4.5A PARAMETRIZATION OF FRESNEL RETURNS IN MIDDLE-ATMOSPHERE RADAR EXPERIMENTS

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ABSTRACT

Weak reflections from sharp discontinuities in radio refractivity have been invoked over many years to explain the results of radio propagation experiments. In this contribution, the characteristics of refractivity structures required to produce Fresnel returns are first examined. The experimental evidence for Fresnel returns in middle-atmosphere radar experiments is then reviewed. The consequences of these returns on estimating the turbulence and wind parameters are briefly outlined.

INTRODUCTION

The role of turbulence-induced irregularities in producing scattering and reflection of radio waves was first considered over two decades ago in connection with tropospheric and ionospheric forward-scatter experiments. The shape of the irregularities that could cause the supposed reflections was described in terms such as blinis (pancakes) or feuillets (sheets or leaves) to emphasize their planar nature. Regions of sharp transitions in radio refractivity, that are required to produce the reflections, were indeed observed with microwave refractometers carried aloft by balloons to heights of several kilometers. Much of the related work is described in texts such as BECKMANN and SPIZZICHINO (1963) and DU CASTEL (1966). A similar mechanism was invoked to explain the weak "partial-reflections" of 2-3 MHz radio waves from the D-region (GARDNER and PAWSEY, 1953).

The relevance of such reflections to the middle atmosphere radar experiments (ROTTGER, 1980; BALSLEY 1981), in addition to backscatter from the turbulence-induced refractivity fluctuations at half the radar wavelength (BOOKER, 1956), has been emphasized by several groups in recent years (GAGE and GREEN, 1978; ROTTGER, 1978; FUKAO et al., 1979). The terms that have been used for these reflections -- partial, specular, diffuse, aspect-sensitive and Fresnel -- tend to ascribe an underlying physical mechanism to explain the returns. Thin regions of refractivity gradients that extend horizontally over a a Fresnel zone are crucial to all these mechanisms. The term "Fresnel reflection" is therefore more appropriate.

Here, we first examine those characteristics of refractivity structures that are effective in producing reflections as opposed to scattering. Evidence for the occurrence of reflections in middle-atmosphere radar experiments is reviewed next, and finally, the consequences of such reflections on inferring the parameters of turbulence and the wind field from radar observations are discussed briefly.

REFLECTIONS FROM REFRACTIVITY STRUCTURES

The scattering of radio waves from a random field of refractivity fluctuations, assumed homogeneous and isotropic for simplicity, has been discussed in detail by TATARSKII (1971) and ISHIMARU (1978). The scale of refractivity that is half the radar wavelength for monostatic radars. The refractivity fluctuations are produced locally by turbulent mixing of refractivity gradients. There now is ample evidence that, in a convectively stable atmosphere, turbulence occurs in thin layers. The assumption of homogeneity of turbulence throughout the radar cell often is invalid due to the presence of such layers. Depending on the Bragg scale and the length scales associated with turbulence, the assumption of isotropy of Bragg-scale turbulence may also be violated within thin layers. Radio waves would be scattered by refractivity fluctuations within the layers, but are liable to be reflected by sharp refractivity gradients at the layer interfaces.

In order that reflections may be a viable mechanism for producing the radar returns, the refractivity structures must satisfy several conditions. First, the surfaces of constant refractivity must be oriented approximately normal to the Bragg vector, and the average direction of the refractivity gradients at these surfaces must be parallel to the Bragg vector. Second, these surfaces must be sufficiently smooth. Finally, they must be horizontally extended to cover a substantial part of a Fresnel zone.

Due to the horizontal stratification of the atmosphere, the iso-refractivity structures also are predominantly horizontal and will produce reflections for vertical Bragg-vector orientations. For monostatic radars, the radar must be pointed close to the vertical. For bistatic radars, the transmitter and receiver antenna must be oriented symmetrically about the vertical. The criterion for smoothness of iso-refractivity surfaces is stated by the Rayleigh condition, that a roughness-scale for these surfaces (parametrized e.g., by the standard deviation of the surface height above a reference level) be smaller than one-fourth of the Bragg scale (BECKMANN and SPIZZICHINO, 1963; ISHIMARU, 1978). For middle-atmosphere applications, this roughness-scale should be smaller than 0.75m for VHF and 0.1 m for UHF radars. For horizontally extended iso-refractivity surfaces, the contributions from those parts of the surface that are in a Fresnel zone arrive in phase at the receiver and therefore add coherently. This is illustrated schematically in Figure 1. In the far field, the diameter of the first Fresnel zone exceeds the antenna dimension, and is smaller than the size of the region illuminated by the radar beam.

