2.1A ON THE MORPHOLOGY OF THE SCATTERING MEDIUM AS SEEN BY MST/ST RADARS

K. S. Gage

Aeronomy Laboratory
National Oceanic and Atmospheric Administration
Boulder, CO 80303

ABSTRACT

Much can be learned about the morphology of the small-scale structure of the atmosphere from analysis of echoes observed by MST radars. The use of physical models enables a synthesis of diverse observations. Each model contains an implicit assumption about the nature of the irregularity structure of the medium. A comparison is made between the irregularity structure implicit in several models and what is known about the structure of the medium.

INTRODUCTION

Much has been written in the past five years about the scattering and reflection mechanisms responsible for the echoes observed by MST radar (GAGE and BALSLEY, 1980; ROTTGER, 1980). At UHF it is fairly widely accepted that echoes arise from turbulent irregularities in the radio refractive index. At lower VHF, echoes from stable regions of the atmosphere are very anisotropic and appear to involve Fresnel scattering/reflection as well as turbulent scattering. While the specular nature of these echoes is widely recognized, there is still no consensus as to the detailed mechanism responsible for the echoes.

The occurrence of echoes from the clear atmosphere requires structure in the medium at the scale of half the wavelength of the probing wave. In the case of turbulent scattering this structure is random and presumably associated with active turbulence in the medium. In the case of Fresnel reflection or scattering the medium possesses a coherent structure at least transverse to the probing beam. In both cases the character of the observed echoes reveals much about the structure of the medium. Unfortunately, ambiguities arise when an attempt is made to "work backwards" and infer the structure of the medium from radar observations. To resolve ambiguities and to validate models precise, high-resolution, in situ probing of the medium is required to supplement radar observations.

In this paper I consider the structure of the medium implicit in diverse models for the echoes observed by MST radars. By identifying the implicit structure and comparing it with what is known about the structure of the real atmosphere and what has been learned from radar observations it is possible to judge the reality of some of the proposed mechanisms.

AN OVERVIEW OF ECHOING MECHANISMS

A diversity of scattering and reflection mechanisms appears to be responsible for the echoes observed by radars operating in the lower VHF. The attempt to understand these mechanisms as they pertain to the MST radar has motiviated a reexamination of the broader literature on radio propagation. Indeed, some of the long standing issues in radio propagation are brought into sharp focus in the attempt to understand the nature of the echoes observed at lower VHF. In the following paragraphs I briefly describe several of the mechanisms:

(a) Isotropic Turbulent Scattering

Turbulent scattering was proposed by BOOKER and GORDON (1950) to explain the over-the-horizon propagation of UHF radio signals in the lower atmosphere. It has also been widely accepted as the mechanism responsible for most of the clear air echoes observed at UHF (HARDY and KATZ, 1969) and the oblique echoes observed at VHF. The mechanism requires active turbulence and gradients of refractive index to produce refractivity turbulence at the scale to which the radar is sensitive (OTTERSTEN, 1969).

(b) Anisotropic Turbulent Scatter

While active turbulence is supposed to be isotropic in the inertial range, at larger scales active turbulence must become anisotropic. For refractivity turbulence all that matters is that the correlation scales which characterize the turbulence be different. For a stable atmosphere this usually means that the correlation distance is much less in the vertical than in the horizontal. The anisotropy in the turbulence field implies an angular dependence in the echo magnitude which resembles the observed variation (GAGE and BALSLEY, 1980; DOVIAK and ZRNIĆ, 1983).

(c) Fresnel Reflection

Occasions arise, especially in the stable atmosphere, when coherent structure is evident. This coherent structure takes the form of stable laminae which possess coherency over horizontal distances comparable to a Fresnel zone. Reflections from sharp gradients of index of refraction have long been thought to play a role in tropospheric radio propagation (DU CASTEL, 1966). Models of Fresnel reflection are deterministic and usually treat single layers of specific shape. The process of reflection from these layers is often referred to as partial reflection.

(d) Diffuse Reflection

Conceptually, diffuse reflection is pertinent to reflection from a surface which is rough compared to the probing wavelength. The mechanism is discussed by DU CASTEL (1966) as an important component of over-the-horizon tropospheric radio propagation and by ROTTGER (1980) as an important mechanism for lower VHF radar echoes.

