ is the unit vector pointing from the scattering volume to the receiver. The formula applies to general types of inhomogeneities which are imbeded in a homogeneous background. For back-scatter geometry, (1) reduces to the familiar expression for plane incident wave

$$\vec{E}_s(\vec{r}) = \frac{k^2 \vec{a} \, e^{ikr}}{2\pi r} \int_{V'} d\vec{r}' \, N_1(\vec{r}') \, e^{-i2k\hat{a}_n \cdot \vec{r}'} \qquad (2)$$

where $\vec{a} = \hat{a} \times (\vec{E}_0 \times \hat{a}_n)$.

This formula has been used in the statistical formulation to study

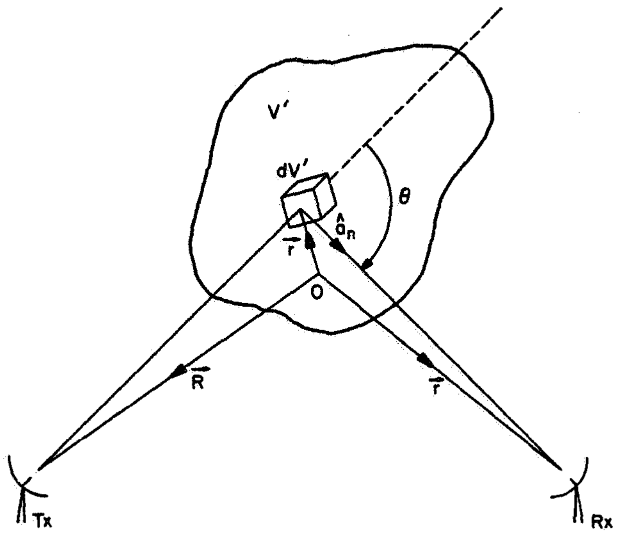

Figure 1.

scattering from turbulence, isotropic or anisotropic, yielding the radar reflectivity

$$\eta_{turb} = 8\pi^2 k^4 S_N(2k\hat{a}_n) \tag{3}$$

where $S_N(\vec{\kappa})$ is the three dimensional power spectrum for the fluctuation of the refractive index, N_1. It is worthwhile to point out that the argument of S_N is a vector $2k\,\hat{a}_n$ indicating that the formula can be applied to anisotropic turbulence in general.

Equation (1) can also be used to derive the formula for partial reflection. For this case, the refractive index inhomogeneities form horizontally stratified laminae that extend to horizontal dimensions greater than several Fresnel zone size. For a vertically incident wave, equation (1) can then be integrated first with respect to the horizontal coordinates and yield the expression for a reflected field.

$$E_s(z) = ikE_0\, e^{ikz} \int_L N_1(z')\, e^{-2ikz'}\, dz' \tag{4}$$

From this equation the formula used in partial reflection calculations can be derived

$$E_r(z) = \frac{1}{2} E_0 e^{ikz} \int_L \frac{dN_1}{dz'}\, e^{-2ikz'}\, dz' \tag{5}$$

where the condition that outside the inhomogeneous region L, N_1 vanishes has been used. Equation (4) or (5) can be applied for statistical or deterministic analysis of the partial reflection problem. In the statistical approach the scattered power is proportional to

$$\langle E_s E_s^* \rangle = k^2 E_0^2 \int_{-\Delta r/2}^{\Delta r/2} dz_1 \int_{-\Delta r}^{+\Delta r} d(z_1-z_2)\ \langle N_1(z_1)N_1(z_2)\rangle\ e^{-2ik(z_1-z_2)} \qquad (6)$$

where the integration limits $-\Delta r/2$ to $\Delta r/2$ correspond to a range gate of width Δr. In the usual statistical approach, the fluctuating field $N_1(z)$ is assumed to be statistically homogeneous such that $\langle N_1(z_1)N_1(z_2)\rangle$ is a function of (z_1-z_2). If the correlation length ℓ_c of $\langle N_1(z_1)N_1(z_2)\rangle$ is much less than the range gate Δr, then the limits of integration with respect to (z_1-z_2) in equation (6) can be extended to $\pm\infty$ which results in spectral resolution of N_1, yielding

$$\langle |E_s|^2 \rangle = k^2 E_0^2 \cdot (\Delta r) \cdot S_N(2k) \qquad (7)$$

