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S. Fukao and T. Sato

R. M. Harper

S. Kato

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S. Fukao and T. Sato

Department of Electrical Engineering, Kyoto University, Kyoto 606, Japan

R. M. Harper

Department of Space Physics and Astronomy, Rice University, Houston, Texas 77001

S. Kato

Ionosphere Research Laboratory, Kyoto University, Uji 611, Japan

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Using the VHF radar (49.92 MHz) at Jicamarca (12.0°S, 76.9°W), radio wave scattering from the tropical mesosphere was observed for more than 60 hours on November 14–16, 1977. The 60- to 90-km region was probed at 2.5-km intervals in two antenna beam directions: the vertical and 3.45° from the zenith to the west. Strong aspect sensitive scattering that is accompanied by a marked positive correlation between the temporal variation of the echo power and the signal correlation time is observed below about 75 km as in previous measurements. Above that altitude, the correlation becomes negative while the scattering is virtually isotropic. This difference appears to be directly related to the stability of the atmosphere, and enhanced reflectivity regions seem to be narrow structures that are horizontally stratified below 75 km. The rms turbulent velocity fluctuations generally increase above 75 km. Signal correlation time depends upon the period of data used to calculate power spectra in the period of 10–60 s, suggesting that there exist substantial velocity fluctuations on short time scales.

1. INTRODUCTION

The MST (mesosphere-stratosphere-troposphere) radar offers a promising new way of understanding the dynamic process occurring in the mesosphere [*Woodman and Guillen,* 1974]. We will not restate the wide-ranging results obtained to date; readers are referred to recent papers by *Balsley and Gage* [1980], *Gage and Balsley* [1978], and *Röttger et al.* [1978].

The technique makes use of radio wave scattering from fluctuations in the index of refraction. Two types of scattering have been identified in the troposphere and stratosphere. One is the scattering from refractive index fluctuations due to small-scale (one half the transmitted wavelength) inertial sub-range turbulence [*VanZandt et al.,* 1978]. The other is Fresnel or diffuse reflection from narrow structures of enhanced reflectivities [*Gage and Green,* 1978; *Röttger and Liu,* 1978].

Röttger et al. [1979], using the high-resolution SOUSY radar, have reported that there are basically three types of turbulence structure in the mesosphere: narrow structures they called blobs and sheets, differentiated by their lifetimes, of a few hundred meters thickness predominate in the 60- to 70-km region, while more diffusive layered structures of the order of 1 km thick preferentially occur above 70 km. *Czechowsky et al.* [1979], in addition, observed considerably thicker scattering layers above 80 km and a marked seasonal variation in the height distribution of scattering using the same radar.

Similarity between the coherent VHF scatter and partial reflection at much lower frequencies has been pointed out over the past few years [*Cunnold,* 1975; *Rastogi and Bowhill,* 1976*a, b*; *Vincent and Belrose,* 1978; *Hocking,* 1979]. *Fukao et al.* [1979] recently reported an aspect sensitivity in power scattered from lower mesospheric heights at Jicamarca, with a vertical antenna receiving from 2 to 10 times the mean power of an off-vertical antenna below 75 km. These investigations generally support a conjecture that, at least at some heights,

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the VHF scatter and partial reflection are due to the same scattering mechanisms.

This paper will discuss some statistical features of mesospheric scattering, especially echo power and signal correlation time (or, equivalently, spectral width) of these echoes, that are observed with the VHF radar (49.92 MHz) at Jicamarca/Peru (12.0°S, 76.9°W) in the tropical region during a 3-day experiment in November 1977. It will be shown that below 75 km, the mean scattered power was aspect sensitive and that in this region, echo power and signal correlation time were positively correlated, while above 75 km, the scattered power showed no aspect sensitivity, and the echo power and signal correlation time tended to be negatively correlated. The limited data base and poor height resolution of the Jicamarca radar must be recognized in interpreting these results.

