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2.4A OBSERVATIONS OF MESOSPHERIC TURBULENCE BY ROCKET PROBE AND VHF RADAR

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INTRODUCTION

Irregularities in the refractive index result in coherent backscattering of VHF radar signals from the mesosphere (WOODMAN and GUILLEN, 1974). There are two well-known characteristics of the scattered radar signal which appear to be particularly relevant to the scattering mechanism. The scattered signal is aspect sensitive so that a stronger echo is received when the radar antenna is pointed vertically than when it is pointed off-vertical (FUKAO et al., 1980). This aspect sensitivity is altitude dependent. Correlation between the echo power and the signal correlation time (P/C correlation) is also altitude dependent. A strong positive correlation is present in the lower mesosphere, changing to negative above about 75 km.

FUKAO et al. (1980) and others have suggested that radar echoes from the lower mesosphere may be caused by partial reflection from stratified layers modulated by gravity waves or turbulence, thus causing the observed amount of off-vertical scatter. In the upper mesosphere, however, where the scattering is isotropic, it is generally assumed that turbulence is the only mechanism generating refractive index fluctuations.

THRANE et al. (1981) compared irregularities in ion density data from a probe to echo power observed by a 2.75 MHz radar near Tromso, Norway. They concluded that the data were consistent with radio waves scattered from homogeneous, isotropic turbulence from 70 to 95 km. HOCKING and VINCENT (1982) have also presented data from a similar set of experiments performed at Woomera, Australia. They, however, concluded that partial reflections from horizontally stratified steps in the electron concentration play an important role in causing the radar echoes, at least up to an altitude of 85 km.

Here we compare data obtained simultaneously from rocket-borne Langmuir probes and from a 50 MHz MST radar. Rockets carrying Langmuir probes were launched from Punta Lobos in Peru during the CONDOR campaign of February-March 1983. In support of these rocket experiments, the Jicamarca VHF radar obtained data in the mesosphere and upper E-region.

OBSERVATIONS

The rocket (Nike Orion 31.028), launched on 27 February 1983, observed some irregularities in a narrow altitude region around 86 km. The echo power map obtained by the Jicamarca radar between 10:16 LST and 11:56 LST is shown in Figure 1. Note that the data recording system was operated intermittently during the one-hour period prior to the rocket launch. The mesospheric region showed scattering in a narrow layer initially located at 79 km and largely stationary at that altitude for at least one hour prior to the rocket launch at 11:33 LST. The scattering was so localized in altitude that it appeared in only one range gate indicating a thickness of at the most 3 km. Immediately prior to the rocket launch the scattering region moved upwards to cover both the 79 km and the 82 km range gates.

The relative electron density irregularity ($\Delta N/N$) profile in different frequency bands observed by the rocket on the up leg is shown in Figure 2.

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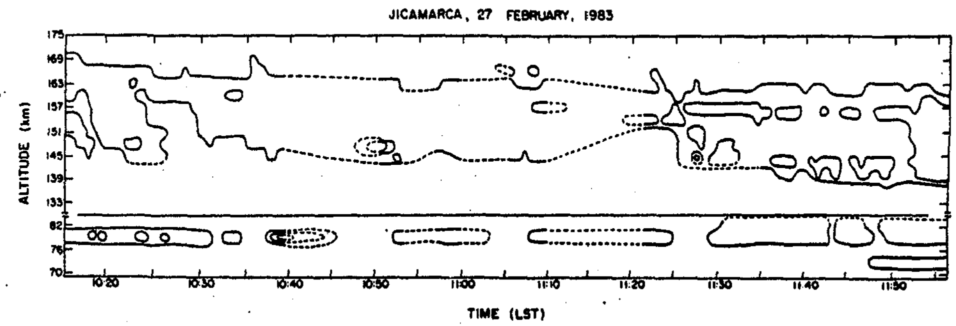

Figure 1. Jicamarca radar echo power map from February 27, 1983 between 10:15 and 11:56 LST. Data from the upper mesosphere (70-82 km) and the upper E region (133-175) were recorded intermittently. The power level visually observed during times of no data are indicated by the broken contours. Contour levels indicate signal-to-noise levels of 1, 5 and 10. Note the break in the altitude scale between 82 and 133 km.