If, on the other hand, the correlation length ℓ_c is not so short as compared to the range gate Δr, then the $d(z_1-z_2)$ integration will depend on the limits of integration, Δr and $\langle |E_s|^2 \rangle$ will not have a strict linear dependence on Δr. Depending on the correlation function of N_1 and the ratio $\Delta r/\ell_c$, the dependence of $\langle |E_s|^2 \rangle$ on Δr may vary.

It should be emphasized that it is under the assumption that the linear dimension of the scattering volume is much greater than the correlation length of the turbulence, the scattering process results in the selection of the component of the turbulence spectrum at the Bragg wave number, leading to the results shown in equations (3) and (7). This does not justify in general the pre-selection of that particular Bragg component of the turbulence spectrum alone to represent the refractive index fluctuations in the derivation of the reflectivity formula.

Other complications may arise in the effort to model the scattering process statistically. For example, how much are the results affected if the homogeneity (stationarity) of the scattering region is not strictly satisfied?

SIGNAL STATISTICS

The statistics of the received signal depend on the scattering mechanism. When the returned signal comes from independent scatterers or reflectors of similar strength which are distributed in space in such a way that the rms deviation from the mean position is greater than one wavelength, then the amplitude of the received signal will have the classical Rayleigh distribution. If a dominating specularly reflected component exists in the received signal, the data will exhibit the Rice-Nakagami distribution for the amplitude. Another type of distribution known as the "Hoyt distribution" (BECKMANN, 1962) may result when the phase distribution of the independently scattered/reflected signals is not uniform. This occurs, for example, when the rms deviation from the mean position for the scatterers is less than a wavelength. Examples of these different types of signals are shown in Figures 2 and 3. Numerical simulations can be devised to study these signal statistics. Comparisons between the numerical models with observed data may help us understand more clearly about the various scattering/reflection mechanisms.

Another aspect of signal statistics is the spectral characteristics of the signal. While the classical turbulence theory predicts that the returned power is proportional to the width of the signal power spectrum, the opposite relation has been observed in many occasions (RASTOGI and BOWHILL, 1976; ROTTGER and LIU,

