2.3A SPECTRAL CHARACTERISTICS OF THE MST RADAR RETURNS

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ABSTRACT

The salient features of the spectra of atmospheric returns due to random refractivity fluctuations in the MST region are reviewed. The nonhomogeneous layered structure of turbulence is often evident as multiple peaks in the spectra. The time evolution of the spectra observed with a fine Doppler resolution provides evidence for thin regions of turbulence associated with gravity waves and shear instabilities. Embedded in these regions are horizontally extended refractivity structures that produce enhanced returns due to specular reflections. It is conceivable that some enhanced returns arise due to anisotropy of small-scale refractivity structures. Observed correlations of the strength of the returns with their Doppler spread, wind shears, and winds provide insights into the physical mechanisms that produce turbulence.

INTRODUCTION

The use of sensitive high power radars at VHF and UHF frequencies in studies of the Mesosphere-Stratosphere-Troposphere (MST) region has been reviewed extensively in recent years (see e.g., ROTTGER, 1980; BALSLEY, 1981). These radars are sensitive to weak fluctuations in the radio refractivity of the atmosphere at a scale that usually is half the radar wavelength (BOOKER and GORDON, 1950; BOOKER, 1956). The refractivity fluctuations are induced by atmospheric turbulence and act merely as tracers for larger-scale motions associated with atmospheric winds and waves.

In most radar experiments it is usual to parametrize the spectra of the received signals by their low-order moments which are then interpreted in terms of the physical and dynamic properties of the medium (WOODMAN and GUILLEN, 1974). Details in the spectra that are not readily characterized by the low-order spectral moments, and observed interrelations between the spectral moments, provide insights into the physical mechanisms that produce the radar returns and are reviewed here.

The response of the radar to the radio refractivity fluctuations is briefly outlined in the following section, where we also discuss the consequences of layered turbulence on the spectra and the inferred parameters. In directions close to the vertical, these turbulent layers often can produce enhanced specular echoes. The spectral characteristics of these enhanced echoes are briefly outlined; observed correlations between the spectral moments, and the implications of these in terms of thin layers of turbulence generated by enhanced wind shears and subsequent thickening of layers are discussed in the respective sections. Finally, the types of observations that may resolve some conflicting evidence for the observed correlations are discussed.

ADAR RESPONSE TO REFRACTIVITY FLUCTUATIONS

The electromagnetic aspects of scattering of radio waves from random efractivity fluctuations in radar experiments are sufficiently well understood see e.g., TATARSKII, 1971; ISHIMARU, 1978). The refractivity fluctuations $(\underline{r},t)$ constitute a random field. The received signal $z(t)$ is linearly related o the spatial Fourier component of this field at the Bragg vector

$\underset{\sim}{k}_b = (\underset{\sim}{k}_i - \underset{\sim}{k}_r)$ corresponding to the propagation vectors $\underset{\sim}{k}_i$ and $\underset{\sim}{k}_r$ or the incident and the received fields. For backscatter (usually the case for MST radars) k_b corresponds to a spatial scale of half the radar wavelength. A second-order statistic of the received signal $z(t)$, either its autocovariance function $R(\tau)$ or the power spectrum $S(f)$, is measured in the radar experiments. These statistics can usually be related to the time or frequency behavior of these components of the field $n(\underset{\sim}{r},t)$ that have a spatial wave number k_b.

To proceed further, assumptions must be made about the nature of the field $n(\underset{\sim}{r},t)$. In the most widely used (and least general) information $n(\underset{\sim}{r},t)$ is assumed to be homogeneous and isotropic at least over the radar cell (BOOKER and GORDON, 1950). The signal spectrum $S(f)$ can be characterized in this case by a single Doppler-shifted peak (ISHIMARU, 1978). Without resorting to the exact shape of the spectrum, the lowest-order moments of $S(f)$ provide information on the turbulence-induced refractivity variance (C_n^2), radial velocity ($v = \underset{\sim}{k}_b \cdot \underset{\sim}{v}$), and the radial velocity spread (σ_v) (see e.g., WOODMAN and GUILLEN, 1974; ZRNIC', 1979).