2. OBSERVATIONAL TECHNIQUE AND DATA PROCESSING

The tropical mesosphere was probed using the Jicamarca radar for more than 60 hours from 1144 LT on November 14 to 2400 LT on November 16, 1977. The observational technique is a refinement of that described by *Harper and Woodman* [1977] and *Fukao et al.* [1978; 1979].

Thirteen heights spaced at 2.5-km intervals over the 60- to 90-km region were simultaneously observed in each of two antennas. One antenna beam was directed toward the position that is thought to be the true zenith according to a theoretical calculation of *Fleisch* [1976]. The other beam was tilted from the zenith by an angle of 3.45° and 0.15° toward the west and north, respectively. Hereafter, the former direction will be called the 'vertical' beam direction and the latter the 'off-vertical' beam direction.

A sequence of pulses of 25-μs width at 1-MW peak output power (nominal) were transmitted on both antennas with an interpulse period (IPP) of 1 ms. Figure 1 illustrates a sequence of such pulses, consisting of 18 IPP's. In each sequence, no pulse was transmitted at the 9th and 18th IPP's. The phase of the pulses was flipped by 180° (or π radians) after every pulse in order to eliminate any system dc offset. At each height the sampled signal was coherently integrated over 7 sequences (or 126 ms) in the following way:

$$I = \sum_{j=1}^{7} \{(I_{1j} - I_{2j} + \cdots - I_{8j}) - (I_{10j} - I_{11j} + \cdots - I_{17j})\} \quad (1)$$

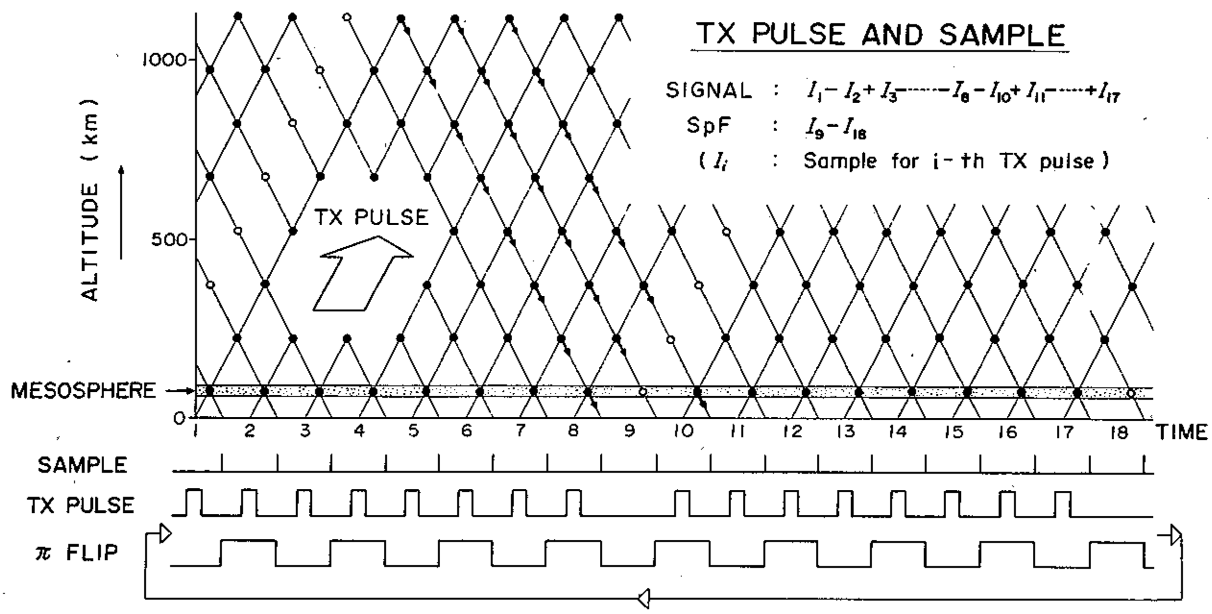

Fig. 1. Altitude-time diagram for a unit sequence of transmit (TX) pulses and samples. Sampling is done at 13 levels in the mesosphere of 60–90 km. No TX pulse is transmitted at the 9th and 18th IPP's. The pulse phase is flipped by 180° (or π radians) after every pulse. Each dot indicates a region where radio echo arises in response to a TX pulse. The arrows show that ionospheric echoes due to preceding TX pulses contaminate the desired mesospheric echo.