When the individual layers of turbulence are not adequately resolved by the radar, a radar cell may contain several reflecting structures distributed along the range. The contributions of these structures can mutually interfere to produce large amplitude and phase fluctuations. If the other conditions are satisfied, then the requirement on the horizontal size of the structures is not too stringent. Within a Fresnel zone, the signal power attributable to the reflected component increases approximately as the square of the surface area contributing to the reflections. It is not necessary that the structures be uniform. For structures of larger size, contributions over different Fresnel zones would mutually interfere.

It is also instructive to consider the reflecting structures as antenna. These structures should then produce a diffraction pattern at the ground level. The size of this diffraction pattern depends inversely on the horizontal size of the reflecting structures. Movement of "drift" of this diffraction pattern provides information on horizontal motion of the structures using the spaced antenna drifts method (ROTTGER, 1981).

RADAR EVIDENCE FOR FRESNEL RETURNS

Three different methods have been used to discriminate reflections from scattering in radar observations of the middle atmosphere -- (1) from observations of signal power along the vertical and off-vertical directions, (2) from temporal coherence of the reflected components, and (3) from observations of the

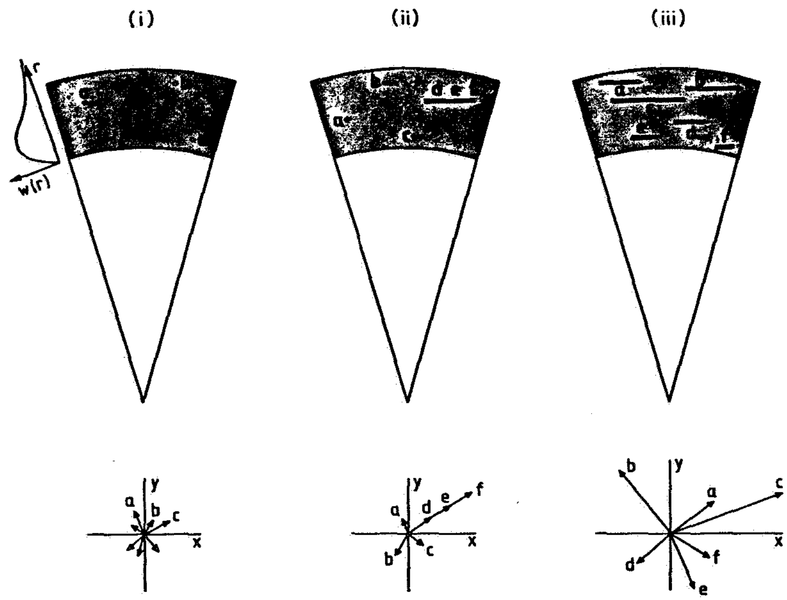

Figure 1. A schematic illustration of scattering and reflection from refractivity structures in a radar cell (shaded region). w(r) is a weighting function along the range. In case (i), signals scattered from randomly distributed irregularities (a,b,c..) add incoherently at the receiver as shown by the vector diagram at the bottom. In case (ii), signals scattered from the different parts (d,e,f..) of a horizontally extended surface arrive in phase at the receiver to produce a reflected component. In case (iii), irregularities at several horizontally extended surfaces (a,b,c..) produce reflections that mutually interfere at the receiver (from RASTOGI and HOLT, 1981).

diffraction pattern at the ground with spaced antennas. These methods are schematically shown in Figure 2. Almost all the observations of reflections have been made with VHF radars. There is yet scant empirical evidence for UHF radar reflections from the troposphere and stratosphere. This is probably because the roughness scale (0.1 m) required for UHF reflections becomes comparable to the Kolmogorov microscale.