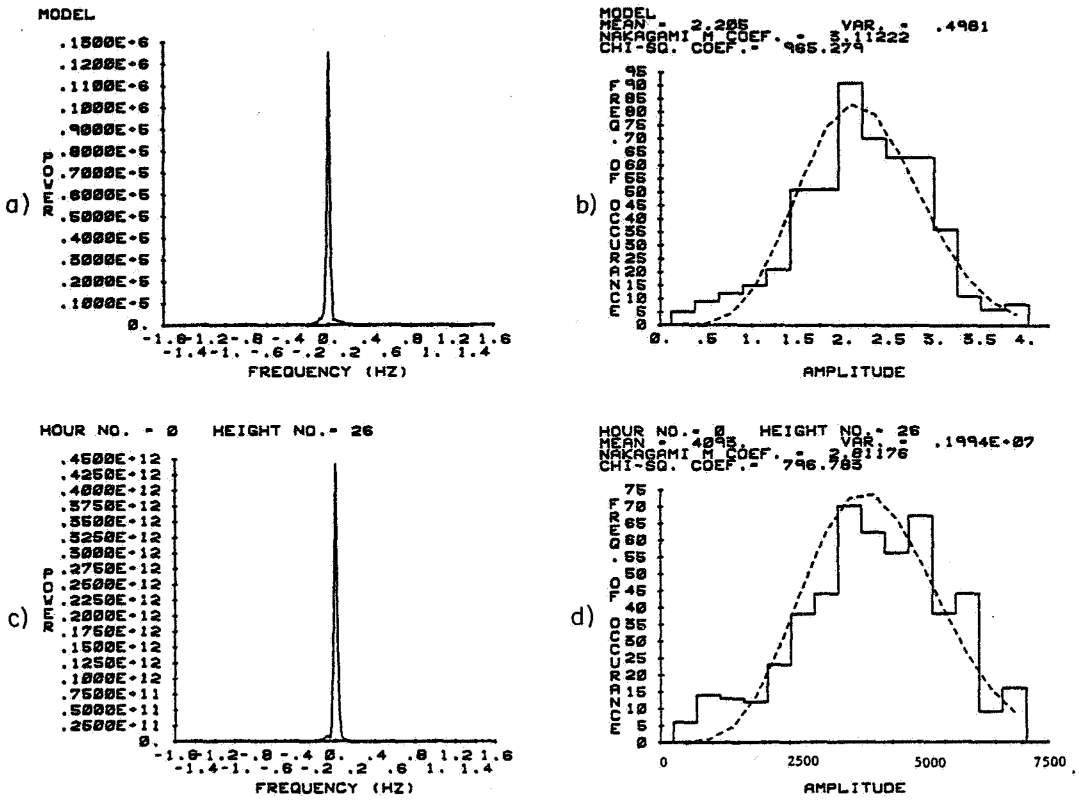

Figure 2. a. Power spectrum of modeled data for specular reflection from a flat layer. b. Histogram of the modeled amplitude data for specular reflection from a flat layer. c. Power spectrum. d. Histogram of the amplitude. Height number 26 corresponds to an actual height of 2.5 km.

1978) in different regions of the atmosphere. Explanations in terms of partial reflection, diffusive scattering etc. have been proposed. However, a satisfactory quantitative explanation of the phenomenon has yet to be developed.

ORIGIN OF REFRACTIVE INDEX FLUCTUATIONS

Wind shears have been considered as one of the possible sources for generating turbulence. Good correlations have been found between received signal power and measured wind shear in the troposphere and stratosphere. The origin of the horizontally stratified laminae that give rise to enhanced signal return when the radar is operating at the vertical position is not well understood. ROTTGER (1980) suggested that temperature steps separating turbulent layers similar to the situation at oceanic thermocline may be the possible cause. VANZANDT (1982) has shown that experimentally measured power spectra of mesoscale wind fluctuations in the troposphere and lower stratosphere can be modeled by a universal spectrum of buoyancy waves. It will be of interest to investigate how the model extends to smaller scales.

At mesospheric heights, electron-density profiles strongly affect the radar returns. Dynamic effects, such as turbulence and wave activities; as well as solar activities, all can influence the received signal power.