where I_{ij} is the sample for the ith pulse in the jth sequence. The clutter echoes from the ionospheric region of about 200–1500 km that were not mixed with mesospheric echoes would appear in the 9th and 18th samples, I_{9j} and I_{18j}, so that the value

$$I_{SF} = \sum_{j=1}^{7} (I_{9j} - I_{18j}) \qquad (2)$$

was used to look for coherent spread F echoes that would contaminate the desired mesospheric echoes. After one coherent integration was done, the transmitter was turned off for 18 IPP's (or 18 ms), and the sky noise was sampled in the same way as when the transmitter was on; i.e.,

$$I_N = (I_1 - I_2 + \cdots - I_8) - (I_{10} - I_{11} + \cdots - I_{17}) \qquad (3)$$

The quantities I_{SF} and I_N were used to monitor the background and aliased noise. Spread F echoes were observed only at night. There were only a few enhanced noise bursts of less than 1 min duration during the 60-hour experiment. Radar malfunction occurred from 1235 to 1420 LT on November 16. The time sequence of the samples I in the good data periods was divided into consecutive sections of 7.2-s period, and 50-point Doppler spectra were calculated with a fast Fourier transform program [*Singleton*, 1969]. Four consecutive 7.2-s spectra were then summed incoherently to give one spectra about every 30 s.

Figure 2 shows a typical altitude variation of such spectra obtained in each of two beam directions. Each spectrum is an average of four of the 30-s spectra. As can be seen from Figure 2, the mesospheric Doppler spectra are, in general, singly peaked. Then the Doppler spectra can be parameterized by three lowest-order moments, i.e., the echo power (zeroth order), mean Doppler shift (first order), and spectral width (second order). Considerable statistical fluctuation was usually observed in each spectral structure. Hence each Doppler spectrum was smoothed with a Hanning window function before being transformed to the corresponding autocorrelation function; the time to 0.5 correlation was defined as 'signal correlation time.' According to this definition the spectral width in s^{-1} corresponds to one half the inverse of the signal correlation time in seconds.

Although most of the mesospheric spectra are singly peaked, a double-peak spectrum occasionally appears. If the frequency gap between the two spectral peaks is larger than the width of each of the two peaks, the signal correlation time for the double-peak spectra is determined largely by the gap rather than the width of each spectral peak. It is noted that no preference to specific altitudes is observed in occurrence of the double-peak spectra.

In the following, attention will be focused on two of the three parameters, i.e., the echo power and signal correlation time (or, equivalently, spectral width), to investigate some statistical properties of the mesospheric scattering. Wind velocities, which are inferred from the mean Doppler shift, will be reported elsewhere [*Fukao et al.*, 1980].

3. SCATTERING CHARACTERISTICS

3.1. *Echo power*

The present Jicamarca observations confirm basic features of the mesospheric echo power that have been reported in previous Jicamarca observations [*Woodman and Guillen*, 1974; *Rastogi and Woodman*, 1974; *Rastogi and Bowhill*, 1976*a*, *b*; *Fukao et al.*, 1979], e.g., below 85 km, the mean echo power generally varies with time according to the solar zenith angle, and no mesospheric echoes were received at night. Above 85 km, sporadic spiky echoes which appear to be due to meteor trails are frequently observed.