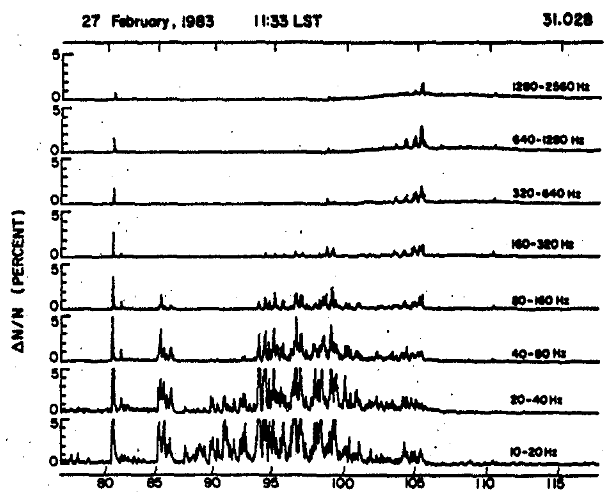

Figure 2. Relative electron density variations in different frequency bands in the altitude region 75 to 115 km for the rocket (Nike Orion 31.028) launched on 27 February 1983. The signal is filtered by narrow band filters and rectified. The peaks at 81 and 82 km are attributed to instrumental effects.

The electrojet region is clearly visible between about 90 km and 106 km. In addition, there appears to be a narrow region of irregularities at about 86 km. The altitude of the irregularities is higher than the scattering layer observed by the Jicamarca radar. However, the horizontal distance separating the two observations and the observed altitude change in the radar data at the time of the rocket launch makes it reasonable to argue that the same layer was observed in the two data sets.

RADAR DATA

The P/C correlation was calculated for the February 27 data set and was found not to be negative but showed distinct, unexplained, features as can be seen in Figure 3. Notice that the short-lived increase in echo power at 11:31 LST at the 79 km altitude is accompanied by a steady increase in correlation time that lasts until the scattered power has decreased to its pre-enhancement level. Other short-lived bursts of scattered power are accompanied by similar unexplainable behavior of the signal correlation time. Typical correlation time seen in Figure 3 is about 0.3 s. In particular this is true for both the two altitude ranges 79 and 82 km at the time of the rocket launch.

