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2. SOME RECENT DEVELOPMENTS IN THE INTERPRETATION OF MST RADAR RETURNS FROM CLEAR AIR

(Keynote Paper)

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MST radar returns from clear air come about through the interaction of electromagnetic waves with the inhomogeneous structures of refractive index in the atmosphere. In order to interpret the data correctly to obtain information concerning the dynamics of the atmosphere, one must first know how the various refrative index structures can affect the propagation and scattering of the radio waves. This can be achieved through theoretical and model studies. On the other hand, in order to carry out realistic theoretical studies, realistic models of the inhomogeneous structures of the atmospheric refractive index are needed. These are available only through observational data. Therefore the close interplays between theoretical and observational investigations are essential in making progress in this area. In this paper, we shall present some results on certain aspects of the problem with emphasis on those that may lead to new developments.

THEORETICAL CONSIDERATION OF THE SCATTERING PROCESS

The classical scattering formula in the form of Booker-Gordon results in general is derived under several assumptions. These are: (1) the inhomogeneous structures of refractive index are weak so that only single scattering needs to be considered; (2) the linear dimension of the scattering volume determined by the radar beam width and pulse length, and the characteristic scale of the irregularities are small compared to the dimension of the Fresnel zone so that the phase incoherence of the scattered fields within the scattering volume can be neglected; (3) the range is sufficiently large so that far-field approximation can be used; (4) the scattering volume is large enough to contain sufficiently large number of irregularities; and (5) the irregular structures are characterized by a homogeneous random field so that integration over the scattering volume can be related to the power spectrum of the irregularities.

Recently, effects of multiple scattering on backscattered radar signals have been studied by FANTE (1982) and YANG and YEH (1984). The results are applicable to cases where the refractive index fluctuations are strong to cause multiple scattering by the probing radar wave. In most MST radar applications, these effects probably are not important. What is important in atmospheric applications is the possible violation of assumptions (2) to (5) for many MST radar configurations. Realizing the possibility that the radar beam size may be comparable to the Fresnel zone dimension, LIU and YEH (1980) modified the classical Booker-Gordon formula. Since the structures in the atmosphere are highly anisotropic with large horizontal dimensions, the Fresnel zone dimension may be smaller than the horizontal coherence distance of the irregular structure. DOVIAK and ZRNIC (1983) derived more general formulae to take this into account by expanding the phase term in the scattering integral to second order. They also derived a criterion to distinguish between Fraunhofer and Fresnel scatter approximations. These general formulae are applicable to most MST radar applications under the assumption that the irregular structures are properly characterized statistically by a homogeneous random field. However, as the range resolution of operating MST radars improve, assumptions (4) and (5) may become invalid. The problem of whether the echo power depends on pulse length or the square of the pulse length underlines the importance of this point

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(GAGE et al., 1981). It was shown (FARLEY, 1983; LIU, 1983; HOCKING and ROTTGER, 1983) that if many layers exist in the scattering volume such that statistical description is valid, the scattered power should depend linearly on the pulse length. Other forms of the dependence will result if the scattering volume does not contain sufficient irregularity layers such that they can be characterized statistically, or the homogeneous random field characterization of the irregularities is not valid. These results have been demonstrated to be consistent with the experimental results obtained by GREEN (1983). To correctly describe the scattering/reflection processes involved when the statistically homogeneous characterization of the scatterers breaks down, one needs to generalize the existing theoretical work to include the effects of the distribution of layers, the finite scattering volume, etc. It is conceivable that numerical modeling involving the Monte Carlo type of simulation may be able to contribute to the progress along this direction.