Figure 3 shows the weight profile of the mean echo power that was observed in each daytime period. The solid curve indicates echo power obtained in the vertical beam direction, whereas the broken curve is the power in the off-vertical beam direction. The white noise (or the cosmic noise) levels are also shown by the vertical lines at the bottom of the figure. As is shown in the figure, a slight drift of the noise level occurred during the experiment. This seems to be caused by a temporal gain change of the receivers connected to each antenna. The difference of the noise levels between the beam directions should be considered when the two echo powers are compared. Results shown in Figure 3 indicate a marked day-to-day variation of the vertical structure of the echo power. A maximum of the echo power observed at 75–77.5 km on November 14 descends to 72.5 km on November 16, 1977. On the third day, another peak appears around 80 km. It is unlikely that any large-scale dynamical instability was responsible for the second peak, since the mean zonal wind shows

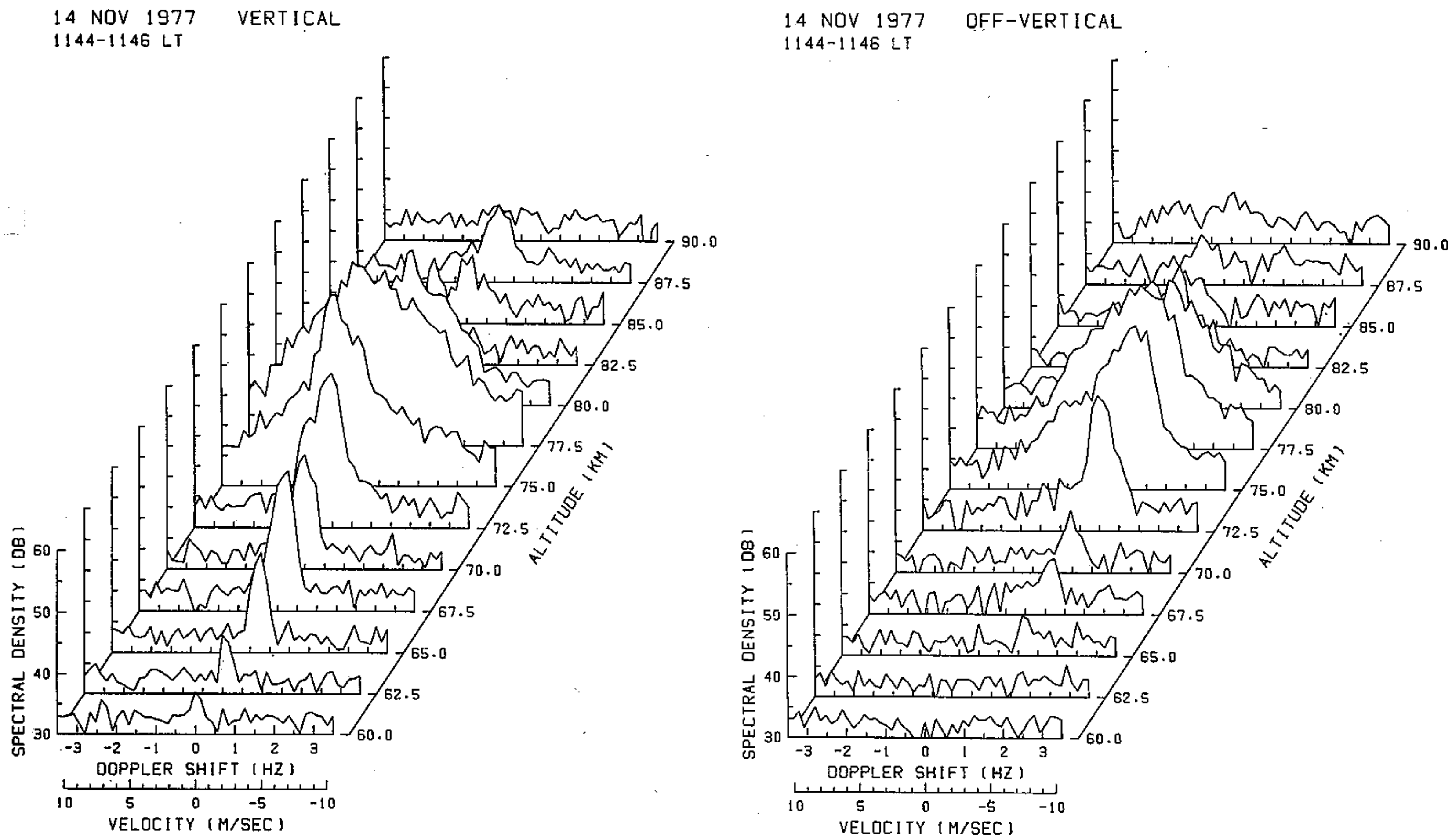

Fig. 2. Doppler spectrum versus altitude in the vertical and off-vertical beam directions obtained by the Jicamarca radar at 1144–1146 LT on November 14, 1977. The ordinate is relative power in decibels with an arbitrary reference level. The abscissa is marked in terms of both the Doppler frequency and the equivalent line-of-sight velocity.

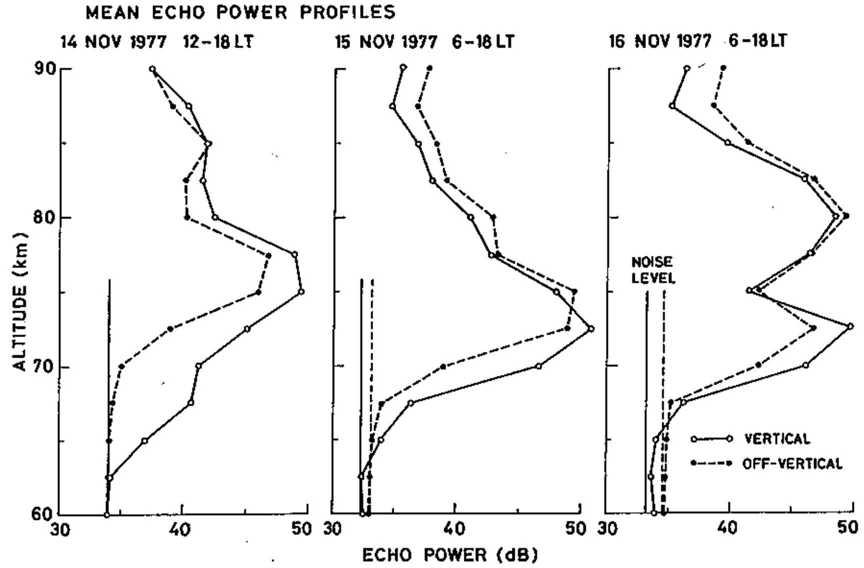

Fig. 3. Mean echo power versus altitude obtained in each daytime period on November 14–16, 1977. The solid and broken curves are for the vertical and off-vertical beam directions, respectively. The corresponding noise values are given by the vertical lines.