The assumption of homogeneiety of the field $n(\underset{\sim}{r},t)$ over a radar cell breaks down in experiments that have a coarse altitude resolution of 1-3 km. This is principally due to a layered structure of turbulence that is characteristic of the atmosphere and ocean. Often these layers have a nominal thickness of tens to hundreds of meter. Early evidence for the occurrence of turbulent layers in the stratosphere (WOODMAN and GUILLEN, 1974) and in the mesosphere (RASTOGI and BOWHILL, 1976) was inferred from VHF radar observations at Jicamarca.

When two or more layers occur in a region of shear through a radar cell, the spectrum $S(f)$ has characteristic multiple peaks as shown in Figure 1. In UHF radar experiments at Millstone Hill, time evolution of these spectral peaks has been observed with a fine Doppler-resolution at low elevation angles to provide evidence for breaking gravity waves, and possibly a Kelvin-Helmholtz stability in the troposphere (WAND et al., 1983). CRANE (1980) shows examples in which the multiple peaks in the spectra can be seen and tracked over contiguous radar cells.

An important consequence of the unresolved layers of turbulence is the error introduced in the estimation of the C_n^2 parameter from the measured signal power. Radar experiments that assume homogeneous turbulence throughout the radar cell, would tend to underestimate C_n^2 by a factor that depends upon the unknown volume fraction (F) of the cell that is actually filled by turbulence. VANZANDT et al. (1978) have proposed a model that can be used to infer C_n^2 from the back-ground wind and temperature profiles measured with radiosondes. Simultaneous radar measurements of C_n^2 can be used to infer the fraction F. The error in the estimates of C_n^2 is usually considerably smaller in fine altitude resolution experiments in which the vertical size of the radar cells is better matched to the layer thickness (SCHMIDT et al., 1979; ROTTGER et al., 1979; WOODMAN, 1980; WOODMAN et al., 1980). In these experiments, the assumption of homogeneiety over the radar cells is approximately valid, except for a possible complication due to specular returns (discussed in the next section).

The assumption of isotropy of turbulence at the Bragg scale (typically 3 meters for VHF radars and 0.3 meter for UHF radars) is reasonable if this scale is sufficiently small compared to the outer scale at which energy is fed into turbulence. For a typical layer thickness of 100 m, anisotropic Bragg-scale turbulence is more likely to occur at VHF, than at UHF frequencies. Scattering from anisotropic refractivity fluctuations (BOOKER, 1956; TATARSKI, 1971; ISHIMARU, 1978) can produce enhanced radar returns. The effect of anisotropy, however, is not expected to be significant at mesospheric heights, where the Kolmogorov scale associated with turbulence increases to 1-5 meter.

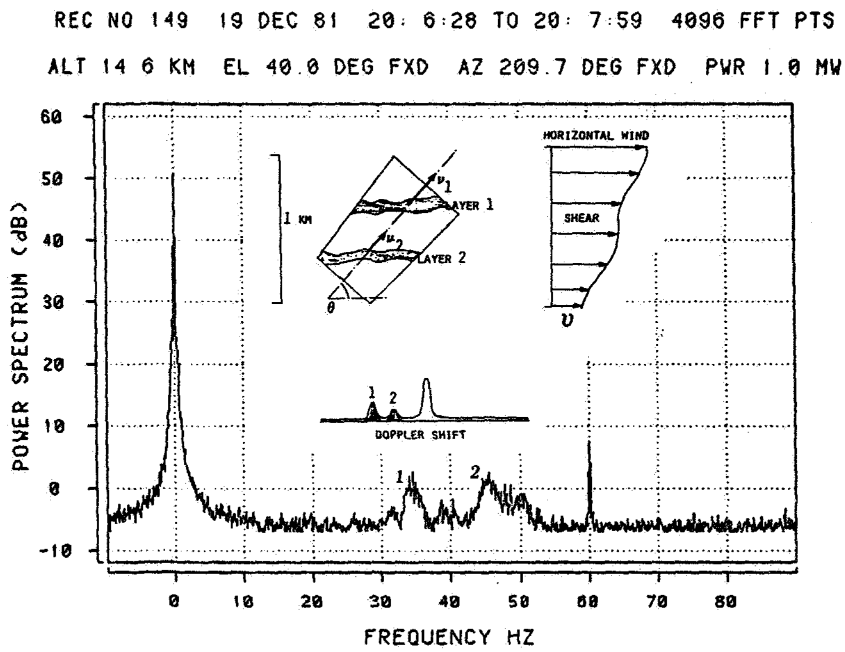

Figure 1. An example of signal spectrum with multiple peaks (identified as 1 and 2) observed with a 0.125 Hz resolution at Millstone Hill. A Doppler shift at 10 Hz corresponds to a horizontal velocity of 4.5 m/s. The ground clutter at zero frequency, and a narrow spike at the power line frequency of 60 Hz are clearly discernible. The inset shows how these peaks can arise due to layers of turbulence in a shear region.