(e) Fresnel Scatter

The concept of Fresnel scatter was introduced to account for the volume-filling aspect of the specular echoes observed by VHF radar. As originally proposed, the Fresnel scatter model envisioned a coherent structure along the beam (as well as across the beam) to account for the pulse-width square dependence apparent in early observations. Recent observations, however, more typically show a pulse-width dependence confirming the volume-filling feature but not the coherency assumed along the beam. Fresnel scatter has many of the features of Fresnel reflection and can be thought to be comprised of the incoherent sum of partial reflections from many thin layers. It also has much in common with anisotropic turbulence.

Several of the mechanisms described above are illustrated in Figure 1. Each panel contains a schematic representation of the structure in the profile of radio refractive index along the radar beam. Two profiles are shown to illustrate the extent of coherency across the beam. The left-most panel illustrates a turbulent medium with much irregularity structure but no coherency across the beam. The right-most panel illustrates a few discrete thin layers which extend across the beam as required for Fresnel reflection. The middle

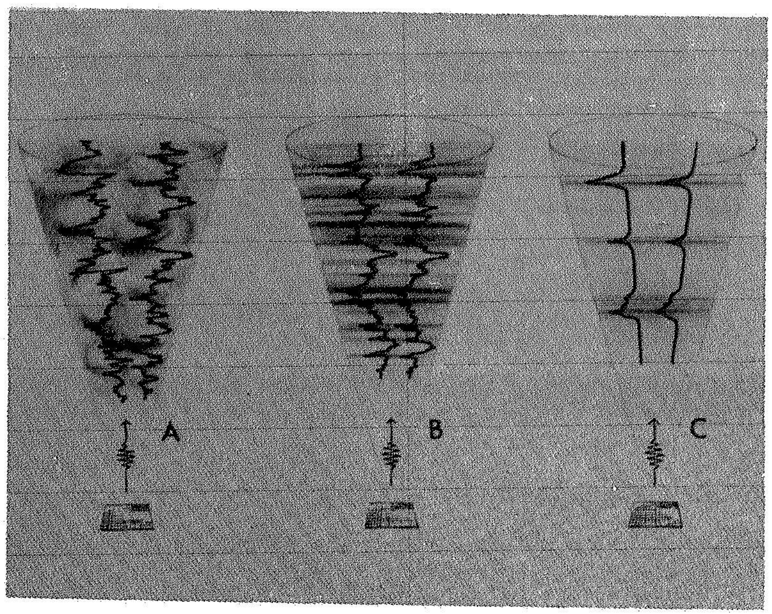

Figure 1. Artist's conception of atmospheric refractivity structure pertinent to i) isotropic turbulence scatter, ii) Fresnel scatter, iii) Fresnel reflection (after GAGE and BALSLEY, 1981).

panel shows a volume-filling irregularity structure which possesses coherency across the beam. This structure is pertinent to Fresnel scatter.

THE MORPHOLOGY OF TURBULENCE IN THE STABLY STRATIFIED ATMOSPHERE

Turbulence has long been recognized as one of the most important mechanisms for the production of the refractivity structure responsible for over-the-horizon tropospheric radio propagation. In addition, it has been shown to provide a reasonable model for many of the clear air echoes observed by radar (HARDY et al., 1966; KROPFLI et al., 1968; VANZANDT et al., 1978).

The nature of turbulence in the free atmosphere has only recently come into focus. Numerous investigations using aircraft, balloons, and radar to probe the atmosphere have shown the relevance of Kelvin-Helmholtz instability for the production of clear air turbulence. Laboratory experiments (see, e.g., THORPE, 1973) have clearly shown the evolution of shear flow instability in a stably stratified fluid. Theoretical investigations have helped provide a common framework for the interpretation of diverse observational and experimental studies (DRAZIN and REID, 1981). In addition, the role of waves in triggering turbulence has been clarified (BRETHERTON, 1969) and the analogous problem of intermittent turbulence in the ocean has been investigated by WOODS (see, for example, WOODS and WILEY, 1972).