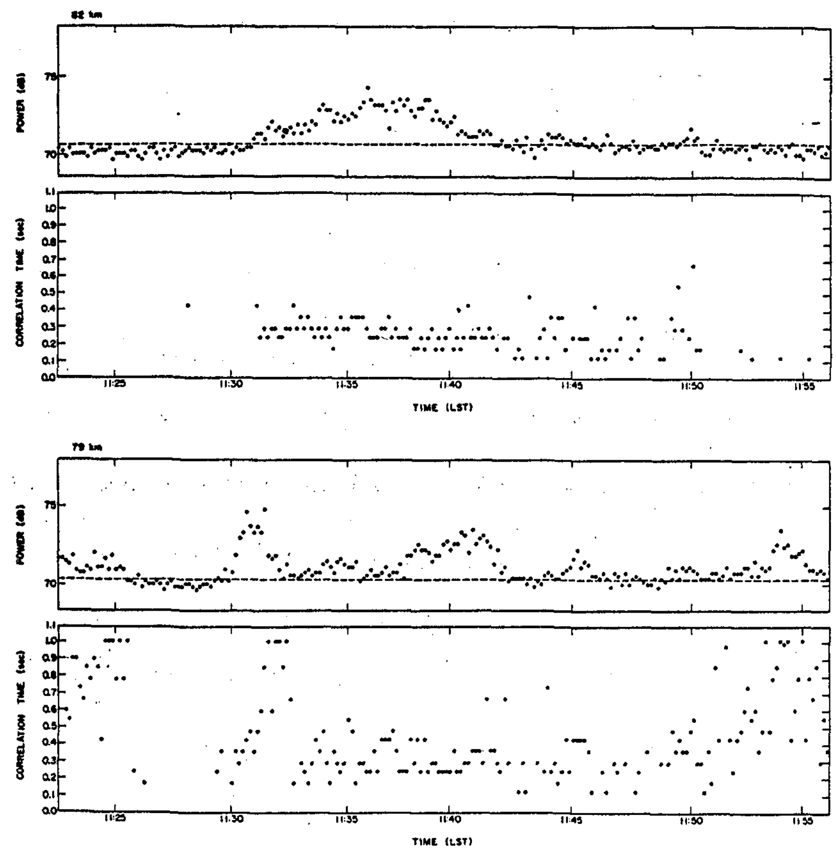

Figure 3. Jicamarca radar signal power and signal correlation time for the 79 and 82 km altitude bins between 11:23 and 11:56 LST on 27 February 1983. Time resolution is about 10 s. Correlation time is calculated when the ratio between the zero and first lag in the autocorrelation function is less than 10.

The present experiment which used only two antenna sections spaced in the east-west direction could detect vertical velocity variations in the east-west direction only by use of the interferometer method (ROYRVIK, 1983). Some examples of vertical velocity differences were found in the present data set and two examples are presented in Figure 4. There is a phase shift accompanying the shift in frequency across the spectral peaks. The east-west size of these structures can be roughly estimated from the total phase shift (ROYRVIK, 1983) and in the present case the size is about 600 m. It has been suggested (ROYRVIK, 1983) that the observations of differential vertical velocities are manifestations of Kelvin-Helmholtz vortices and thus presumably are related to the development of turbulent layers.

ROCKET DATA

The rocket data of $\Delta N/N$, considered here, came from the high-gain channel of the fine-structure probe experiment. Detailed examination of the record between 70 km and 90 km show a single region of irregularities between 85.0 and 86.4 km. The two peaks at 81 and 82 km, visible in Figure 2, are attributed to instrumental effects. Spatial power spectra of the relative density fluctuations were calculated from 2048 data points covering a spatial range of about 600 meters. It is clear that the spectral power of three meter irregularities (500 Hz) is close to or below the noise level even in the region of strong irregularities at 86 km. We thus depend on interpolation of the spectrum of longer wavelengths to calculate the scattered power at the three meter wavelength. The first three spectra in Figure 5 cover the 1400 meter vertical extent of the region of enhanced irregularities. The last spectrum is apparently the noise-level spectrum from the region immediately above the layer of irregularities. At frequencies above 200 Hz (corresponding to 7.5 m spatial wavelength) the spectra are below noise level, but below this