LIU and YEH (1980) have considered scattering from thin layers of urbulence that is frozen-in with the medium, and have obtained specific results or the modified spectral moments. Their analysis is valid when the turbulent elocity component is small compared to the velocity of the medium along the adar axis. This is usually the case when the radar is pointed downwind, ufficiently away from the vertical.

PECULAR REFLECTIONS

Enhanced echoes have been observed from the S-T region (see e.g., GAGE and EEN, 1978; ROTTGER, 1978) and from the mesosphere (FUKAO et al., 1980) in VHF tperiments that use a radar beam pointed close to the vertical. These are :tributed to weak, partial or specular reflections from sharp refractivity :adients associated with turbulent layers.

The spectral characteristics of specular returns have been observed in the T region in VHF radar experiments by examining the autocovariance function of e returns (ROTTGER and LIU, 1978; RASTOGI and ROTTGER, 1982), and directly in F radar experiments (SATO, 1981). The temporal coherence of specular returns manifest in their longer correlation time or smaller spectral width. ecular returns can be discriminated, to some extent, from the scattered gnals by examining the spectra in the vicinity of the Doppler profile through ndows of different width. The Doppler resolution in the frequency spectra served with most MST radars, however, has not been adequate for fruitfully rsuing this approach.

RELATION BETWEEN SPECTRAL MOMENTS

Empirical correlations between the low-order spectral moments, or parameters derived therefrom, have been observed in several radar experiments. Some of these correlations, e.g., those between wind (from the first-order moment), wind shear (height derivative of wind), and signal power (zeroth-order moment), can be reconciled with physical mechanisms that generate turbulence. Others, e.g., a correlation (positive or negative) between signal power and the spectral width (second-order moment) remain physically elusive, but probably depend on the growth of turbulent regions.

In the absence of convection processes, local wind shears are the principal source of turbulence. A necessary condition for the onset of turbulence is that the local Richardson number Ri should become smaller than 0.25. The signal power measured in radar experiments is an indicator of the strength of turbulence. The shear inferred from the radial wind at contiguous radar cells has a scale corresponding to the altitude resolution. An excellent similarity has been observed in the stratosphere and troposphere between the profiles of inferred shear (at a 300-m scale) and signal power in a series of fine-altitude resolution (150 m) experiments at Arecibo (SATO, 1981).

Even with altitude resolutions of 1-2 km, a correlation of the order of 0.7 between wind shear and signal power has been observed in experiments at Poker Flat (SMITH et al., 1983), and at Millstone Hill. A similar order of correlation is observed between wind and signal power, especially in regions of large (>30 m/s) horizontal wind. The fact that even the shear inferred at a 2-km scale appears to bear a good correlation with the signal power, suggests that small-scale shears probably are enhanced in regions of large background shear. The correlation of signal power with strong winds can be explained either on the basis of large Reynolds number, or alternatively because regions of strong winds (e.g., the jet streams) also have a large shear associated with them (SMITH et al., 1983).

An intriguing correlation between the signal power and fading time (inverse of spectral width) of mesospheric VHF echoes was first seen in A-scope traces by BOWLES (1958) in his pioneering incoherent-scatter experiment. A similar correlation was noticed in A-scope traces at Jicamarca (FLOCK and BALSLEY, 1967). Later experiments showed that this type of correlation is often quite pronounced in the lower mesosphere (RASTOGI and BOWHILL, 1976), though its sense is frequently reversed above 80 km (FUKAO et al., 1980; COUNTRYMAN and BOWHILL, 1979).

Since the signal power is related to the refractivity variance, and spectral width to the radial velocity variance, a positive correlation between these quantities is normally to be expected. This argument fails to explain the observed correlation, however.