Perhaps the most pronounced feature of radar observations of turbulence in the free atmosphere is the layered structure evident in time-height cross sections of echo magnitude. Figure 2 contains an example of such a cross section as observed by the Arecibo radar (SATO and WOODMAN, 1982). It shows a

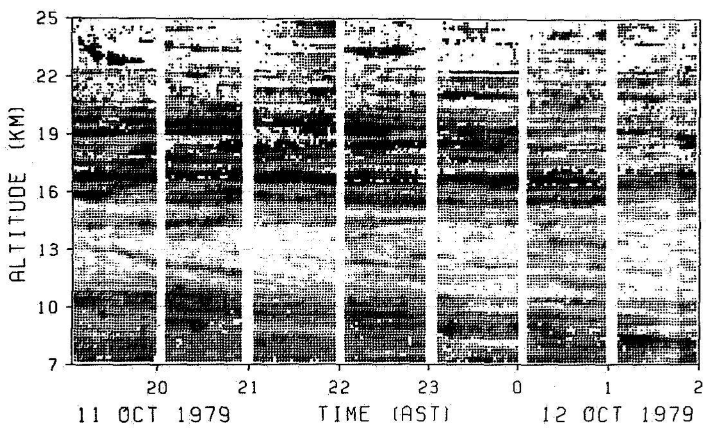

Figure 2. 8-level height-time shade plot for the echo power received by the Arecibo radar. The dynamic range is 32 dB (after SATO and WOODMAN, 1982).

persistent layering on a scale larger than the 150 m range resolution used by the radar. The strong echoes are confined to thin regions in which the Richardson number is small. For example, Figure 3 shows a clear association of strong echoes with strong shear. The fact that the echoes have a wide spectral width confirms that they are due to active turbulence.

CRANE (1980) has summarized the conditions under which turbulence should be observable by a radar of given wavelength. Briefly, the half-wavelength scale to which the radar is sensitive must be larger than the inner scale of turbulence and smaller than the outer scale of turbulence. The inner scale is proportional to $(\nu^3/\bar{\varepsilon})^{1/4}$, where ν is kinematic viscosity and $\bar{\varepsilon}$ is the eddy dissipation rate. Since kinematic viscosity increases (as density decreases)

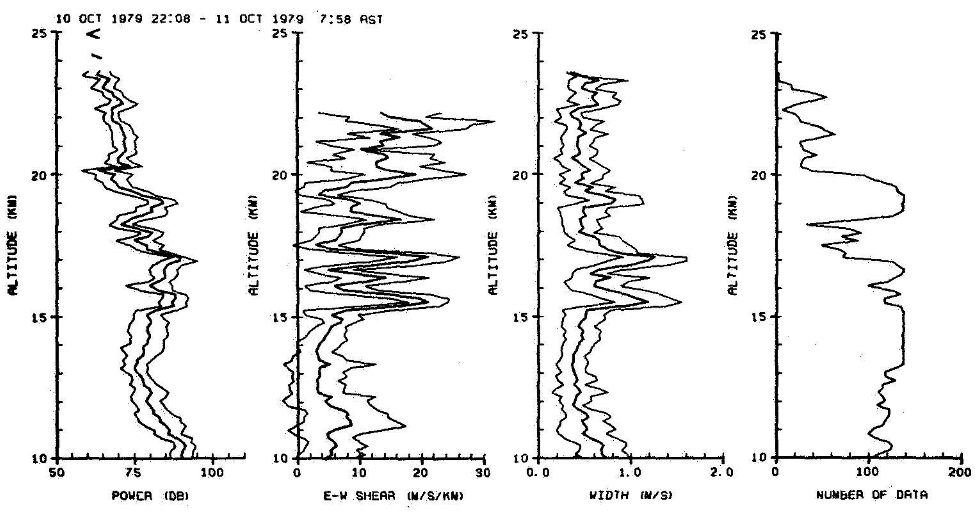

Figure 3. 10-hour mean echo power, E-W component of the wind shear, and the spectral width versus height. The number of good data points used in the average are plotted on the right. Two thin lines around the thick line in each profile indicate the standard deviation from the mean (after SATO and WOODMAN, 1982).