Radar measurements along the vertical and an off-vertical direction show an enhancement in signal power along the vertical direction. Such observations have been reported by GAGE and GREEN (1978) at Sunset for the stratosphere, and by FUKAO et al. (1979) at Jicamarca for the stratosphere and the mesosphere. GAGE and GREEN interpreted their results as due to reflection from an extended layer of 1-m thickness. GAGE and BALSLEY (1980) considered anisotropic scattering from model irregularities to show that the observed enhancements along the vertical direction can be reconciled with weakly anisotropic disc and rod-shaped irregularities. GAGE et al. (1981) suggest that the observations at Sunset can also be reconciled with scattering from Bragg-scale fluctuations within a thin, extended layer - a process for which they suggest the term "Fresnel Scattering". Enhanced mesospheric reflections along the vertical have been observed only below 75-km altitude (FUKAO et al., 1979; ROTTGER et al., 1979; FUKAO et al., 1980). This is probably due to the increase in the

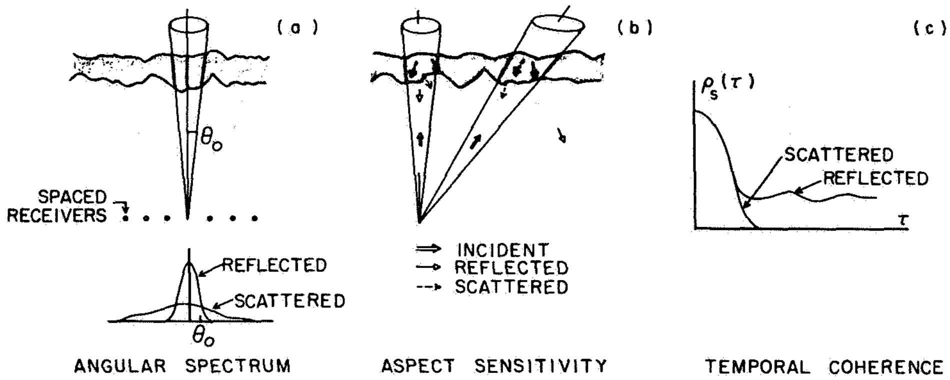

Figure 2. A schematic illustration of three methods of discriminating reflections from scattering. In the spaced-receiver method (a), the diffraction pattern produced by the irregularities is measured at ground level. Reflected components produced by a horizontally extended irregularity produce a diffraction pattern with a narrow angular spectrum. In the angular variation or aspect sensitivity method (b), signals received from the vertical and an off-vertical direction are compared. In the temporal-coherence method (c), reflections are detected on the basis of their longer correlation time. $\rho_S(\tau)$ is the autocovariance function of the received signal (from RASTOGI and ROTTGER, 1982).

Kolmogorov microscale associated with turbulence, that makes the Rayleigh condition rather difficult to satisfy in the upper mesosphere.

ROTTGER and LIU (1978) have used the longer coherence time of the reflected signals (up to several tens of seconds) to discriminate tropospheric reflections from scattering. ROTTGER (1980) and RASTOGI and ROTTGER (1982) have used the temporal coherence of the reflected returns to detect stable structures in the lower stratosphere.

The diffraction characteristics of the reflected and scattered components in the troposphere have been studied with spaced antennas by VINCENT and ROTTGER (1980) and the applicability of this method to measure winds up to mesospheric heights has been established by ROTTGER (1981). The spaced-antenna technique has also been used to detect in some cases a slight tilt in the refractivity structures (VINCENT and ROTTGER, 1980).

The statistical distribution of the received signals is affected significantly by the presence of reflected components. For scattering alone, the real and imaginary parts of the received signal envelope are expected to have a Gaussian distribution and its amplitude, a Rayleigh distribution (ISHIMARU, 1978). In presence of a constant reflected component, the amplitude has a Rice distribution. For several dominant reflectors, the distribution reverts to Rayleigh. RASTOGI and HOLT (1981) discuss the use of these distributions to detect strong reflections in the presence of scattering. The statistical distribution of MST radar signals does not seem to have received much attention.

DISCUSSION

The characteristics of radar reflections from the middle atmosphere have been studied in several VHF experiments. It is generally recognized that thin, horizontally extended refractivity structures play a significant role in producing these reflections. Several mechanisms have been proposed to explain the observed characteristics of reflections, on the basis of assumed or inferred properties of small-scale refractivity fluctuations.

At directions close to the vertical, reflections can produce undesirable effects. In the presence of reflections, care is needed to estimate the turbulence parameters (e.g., C_n^2) from the received signal power. Measurements of vertical wind are also likely to be biased by the winds at reflection heights, especially when the altitude resolution is coarse.

Most of the reported radar studies of reflections tacitly assume that the iso-refractivity surfaces are planar. Weak undulations of these surfaces are expected, however, in the presence of atmospheric waves and shears. These undulations can produce a focussing and defocussing effect on the signals received at ground level. Such effects become important with small antennas, and also influence the validity of estimating instantaneous horizontal velocity from simultaneous Doppler observations along beams pointed in different directions.

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