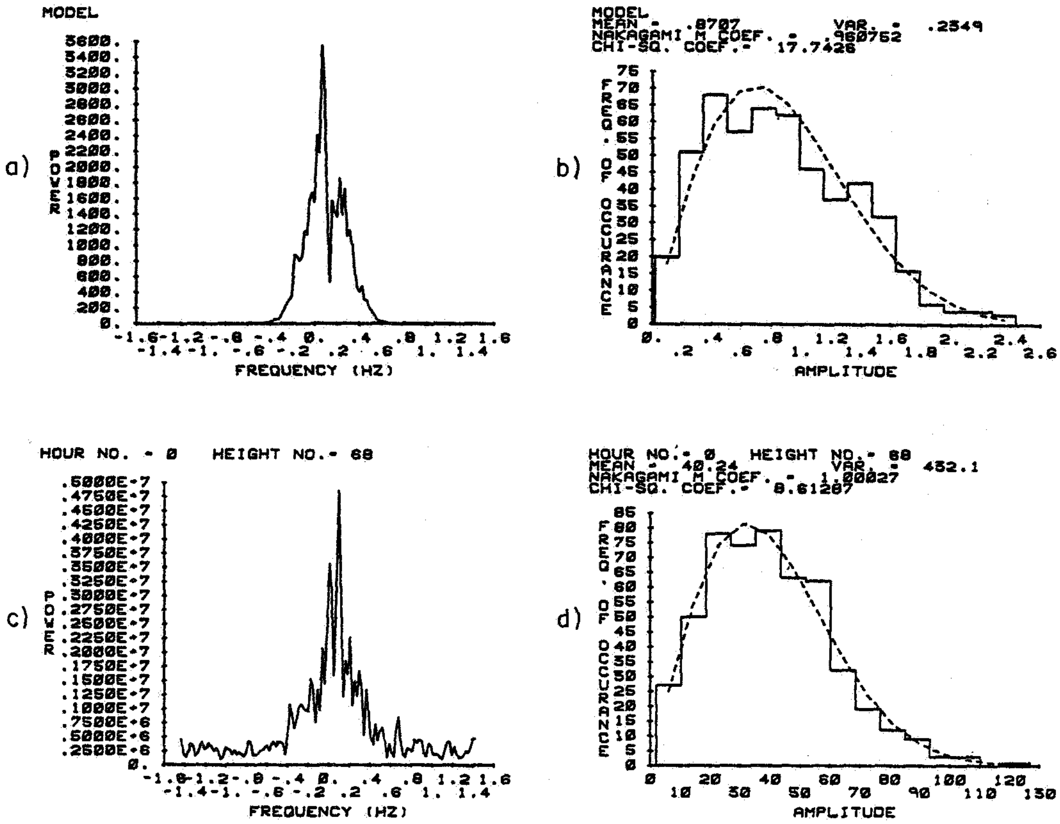

Figure 3. a. Power spectrum of modeled volume scattering data.
b. Histogram of the amplitude for modeled volume scattering data.
c. Power spectrum. d. Histogram of the amplitude.

RESTRUCTURE OF IRREGULARITIES

Coherent signals of the complex field received at the three receivers in the spaced antenna drift measurements can be used to study the restructuring of the inhomogeneities. The temporal evolutions of the irregularities give rise to change of signal pattern as they drift across the radar beams from the spaced antennas. A number of physical phenomena can be responsible to make the flow non-frozen. For example, the random velocity fluctuations superposed on the mean flow; the diffusion of inhomogeneities; velocity gradient (wind shear) in the scattering volume, etc. To take these factors into account either individually or collectively one needs to examine the space-time structure of the scattering region and model them accordingly. Each model will give rise to a certain radio signal signature which can be compared with experimental data. Hopefully, the physical model and the experimental data can be related following this procedure. The basic starting point is the scattering formulation of Booker-Gordon applied to non-frozen scatterers. Model space-time spectra for non-frozen turbulence can be applied. Both cross-correlation and cross-spectra dispersion analysis should be studied. A clear understanding of the scattering process under the non-frozen condition will help us gain information about the temporal evolution of the irregular structures from the experimental data.

EFFECTS OF ANTENNA BEAM SIZE

The first order scattering theory as discussed earlier neglects the change of phase in the scattering volume. As the scattering volume increases such that the linear dimension becomes comparable or greater than the Fresnel zone, phase incoherency within the scattering has to be taken into account. Indeed, it turns out that a parameter $P=(kd\ell_c/r)$ plays a role in determining whether the phase incoherence is important or not (LIU and YEH, 1980), where k is the wavenumber corresponding to the radar frequency, d is the linear dimension of the antenna beam, ℓ_c is the correlation length of the turbulence and $\underset{\sim}{r}$ is the range. For $P<<1$, the usual Booker-Gordon formula applies. For $P>1$, the antenna beam width is comparable or larger than the coherent cone of the scattered wave, higher order phase terms in the scatter integral have to be taken into account. These effects should be studied in the general case with the space-time variation of the irregularities also taken into account.