with altitude, the inner scale increases with altitude. At tropopause heights it is close to 1 cm. The outer scale of turbulence is proportional to the buoyancy scale $\bar{\varepsilon}^{1/2}\,\bar{N}^{-3/2}$ where $\bar{N}$ is the Brunt-Vaisala frequency $\bar{N} \equiv (g/\theta\ \partial\theta/\partial z)^{1/2}$. Values of the outer-scale are typically a few tens of meters in the free atmosphere. However, the outer scale can be much less in stable regions where $\bar{N}$ is large and $\bar{\varepsilon}$ is small. To take an extreme example, if $\Delta\theta/\Delta z$ is .1° C/m and $\bar{\varepsilon}$ is $10^{-6}\ m^2 s^{-3}$ the outer scale would be about 10 cm. Regions of active turbulence, on the contrary, are usually associated with small $\bar{N}$ (see, for example, BARAT, 1982) and enhanced $\bar{\varepsilon}$ so that the outer scale will be increased. The outer scale of turbulence has been measured to be a few tens of meters (BARAT, 1982) which is often a small fraction of the turbulent layer thickness.

The creation of layered structure by local regions of Kelvin-Helmholtz instability was discussed by ROTTGER (1981). As illustrated in Figure 4, turbulence acts to concentrate gradients at the boundaries of turbulent layers. Many localized instabilities acting in concert could produce an evolving fine structure of thin regions of turbulence bounded by thin stable layers. It is important to realize, however, that this is not the only mechanism which can produce layered structure. A coherent layered structure can also be produced by large-scale buoyancy-inertia waves. For example, the layered structure evident in Figure 2 is probably associated with such waves.

THE MORPHOLOGY OF STABLE LAYERS IN THE FREE ATMOSPHERE AND THE SPECULAR ECHOES OBSERVED BY MST/ST RADARS

While the echoes observed by MST/ST radars directed more than 10 degrees or so off vertical are associated with active turbulence, the echoes observed at vertical incidence are associated with stable regions of the atmosphere as shown in Figure 5 (GAGE and GREEN, 1978). Another example of the clear correspondence between echo magnitude at lower VHF and static stability is contained in Figure 6 (LARSEN and ROTTGER, 1982, 1983) which shows an evolutionary pattern of strong stratospheric echoes corresponding to a changing stability structure during the passage of a frontal zone.

The nature of the mechanism responsible for the specular echoes observed at lower VHF has been the subject of continuing controversy. The models which have been proposed to explain these echoes include Fresnel reflection (GAGE and

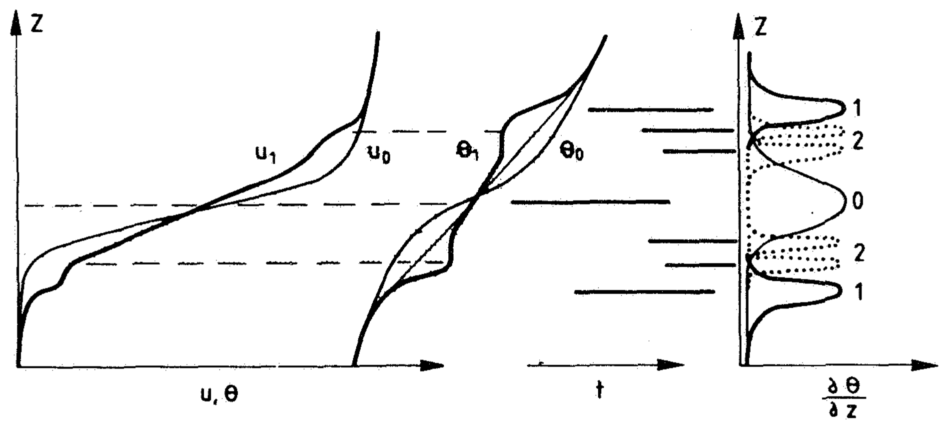

Figure 4. Formation of ensembles of stable layers (sheets) by Kelvin-Helmholtz instability (adapted from PELTIER et al., 1978, by ROTTGER, 1981).