RASTOGI and BOWHILL (1976) proposed that for thinner layers of turbulence, a broader range of wave numbers in the vicinity of k_b are involved in scattering and the fading time would be longer. An association of stronger signals with longer fading times in the lower mesosphere then appears to imply that stronger turbulence should occur in thinner layers. In the upper mesosphere, however, stronger signals appear to be associated with shorter fading times implying that regions of stronger turbulence ought to be thicker. VHF radar observations with 150-300 m resolution actually do reveal layers 1-2 km thick at heights above 80 km. These layers are several times thinner and often unresolved in the lower mesosphere (ROTTGER et al., 1979; RUSTER et al., 1980). The increased layer thickness above 80 km is also consistent with variation of the Kolmogorov micro-scale with height (see e.g., BALSLEY, 1981).

Figure 2 shows a scatter plot of changes in signal power and changes in spectral width observed for a few selected tropospheric range cells in a low-elevation experiment at Millstone Hill. The two regression lines also are shown for each plot. These plots imply that an increase in the signal power is associated with a decrease in spectral width, or an increase in fading time (similar to that observed in the lower mesosphere at Jicamarca). At low elevation angles, for shear-generated turbulent layers, the spectral width is proportional to the layer thickness (WAND et al., 1983).

These observations tend to favor the notion that the observed correlations are an indication of the broadening of turbulent layers by entrainment. Thin layers are possibly generated as a consequence of instabilities in the flow. Eventually the transfer of energy from the background flow into the turbulent layers ceases, and the intensity of turbulence (hence the signal power) must decrease with time due to viscous dissipation. The outer edges of a turbulent layer, however, are usually intermittent and would entrain the ambient non-turbulent fluid into the layer, making it thicker. Regions that have just become turbulent should then show high signal powers confined to narrow spectra. Those containing decaying turbulence would exhibit lower signal power associated with wider spectra, thereby explaining the observed correlation.

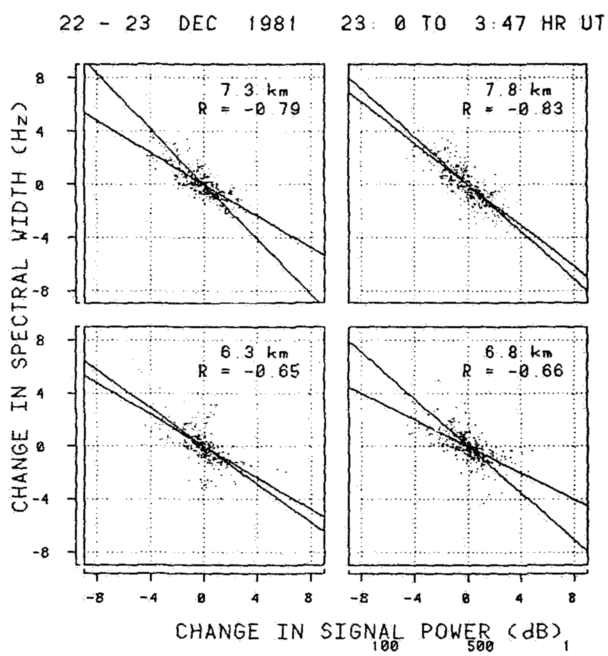

Figure 2. Scatter plots of changes in spectral width and signal power for a few heights in the troposphere observed at a 20 elevation angle with the Millstone Hill radar. The plots have about 400 points each. Trends with periods larger than 30 min have been removed. The two lines of regression and correlation coefficient also are shown. The sense of the implied correlation is similar to that observed in the lower mesosphere with VHF radars. A tentative interpretation is given in the text.

DISCUSSION

We have briefly discussed some characteristics of the spectra observed with MST radars, that provide interesting insights into the mechanisms that may be responsible for producing the radar returns. Most of the results in this area have been obtained in experiments that use coarse altitude and Doppler resolutions by looking for "statistical" correlations between the low-order spectral moments. A better understanding of the detailed structure of regions of turbulence in the middle atmosphere - and their radar signatures - can be obtained through experiments with improved resolution in altitude (150 m or better) and radial velocity (one to few cm/s). Such experiments may also be helpful in observing isolated cases of the generation, growth and decay of turbulent layers.

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REFERENCES

Balsley, B. B. (1981), The MST technique - a brief review, J. Atmos. Terr. Phys., 43, 495-509.

Booker, H. G. (1956), A theory of scattering from nonisotropic irregularities with application to radar reflections from the aurora, J. Atmos. Terr. Phys., 8, 204-221.

Booker, H. G. and W. E. Gordon (1950), Theory of radio scattering in the troposphere, Proc. IEEE, 38, 401-412.