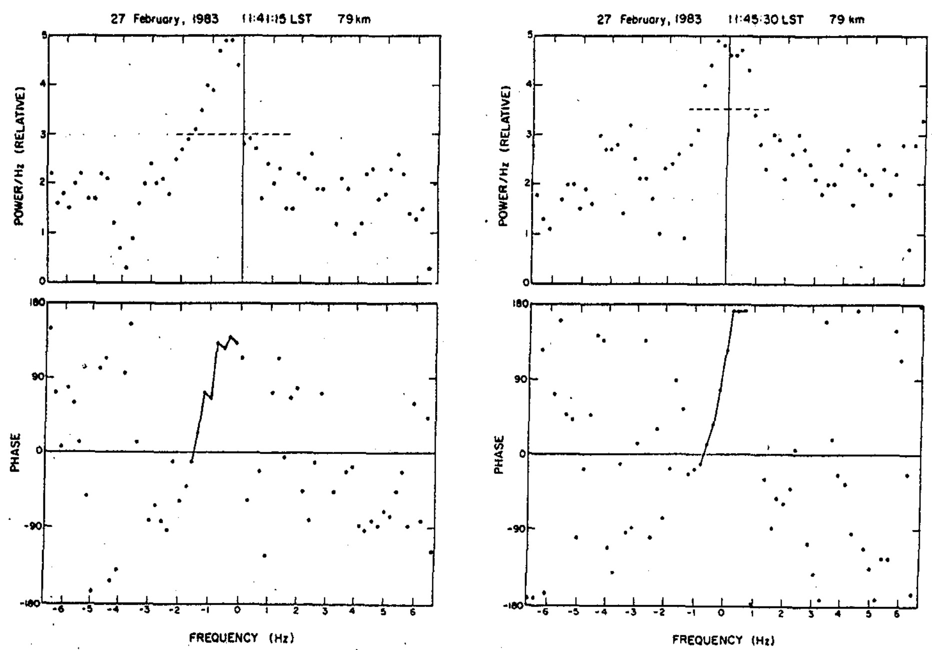

Figure 4. Jicamarca radar cross spectra from 11:41:15 LST and 11:45:30 LST on 27 February 1983. The broken line in the power spectra indicates an upper estimate of the noise level. The phases of the spectral components exceeding this noise level have been joined by a solid curve.

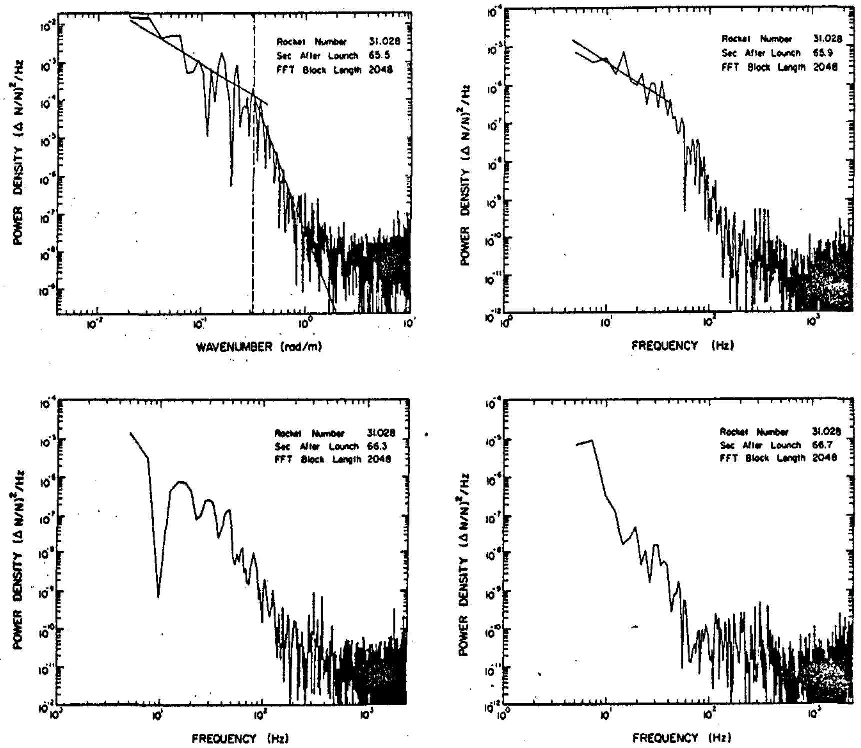

Figure 5. Spectra of relative electron density variations ($\Delta N/N$) in the scattering layer observed by the probe experiment on 27 February 1983 between 85.2 and 86.6 km altitude. The first spectrum has been shown in units of wavelength assuming a rocket velocity of 1.5 km. The three remaining spectra are in units of Hz. The last spectrum is from a region of no detectable turbulence.

frequency there is a marked increase in power above the noise level. This is consistent with the irregularity profiles shown in Figure 2.