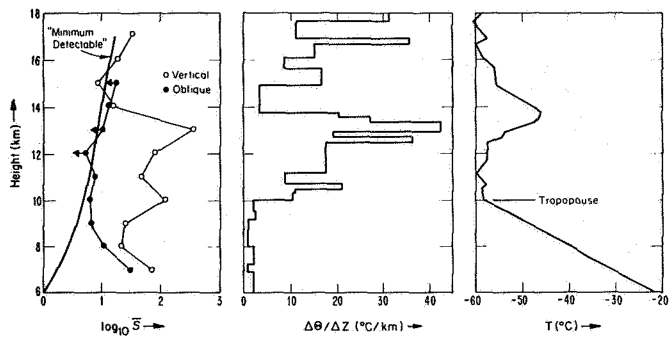

Figure 5. Comparison of the normalized power profiles observed at vertical and oblique incidence by the Sunset radar with stability (after GAGE and GREEN, 1978).

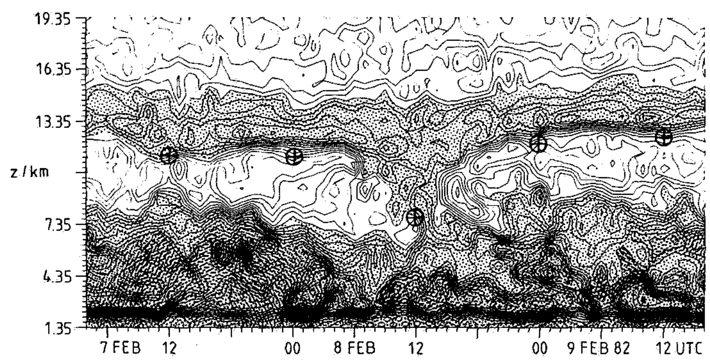

Figure 6a

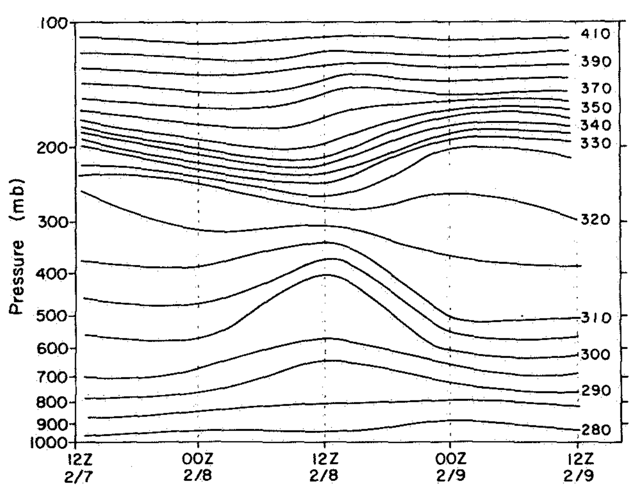

Figure 6b

Figure 6. a. Reflectivity contours observed at vertical incidence for a warm frontal passage by the SOUSY radar during February 1982.
b. Pressure-time cross section of the potential temperature measured by the Hanover radiosonde during the period corresponding to 6a (after LARSEN and ROTTGER, 1982).

GREEN, 1978; ROTTGER and LIU, 1978), diffuse reflection (ROTTGER, 1980), Fresnel scatter (GAGE et al., 1981) and anisotropic turbulent scattering (DOVIAK and ZRNIC', 1983). As discussed earlier, the first two mechanisms involve partial reflections from smooth or rough surfaces while the last two mechanisms involve volume scattering processes.

Fresnel reflection requires a very stable layer which is thin compared to the probing radar wavelength. For example, GAGE and GREEN (1978) estimate that a strong echo would be received from a stable layer of 1-m thickness and .1°C temperature difference located at 12 km. The occurrence of meter-scale microstructure has been reported (METCALF, 1975; METCALF and ATLAS, 1973). Such thin stable layers could be produced by the action of turbulent mixing. Under these circumstances one might anticipate that the echo magnitude would be proportional to the mean stability of the environment in which the thin turbulent layers are imbedded. Their magnitude should also depend on turbulent layer thickness since (everything else being equal) the largest layers will possess the largest temperature differences across them. Since in the most stable regions turbulence must be confined to very thin regions, the two effects mentioned above might be expected to counteract each other.