a fairly stable profile over the 3 days [*Fukao et al.,* 1980].

The echo power in the vertical beam is clearly larger than that in the off-vertical beam in the region below about 75 km, as was observed in a 1-day observation in May 1974 [*Fukao et al.,* 1979]. Similar aspect sensitivity has recently been reported by *Röttger et al.* [1979] at the SOUSY radar and also from 2- to 3-MHz partial reflection studies by *Vincent and Belrose* [1978] and *Hocking* [1979]. Figure 4 shows the ratio of the mean vertical power to the mean off-vertical power versus altitude. In calculating this ratio the echo-power ratio was multiplied by the noise-power ratio of the vertical to off-vertical beam directions in order to adjust for the gain difference in the two antennas. The ratio was not plotted at altitudes where the average signal-to-noise ratio in one or both of the two beam directions fell below 0.1. The echo-power ratio shows a marked difference between above and below 75 km. Despite a substantial day-to-day variation, the ratio below 75 km is generally 5–15, while it seems to be nearly unity above around 75 km. The ratio is slightly larger than unity on November 14 at all heights.

The contrast of the aspect sensitivity between above and below 75 km may give an important clue as to turbulence structures responsible for the scattering. Weak Fresnel or diffuse reflections may principally contribute to the echo power in the lower mesosphere [*Fukao et al.,* 1979; *Röttger et al.,* 1979].