PARAMETERIZATION OF FRESNEL RETURNS

Ever since the experimental observation of enhanced specular-like returns of MST radars at vertical incidence (GAGE and GREEN, 1978; ROTTGER and LIU, 1978), there have been continuing efforts to understand the mechanism and to parameterize the echo power in terms of atmospheric parameters (GAGE et al., 1981; ROTTGER, 1983). In order to carry out the parameterization, assumptions on the scattering/reflection targets have to be made. Assuming a statistical power spectral characterization of the layers, it is possible to relate the echo power to the meteroological data from rawinsonde (GAGE et al., 1981). ROTTGER (1984), on the other hand, proposed to make use of the specific behavior of the correlation function of the returned signal when the radar beam is vertical to separate the specular component from the scatter component. In many cases, the correlation function can be separated into three parts. The first part is the fast drop between zero and the next time lag corresponding to the effects due to uncorrelated noise. The second part is the smooth decrease of the correlation function at small time lags up to a few seconds. This is viewed as due to random scattering. The last part is the slow decay of the correlation up to many tens of seconds. This is due to the specular component of the return. These three parts can be separated by a parameter-fitting scheme, and used to approximately estimate the scattered contributions to the total received echoes. More accurate estimates of the different contributions can be obtained if we have better understanding of the scattering process. This can be achieved through a modeling.

CORRELATION BETWEEN ECHO POWER AND COHERENCE TIME

A positive correlation between the strength of the echo power and the coherence time of the received signal has been observed in many MST radar experiments (RASTOGI and BOWHILL, 1976; ROTTGER and LIU, 1978; WAND et al., 1983; ROYRVIK, 1984). This is quite intriguing. If the echoes are due to scattering from turbulence, then from statistical theory of scattering, the signal power should be proportional to the variance of the refractivity fluctuation. On the other hand, the coherence time of the returned signal is inversely proportional to the spectral width of the signal which is directly related to the variance of the fluctuation of the radial velocity, hence, the strength of the turbulence. Therefore, if there is a direct relation between the variance of the refractivity fluctuations and the velocity variance, one should expect a negative correlation between the echo power and the coherence time (P/C). The fact that in many cases this is opposite to what has been observed, indicates that further investigation of the scattering mechanisms is needed.

ROTTGER and LIU (1978) related the observed positive P/C correlation to the specular partial reflection process due to layered structures when the radar was looking vertically. This will not apply to the tropospheric data reported by WAND et al. (1983) for low-elevation observations, where they also found that the spectral width of the signal is proportional to the layer thickness. RASTOGI (1983) proposed the idea of turbulent layer broadening by entrainment to explain the data.

Recently, in an attempt to interpret the mesosphere data, ROYRVIK (1984) proposed to re-examine the relation between the variance of the refractivity and the velocity variance.

Currently, our understanding of the various mechanisms that cause the radar echoes is still not complete and a definitive explanation of the observed P/C correlation is not available. On the other hand, this phenomenon does provide us with important information that can be applied to verify proposed models of scattering/reflection processes.

SIGNAL STATISTICS

It has long been recognized that by studying the statistics of the returned radar signal, certain detailed information about the targets can be extracted (RASTOGI and HOLT, 1981; ROTTGER, 1980). Signal statistics include the distributions of the intensity and the phase; the distribution of angle of arrival; the spectra of intensity and phase, etc. Ultimately the signature of the signal itself should be investigated.

Using the signal signature, the Doppler spectrum and the distributions of the intensity and the in-phase and quadrature components of the signal, SHEEN et al. (1984) studied the vertical radar returns from the troposphere and lower stratosphere. They found that the spectral width and the Nakagami m-coefficient for the intensity distribution can be used to characterize the scattering/reflection processes. When the returned signal comes from independent scatterers or reflectors which are distributed in space with rms separations greater than one wavelength and moving with different velocities, then the intensity of the received signal will have the classical Rayleigh distribution with $m = 1$. If a dominant specular component exists in the signal, the distribution will have an m-coefficient greater than one, satisfying the Rice Nakagami distribution. Therefore signals with broad Doppler spectra and an m-coefficient close to unity characterize scattering by anisotropic turbulence or multiple thin layers. The majority of the data are found to be of this type. There are almost no cases, however, where the m-coefficient is substantially greater than unity. On the other hand, signals with narrow Doppler spectrum and an m-coefficient close to 1/2 are found in many cases. By modeling, it is shown that these features are consistent with returns from single diffusive layers causing focusing and defocusing of the signals. This indicates that reflections from single layers do occur. The layers, however, are invariably undulating. Therefore, more than one specularly reflected ray will come into the rather broad radar beam, interacting with each other, giving rise to the observed signal signature.