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SUMMARY

(a) Range Gate Dependence of Specular Echoes

The question of ΔR vs $(\Delta R)^2$ dependence of specular echoes was resolved during the discussions. More careful and realistic theoretical analyses have led to this conclusion. The main point is that as long as the correlation length of the irregular structure is much shorter than the range gate, ΔR dependence should be valid in the statistical treatment of the problem. As the range gate is decreased, or other assumptions such as homogeneity of the structure etc. are violated, dependence other than linear on (ΔR) will arise. Careful experimental results agreed with this conclusion.

(b) Mechanisms for Layered Structures

Two possible mechanisms for generation of the layered structures were discussed. One corresponds to vertical mixing in a local turbulent region due to Kelvin-Helmholz instability. Sharp, step-like gradients will appear at the boundaries of the turbulent regions as the consequence of the mixing. More quantitative study of this mechanism is needed. The other mechanism proposed is that the horizontally stratified laminae of the refractive index may be due to the displacement of low frequency buoyancy waves acting on the background vertical gradient of refractivity. The radar reflectivity based on this model has been estimated. Experimental verfication of the model such as measurements of Fresnel reflectivity as a function of Brunt Vaisala frequency or inertial frequency, the aspect dependence of reflectivity, etc. have been suggested. Certainly the understanding of the generation mechanisms will be one of the major efforts for the community. For this effort, statistical characterization of Fresnel scattering/reflection structures is important. In particular, the efforts in studying signal statistics of radar returns to determine the statistical nature of scatterers and reflectors, and parameterization of Fresnel returns were discussed.

(c) Mechanism for Maintaining Long Lasting Turbulent Layers

Observations at Arecibo at 15° off zenith direction showed long lasting turbulent layers in the stratosphere. Strong turbulent patches were also observed by the Chatanika radar at 12 km heights for 15° ∿ 45° off zenith directions. What are the mechanisms that generate these strong turbulent layers and kept them there?

(d) Spectrum

Several interesting points were discussed. The effect of "diffuse reflection" on "vertical" velocity spectrum has to be considered in data analysis. Beamwidth broadening of the spectrum is important in the measurement of velocity variance. In the lower mesosphere, the signal power is often found to have positive correlation with fading time which is inverse of spectral width. Recent tropospheric low-elevation experiments also showed such positive correlation. This is contrary to the results expected from usual turbulence scattering theory. Some explanations have been suggested. A better knowledge of the structure of the scatterers is needed to interpret the data.

(e) Effects of Pulse Repetition (PRF) Rate, Power (P_{ph}) Width (τ_p) and Coding on Signal Detectability

Based on the assumption that the following are constants: antenna area, echo reflectivity, Doppler shift, spectral width, spectral resolution, sampling rate, and incoherent spectral averaging time; the effects of PRF, P_{ph} and τ_p on the detectability of the radar were discussed.

(f) Clutters from Aircraft and Ground

The problem can be solved during data taking or during data processing. Directional filtering by antenna sidelobe suppression, pulse stuttering, more sampling, etc. can be used during data taking. Temporal filtering, spectra estimation, range filtering, interference filter, notch filter, or selection by signal amplitude distribution or by power limit threshold, etc. can be done during data processing. The problems are discussed more fully in Chapter 8, this volume.

(g) Origin of Mesosphere Refractive Index Fluctuations

Mesospheric echoes are strongly influenced by the electron-density profile in the D region. A sudden increase or even moderate variation by VHF radar signal return usually can be attributed to the enhancement of electron density or electron-density gradient. Observations of the enhancement of radar echo power during solar flare events showed the turbulence to be confined to intermittent layers. Solar control of winter mesospheric echoes at Poker Flat was also observed.

DRAFT RECOMMENDATION FROM DISCUSSION IN TOPIC 2

RECOGNIZING the importance for an accurate characterization of the spectrum of refractive index irregularities for the efforts to understand mechanisms of turbulence generation and to measure with MST radar, winds, turbulence and stability;

NOTING the spectral sampling capability of steerable, multiple wavelength radars
we
RECOMMEND that:

Multiple frequency radar observations supported by in situ measurements be carried out with existing equipment such as at Arecibo and other radar facilities.