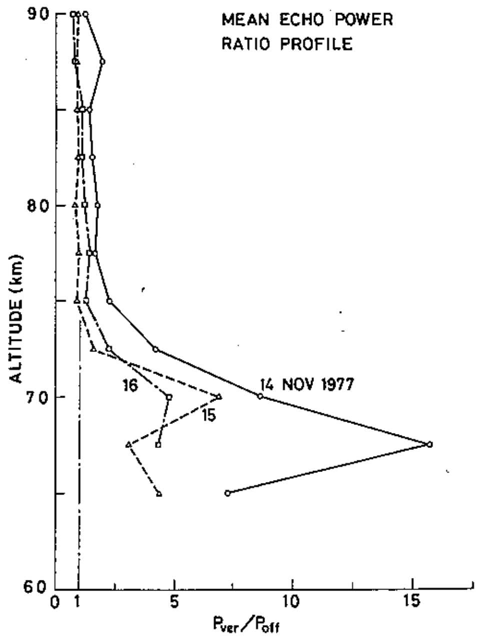

Fig. 4. Mean echo power ratio of the vertical to off-vertical beam directions against altitude. No value is plotted if the average signal-to-noise ratio fell below 0.1 in one or both of the beam directions. Averaging is done over the same periods as in Figure 3.

3.2. *Signal correlation time*

First, the dependence of the signal correlation time (or spectral width) upon the time window used to calculate each power spectrum is examined. The shortest period over which power spectra can be determined without suffering from significant fluctuations seems to be about 7 s, which is several times as large as signal correlation times reported for the mesospheric scattering [*Woodman and Guillen,* 1974; *Rastogi and Bowhill,* 1976*b*; *Fukao et al.,* 1979]. Hence power spectra were calculated using time windows in the range of 7.2–60 s. Figure 5 shows the correlation time and spectral width thus obtained in the vertical and off-vertical beam directions versus length of time window used to calculate the power spectra. The results are given for two altitude levels, 75 and 77.5 km, where signal-to-noise ratios are fairly large. At these altitudes the echo power shows virtually no aspect sensitivity, as is shown in Figure 4.

Two features are worth noting in Figure 5. First, the spectral width varies with the time window, increasing with increasing period. The width is shown to vary by about 20% in the period range under consideration. This suggests that the effect of data length, or observation time, should be considered in evaluating the spectral width. The following explanation could be given for this effect

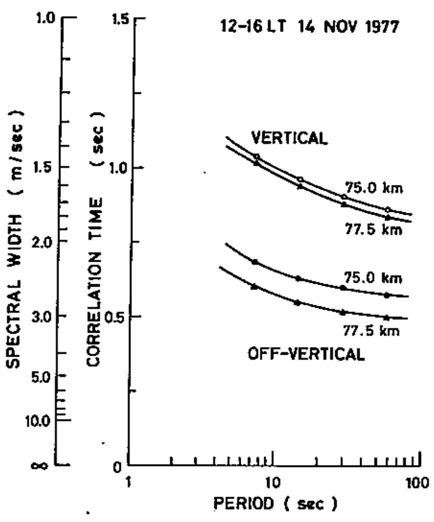

Fig. 5. Signal correlation time and spectral width versus periods used to calculate power spectra at 75 and 77.5 km, where the signal-to-noise ratios are fairly large. Each curve is an average value over 1200–1600 LT on November 14, 1977. The spectral width is given by the equivalent rms velocity fluctuations in meters per second.

[e.g., *Nathanson,* 1969]. An instantaneous spectrum may result from a group of scatterers with internal motion, but also the Doppler shift of the instantaneous spectrum shifts slowly with time. The spectrum inferred from a period of data long enough to include these slow bulk motions would have a variance equal to the sum of the variances for the instantaneous spectrum and slow bulk motions.

The slow bulk motions necessary to explain the observed decrease in correlation time are roughly consistent with the short-period (≈5–15 min) velocity oscillations of amplitude of ± 1 m s^{-1} that are always observed at mesospheric heights over Jicamarca, although other much shorter period motions cannot be ruled out.