In many cases, the Doppler spectra exhibit several sharp spikes indicating that they may come from different "sub-reflectors" moving at different radial velocities. ROTTGER (1984) proposed to study this phenomenon by measuring the statistics of the angle of arrival. He pointed out that more about the nature of the targets can be learned from this study.

BUOYANCY WAVES AS ORIGIN OF REFRACTIVE INDEX FLUCTUATIONS

VANZANDT and VINCENT (1984) proposed the displacement associated with the low-frequency internal gravity waves acting on the background gradient of refractivity may be the cause of the horizontally stratified laminae of refractive index that produce enhanced VHF radar echoes near the zenith. A model spectrum for the displacement corresponding to the modified Garrett and Munk spectrum was used to compute the angular dependence of the radar cross section. They proposed an experimental test for the model.

If the refractive index fluctuations are caused by spectra of buoyancy waves, the wave-associated velocity fluctuations will be seen as wind velocity fluctuations. Indeed, VANZANDT (1982) first proposed a universal buoyancy wave spectrum to interpret the observed mesoscale wind fluctuations in the atmosphere. MST radars have been used to study the velocity spectra (BALSLEY and CARTER, 1982). Since MST radar measures the line-of-sight Doppler velocity, it senses the components of the wave-associated velocities along the radar beam direction. Because of the polarization relations relating the different wave-associated velocity components, the observed line-of-sight velocity will depend on the wave frequency and wave number as well as the observation geometry. Therefore, the observed velocity spectrum will be different from the original wave spectrum. For example, if the radar is in an exact zenith direction, the radar is only sensitive to vertical velocity fluctuations. As the wave frequency $\omega \to 0$, the waves will propagate almost in the vertical direction. Since the buoyancy waves are transverse waves, there will be no vertical velocity component associated with these very low frequency waves. Therefore, in the vertical observation mode of the radar the low frequency portion of the wave spectrum is suppressed. As $\omega \to \omega_b$, the Brunt Vaisala frequency, the waves propagate almost horizontally and the wave-associated velocity is almost completely vertical. Therefore the wind fluctuation spectrum observed by vertical radar will be the same as the wave spectrum in the neighborhood of ω_b. This example indicates how the observation geometry can affect the interpretation of the observed wind velocity fluctuation spectra in terms of gravity-wave spectra.

If the radar observation geometry is oblique, the relation between the observed wind fluctuation spectrum and the buoyancy wave spectrum is more complicated. This relation has been studied by SCHEFFLER and LIU (1984). Because of the angular dependence of the relation, it is possible to design experiments to test the assumption that buoyancy waves are the causes of mesoscale wind velocity fluctuations, as well as the origin of refractive index fluctuations in the atmosphere.

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ISSUES AND RECOMMENDATION

ISSUES:

1. Parameterization of Fresnel Returns:
   - (a) Is the statistical description of the process satisfactory?
   - (b) Can anisotropic turbulence explain both the aspect sensitivity and absolute power of the echoes?
   - (c) Dependence of $E_\zeta(k,z)$ — spectrum of displacement.
2. Echo Power -- Coherence Time Correlation:
   - (a) Relation between $\sigma_{\text{refractive index}}$ and σ_{velocity} in the troposphere, stratosphere and mesosphere.
   - (b) The issue may contain key information about targets.

3. Angle-of-Arrival Statistics:
    (a) What can be learned from them?
    (b) Requirements

RECOMMENDATION:

Recommend future experimenters to include absolute power and refractive index gradient information in their publications; whenever possible, simultaneous in situ measurements and radar observations should be carried out.

Important for modeling and checking scattering-reflection processes.