Turbulence theory (TATARSKII, 1971) predicts a spectral index of -5/3 in the inertial subrange of turbulence. Figure 5 shows, however, that there is a noticeable break in the spectral slope at about 50 Hz corresponding to a wavelength of about 30 m. At lower frequencies (longer wavelengths) the spectral slope -5/3 fits the observed spectra quite well. At higher frequencies (shorter wavelengths) the spectral slope is much steeper, apparently close to a slope of -7.

DISCUSSION

Several comparisons can be made between the VHF radar data and the rocket electron-density measurement. The most straightforward is to compare the radar scattering cross section per unit volume (σ) measured by the radar to the cross section calculated from the spectrum of irregularities observed by the rocket. We adopt the formula for the radar reflectivity from VANZANDT et al., (1978)

$$\sigma = \frac{9\pi}{2} \frac{c\, k_B\, B\, (T_c + T_{rx}/\alpha)}{\alpha\, P_t\, F_r\, A} \left(\frac{r}{\Delta r}\right)^2 \left(\frac{S}{N}\right) \tag{1}$$

where c is the velocity of light and k_B is the Boltzmann's constant. The definitions and values of the radar parameters are given in Table 1. From Figure 1 it is seen that the signal-to-noise ratio $(\frac{S}{N})$ varies between 1 and 10 in the altitude range around 80 km. If we assume what seems to be a typical S/N ratio of 2 for the time of the rocket launch we calculate:

$$\sigma = 2 \times 10^{-18}\ m^{-1}$$

We have used $A = 4.2 \times 10^4\ m^2$ since only two quarter-sections of the antenna were used for reception.

To calculate the reflectivity resulting from the rocket irregularity data we start with the formula given by OTTERSTEN (1969)

$$\sigma\ (k) = \frac{\pi^2}{2}\ k^4\ \phi_n\ (\underline{k}) \tag{2}$$

where k is the wave number and $\phi_n\ (\underline{k})$ is the spectrum representing the three dimensional refractive index field. The rocket experiment, however, measures the one-dimensional relative variation in the electron density $S_N(k)/N^2$ and we will have to modify (2). The relationship given by WOODMAN and GUILLEN (1974) relates the spectra of the refractive index and the spectra of electron density variations $(\phi_N(\underline{k}))$ as

$$\phi_n\ (\underline{k}) = \frac{f_p^{\ 4}}{4\ f^4}\ \frac{\phi_N(\underline{k})}{N^2} \tag{3}$$

Here f_p is the plasma frequency and f is the frequency of the probing radio wave. So, for the mesosphere, we get

$$\sigma\ (\underline{k}) = \frac{\pi^2}{2}\ k^4\ \frac{f_p^{\ 4}}{4\ f^4}\ \frac{\phi_N(\underline{k})}{N^2} \tag{4}$$

Note that $\phi_N(\underline{k})$ is a three-dimensional spectrum, whereas the one measured by the rocket is a one-dimensional spectrum. OTTERSTEN (1969) has discussed this conversion in detail and if the spectra are isotropic and follows the negative power law one can substitute for $\phi_N(\underline{k})$

$$\phi_N\ (\underline{k}) = -(n)\ \frac{1}{4\pi}\ k^{-2}\ S_N\ (k) \tag{5}$$

where $S_N(k)$ is the one-dimensional spectrum measured by the rocket. By substituting (5) into (4) we end up with the appropriate relationship between the radar reflectivity and the rocket irregularity spectrum

$$\sigma\ (k) = -n\ (\frac{\pi}{8})\ k^2\ \frac{f_p^{\ 4}}{4\ f^4}\ \frac{S_N\ (k)}{N^2} \tag{6}$$

The question of isotropic irregularity spectrum cannot be independently determined in this case, however, we feel justified in assuming isotropy since previous radar experiments (COUNTRYMAN and BOWHILL, 1979, FUKAO et al., 1980, and and ROYRVIK, 1983) have shown isotropic coherent scattering of VHF radio waves at and above 80 km in the mesosphere.