Second, there is a marked difference in the spectral width between the vertical and off-vertical beam directions, the off-vertical spectrum being about 1.5 times wider than the vertical one. There is no aspect sensitivity in the echo power at these altitudes. This difference may be due to an anisotropy of the internal turbulent motions, but owing to Jicamarca's poor height resolution, the spectral broadening in the off-vertical antenna is also possibly due to scatterers extended in height in the presence of a background wind. A scattering layer 1 km thick in the presence of a 10 m s^{-1}/km vertical gradient in the horizontal wind would roughly produce the observed broadening. Improved height resolution is extremely important in future measurements at Jicamarca.

The mean signal correlation time inferred from the 30-s periods of data is given versus altitude for the vertical and off-vertical directions in Figure 6. Data were not used in the average if their signal-to-noise ratios fell below 0.2, and no value was plotted in the figure at the altitudes where the number of available data was less than 10% of the total number of data. A more strict threshold was used for the signal correlation time than the echo power, since estimates of the signal correlation time have greater statistical fluctuations than the echo power. Figure 6 generally shows that the signal correlation time (or spectral width/velocity fluctuation) monotonously decreases (or increases) with increasing altitude. The mean value inferred is 1–1.5 s at the 65- to 70-km region, whereas it is of the order of 0.5 s at 85 km. Meteor trail echoes that have signal correlation times of the order of 0.1–0.2 s may influence the correlation time above 85 km. This increase in velocity fluctuations with altitude

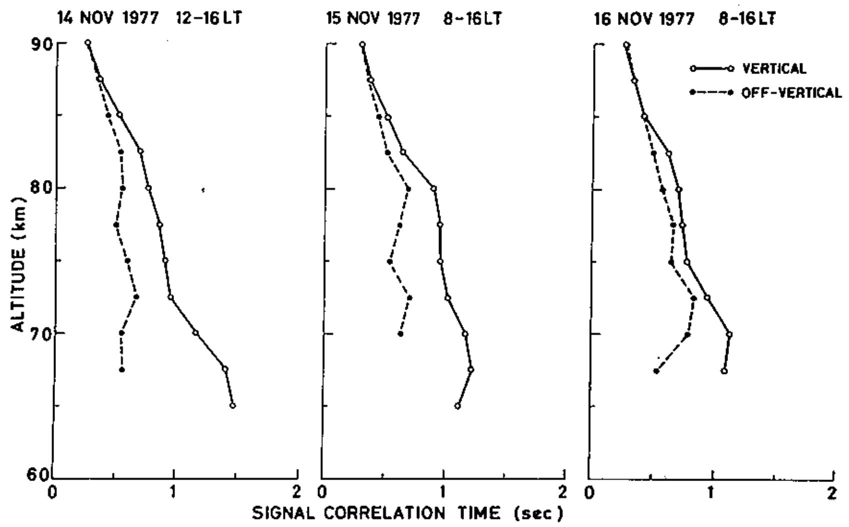

Fig. 6. Mean signal correlation time versus altitude obtained in each daytime period on November 14–16, 1977. The solid and broken curves are for the vertical and off-vertical beam directions, respectively.

seems to be consistent with studies of turbulence by *Zimmerman and Murphy* [1977] and roughly parallels the height variation of molecular diffusion and incoherent scatter correlation times. Similar altitude variation is also observed by the 54-MHz SOUSY radar [*Röttger et al.,* 1979]. They reported that narrow structures, i.e., blobs and sheets, predominantly occur at lower altitudes, while thick and diffusive layers occur at higher altitudes, concluding that the thicker structures are associated with a larger spectral width. In Figure 4 it is noted that no aspect sensitivity exists in echo power above 75 km, which is also consistent with the predominance of thicker and more diffusive turbulence structures there.

Another feature worth mentioning in Figure 6 is the difference of the signal correlation time noted between the two beam directions. The ratio of the vertical to off-vertical values is 1.2–2.0 at 70 km, approaching unity with increasing altitude. This is possibly due to the decreasing contribution of spectral broadening due to height gradients to the total spectral width as the inherent width of the signal becomes greater. The difference could also be due to a real anisotropy in the turbulence, but that cannot be determined owing to the poor height resolution.