Bowles, K. L. (1958), Observations of vertical incidence scatter from the ionosphere at 41 Mc/sec., Phys. Rev. Lett., 1, 454-455.

Countryman, I. D. and S. A. Bowhill (1979), Wind and wave observations in the mesosphere using coherent-scatter radar, Aeron. Rep. No. 89, Aeron. Lab., Dep. Elec. Eng., Univ. Ill., Urbana-Champaign.

Crane, R. K. (1980), Radar measurements of winds at Kwajalein, Radio Sci., 15, 383-394.

Flock, W. L. and B. B. Balsley (1967), VHF radar returns from the D region of the equatorial ionosphere, J. Geophys. Res., 72, 5537-5541.

Fukao, S., T. Sato, R. M. Harper and S. Kato (1980), Radio wave scattering from the tropical mesosphere observed with the Jicamarca radar, Radio Sci., 15, 447-457.

Gage, K. S. and J. L. Green (1978), Evidence for specular reflection from monostatic VHF radar observations of the stratosphere, Radio Sci., 13, 991-1001.

Ishimaru, A. (1978), Wave propagation and scattering in random media, Academic, New York, 572 pp. (in two volumes).

Liu, C. H. and K. C. Yeh (1980), Scattering of VHF and UHF radar signals from the clear air, Radio Sci., 15, 277-282.

Rastogi, P. K. and S. A. Bowhill (1976), Scattering of radio waves from the mesosphere, 2. Evidence for intermittent mesospheric turbulence, J. Atmos. Terr. Phys., 36, 1217-1231.

Rastogi, P. K. and J. Rottger (1982), VHF radar reflections in the vicinity of the tropopause, J. Atmos. Terr. Phys., 44, 461-469.

Rottger, J. (1978), Evidence for partial reflection from VHF radar signals from the clear air, J. Geophys., 44, 393-394.

Rottger, J. (1980), Structure and dynamics of the stratosphere and mesosphere revealed by VHF radar investigations, Pure Appl. Geophys., 118, 494-527.

Rottger, J. and C. H. Liu (1978), Partial reflection and scattering of VHF radar signals from the clear atmosphere, Geophys. Res. Lett., 5, 357-360.

Rottger, J., P. K. Rastogi and R. F. Woodman (1979), High-resolution VHF radar observations of the mesosphere, Geophys. Res. Lett., 6, 617-620.

Ruster, R., P. Czechowsky and G. Schmidt (1980), VHF-radar measurements of dynamical processes in the stratosphere and mesosphere, Geophys. Res. Lett., 7, 999-1002.

Sato, T. (1981), Coherent radar measurements of the middle atmosphere and the design concepts of the MU radar, Ph.D. Thesis, Kyoto Univ., Kyoto, Japan.

Schmidt, G., R. Ruster and P. Czechowsky (1979), Complementary code and digital filtering for detection of weak VHF radar signals from the mesosphere, IEEE Trans. Geosci. El., GE-17, 154-161.

Smith, S. A., G. J. Romick and K. Jayaweera (1983), Poker Flat MST radar observations of shear-induced turbulence, J. Geophys. Res. (in press).

Tatarskii, V. I. (1971), The effects of the turbulent atmosphere on wave propagation, Nat. Tec. Inf. Serv., Springfield, VA, 472 pp.

VanZandt, T. E., J. L. Green, K. S. Gage and W. L. Clark (1978), Vertical profiles of refractivity turbulence structure constant: Comparison of observations with by the Sunset radar with a new theoretical model, Radio Sci., 13, 819-829.

Wand, R. H., P. K. Rastogi, B. J. Watkins and G. B. Loriot (1983), Fine Doppler resolution observations of thin turbulence structures in the tropo-stratosphere at Millstone Hill, J. Geophys. Res., 88, 3851-3857.

Woodman, R. F. (1980), High-altitude resolution stratospheric measurements with the Arecibo 430-MHz radar at Arecibo, Radio Sci., 15, 417-422.

Woodman, R. F. and A. Guillen (1974), Radar observations of winds and turbulence in the stratosphere and mesosphere, J. Atmos. Sci., 31, 493-505.

Woodman, R. F., R. P. Kugel and J. Rottger (1980), A coherent integrator-decoder preprocessor for the SOUSY-VHF radar, Radio Sci., 15, 233-242.

Zrnić, D. (1979), Estimation of spectral moments for weather echoes, IEEE Trans. Geosci. El., GE-17, 113-128.