It is clear from Figure 5 that the spectral component at 3 m (k = 2.1 rad/m) is below the noise level, however, fitting of a power law with spectral index n = -7 gives an estimated power of 3×10^{-10} $(\Delta N/N)^2$ m/rad. This value when substituted into (6) gives

$$\sigma = 4 \times 10^{-18}\ m^{-1}$$

in good agreement with the value calculated from the radar data.

According to elecmentary isotropic turbulence theory (TENNEKES and LUMLEY, 1972) the energy dissipation rate can be related to turbulent velocity and to the scale size of the turbulence through

$$\varepsilon \sim v^3/1 \tag{7}$$

For stationary turbulence it must be assumed that the energy dissipation rate is equal to the rate of energy input at the largest scale of turbulence so that $\varepsilon \sim V^3_B/L_B$. HOCKING (1982) has discussed this point and suggested the relationship

$$\varepsilon \approx 2.9\ \overline{v^2}\ f_B \tag{8}$$

where f_B is the Brunt-Vaisala frequency (in Hz) and v is the horizontal rms velocity. The total rms value of the line-of-sight $\tilde{v}$elocity variations can be obtained from the Doppler spectrum of the scattered signal through the equation

$$V_z = \frac{\lambda}{2} f_{1/2}\ (2\ \ln\ 2)^{-1/2} \tag{9}$$

where $f_{1/2}$ is the half width of the spectrum (BRIGGS, 1980). It is important to verify that the spectral width is due to turbulence rms velocities only, and do not contain contributions from a host of other phenomena. This has been done.

The correlation half-time, which is the quantity calculated is quite variable at least for the 79 km range gate (Figure 3), however for the 82 km range time it is fairly stable at about 0.3 s giving a half width of the Doppler spectra of about 0.6 Hz. Substituting this value into equation (9) we calculate

$$V_z = 2.2\ m/s.$$

TENNEKES and LUMLEY (1972) have suggested that due to the anisotropy at the largest scales of turbulence the vertical rms velocity is a factor $\sqrt{2}$ smaller that the horizontal rms velocity. We use this assumption when calculating the energy dissipation rate from equation 8, and get $\varepsilon = 0.05\ W\ kg^{-1}$.

The inner scale of turbulence (Kolmogorov microscale) $\eta = (\nu^3/\varepsilon)^{1/4}$ is related to the energy dissipation rate (ε) and the kinematic viscosity (ν). Using values from the U.S. Standard Atmosphere model for the kinematic viscosity we get $\eta = 3.15$ m at 85.5 km. According to TENNEKES and LUMLEY (1972) the velocity spectrum will be in the inertial subrange if $k_\eta < 1$ and in the dissipation subrange for $k_\eta > 1$. Thus it is expected that the change-over between a -5/3 power law spectrum and a much steeper spectrum will occur at $k = 0.31\ m^{-1}$. This value is marked in Figure 5 and appears to be in good agreement with the observed change in the spectral slope.

Finally, we can compare the outer scale of turbulence, or the turbulent layer thickness, estimated from the two data sets. For the radar data we use the equation

$$L_B \sim 1.1\ \overline{v}/f_B = 800\ m$$

where f_B is the Brunt-Vaisala frequency corresponding to a period of 5 min. The 800 m layer thickness compares reasonably well with the 1.4 km region of irregularities observed with the rocket as shown in Figure 2. The difference may be due to the horizontal difference separating the two observation volumes, but it may also be due to the fact that turbulence close to the outer scale L_B is not isotropic and the rms velocity observed in the vertical antenna is not identical to the shear velocity across the turbulent layer.

SUMMARY AND CONCLUSIONS

Data from the Jicamarca VHF radar and from a Langmuir probe fine-structure on a Nike Orion rocket launched from Punta Lobos, Peru have been compared. A single mesospheric scattering layer was observed by the radar. The Langmuir probe detected irregularities in the electron-density profile in a narrow region between 85.2 and 86.6 km. It appears from a comparison between these two data sets that turbulence in the neutral atmosphere is the mechanism generating the refractive index irregularities.

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