There is an increasing body of evidence that the backscattered power received at vertical incidence at lower VHF increases with the pulse width of the probing pulse (GREEN and GAGE, 1980; HOCKING and ROTTGER, 1983; GREEN, 1983). This implies a medium filled with refractivity structure. Consequently, any partial-reflection mechanism must be generalized to include the reflection from an aggregate collection of thin layers. Barring some mechanism to space the layers along the beam, random spacing can be assumed and the Δr-dependence recovered (HOCKING and ROTTGER, 1983).

If the assumption of a coherent structure along the beam is removed from the concept of Fresnel scattering, Fresnel scattering becomes very similar to a volume Fresnel reflection or even anisotropic turbulent scattering. The main difference between volume Fresnel reflection and anisotropic turbulence scattering is that the former consists of gradients concentrated in layers which are thin compared to the radar wavelength while the latter only requires a significant amount of refractivity structure at half the radar wavelength. At this point it should be recognized that the anisotropic turbulence model does not necessarily involve active turbulence. All it requires is an anisotropic distribution of refractivity structure. The issue of when Fresnel scattering is an appropriate description of the scattering process and when anisotropic turbulent scattering is an appropriate description has been addressed recently by DOVIAK and ZRNIC' (1983). These authors show that Fresnel effects do not become important until the transverse correlation length ρ_t of the media exceeds .29 D where D is the diameter of the radar antenna. However, turbulent scattering which fills the antenna beam leads to an R^{-2} range dependence while Fresnel scattering with ρ_t less than a Fresnel zone radius leads to an R^{-4} dependence consistent with the observed range dependence at Poker Flat (BALSLEY and GAGE, 1981), illustrated in Figure 7.

In situ observations of stable atmospheric structure are very sparse. Some insight into the structure of stable layers can be gained from an inspection of routine radiosonde temperature profiles. In such profiles temperatures are specified at mandatory (pre-selected pressures) levels and significant levels. Significant levels are chosen to optimize the agreement between the radiosonde-derived temperature profile and the actual temperature profile. Clearly, the more structure in the actual temperature profile the more significant levels that are required to resolve that structure. Figure 8 contains a histogram of the number of stable layers found in the Fairbanks, Alaska radiosonde soundings between 12 and 14 km during March 1981. Each layer counted was bounded by significant levels above and below. The number of layers is shown as a function

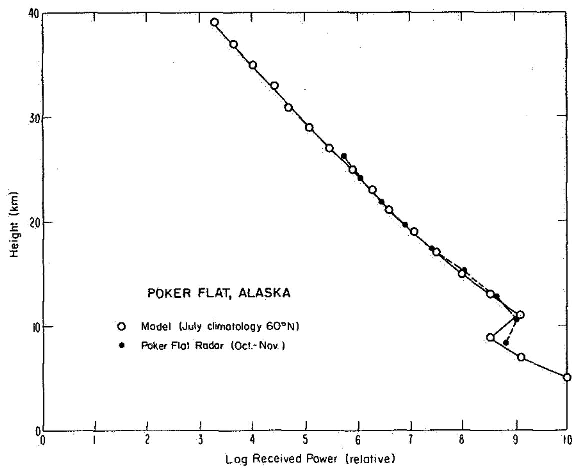

Figure 7. Relative comparison between theoretical and observed backscatter profiles at vertical incidence for the Poker Flat MST radar in Alaska during October-November 1979 (after BALSLEY and GAGE, 1981).

of layer thickness. Note that most layers fall in the range 100 to 500 m. Few layers thicker than 500 m are counted since almost always thick layers are bounded by at least one mandatory level. The distribution of potential temperature gradient with layer thickness is shown in Figure 9. Note the inverse relationship between stability and layer thickness. The most stable layers are very thin. Indeed, the distribution of stability vs. layer thickness can be approximated by $\partial\theta/\partial z \propto 474\Delta z^{-1/2}$.

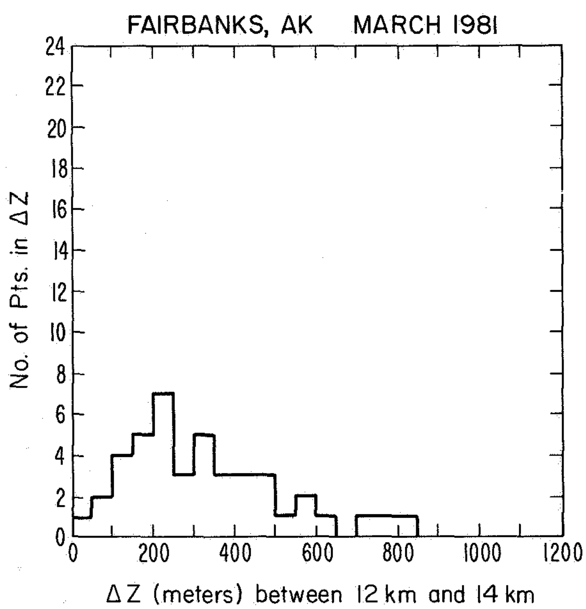

Figure 8. Histograms of occurrence of stable layers between 12 and 14 km versus thickness resolved by the Fairbanks radiosonde for March 1981.

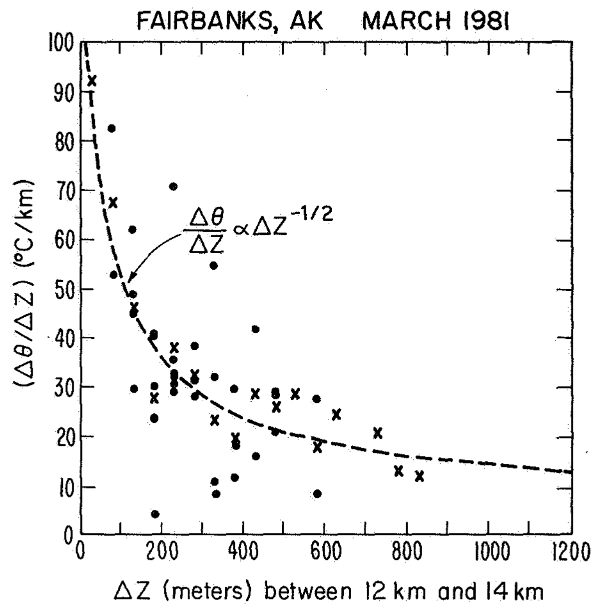

Figure 9. Distribtuion of stability versus layer thicknesses for the stable layers contained in Figure 8. Each dot represents a layer. x's represent the average stability for each bin of layer thicknesses.

The observed dependence of potential temperature gradient upon layer thickness approximates what might be expected for buoyancy waves (VANZANDT, 1982; GARRETT and MUNK, 1979). Indeed, VANZANDT and VINCENT (1983) have argued that buoyancy waves may be used to explain the specular echoes observed by lower VHF radars. Extrapolating the result of Figure 9 to Δz = 3 m implies a temperature gradient of $\sim$.3°/m which should be sufficient to cause a strong specular echo. Note that such thin stable layers can be anticipated only within very stable regions (of greater vertical extent) for only then will the outer scale of turbulence be less than a few meters. If the refractivity structure causing the echoes is due to buoyancy waves, the proportionality of echo magnitude to M^2 can be explained theoretically (VanZandt, private communication).

CONCLUDING REMARKS

In this paper I have examined the mechanisms which have been proposed to explain the echoes observed from the clear atmosphere by MST/ST radars. Each has been considered in relation to the atmospheric refractivity structure implicit for its realization. While the echoes observed at oblique incidence are reasonably explained by turbulent scattering, the specular echoes can be explained by several alternative models of atmospheric refractivity structure. A refractivity structure which possesses some transverse coherency but a volume filling random vertical structure seems most likely. Whether the process is better conceptualized as a composite many layered partial reflection process or as a Bragg scattering, anisotropic turbulence process is not yet clear. To resolve this issue will probably require in situ probing of stable layer structure.

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