4. DISCUSSIONS

Rastogi and Bowhill [1976*b*] reported a marked positive correlation between echo power and signal correlation time at an altitude of 70 km. On the other hand, a negative correlation between the echo power and the signal correlation time was pointed out by *Harper and Woodman* [1977], who observed a sudden decrease of the signal correlation time accompanied by a strong burst of the echo power at 75 km.

In the present observations, both types of correlation were simultaneously noticed, although each type in a different range of altitude. Figure 7 shows a temporal variation of the echo power together with the signal correlation time at 0700–1200 LT on November 16. At the lower altitudes, especially at 70 km, the Rastogi-Bowhill–type positive correlation prevails. On the other hand, the Harper-Woodman–type negative correlation is frequently seen at higher altitudes. For example, the temporal variation of echo power is opposite to that of the signal correlation time in the period of 0930–1100 LT at 77.5 and 80 km.

In order to derive a general sense of correlation between the echo power and the signal correlation time, all data available at each altitude are divided into 15 groups according to signal correlation time. Then the mean signal power for each correlation time was found, giving the graphs shown in Figure 8. All of the signal correlation time data used in this calculation are based upon the 30-s spectra with signal-to-noise ratios larger than 0.2. Only intervals in which at least 10 data points occurred are plotted. The most important feature noted in

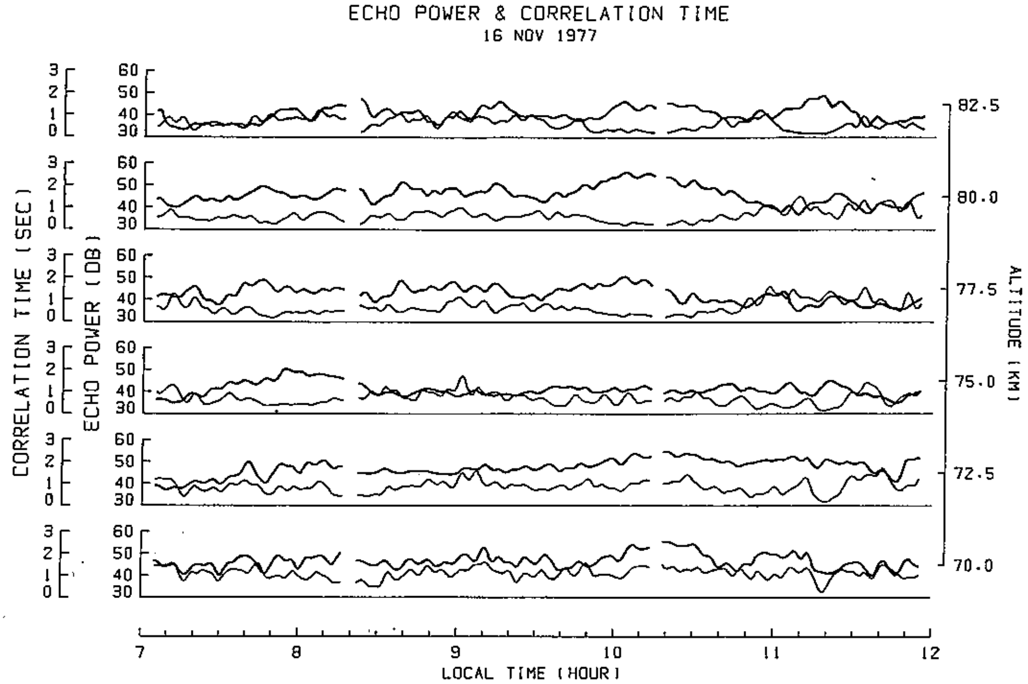

Fig. 7. A typical temporal variation of the echo power (heavy curve) and signal correlation time (light curve) at 0700–1200 LT on November 16, 1977.

the figure seems to be that the general sense of correlation between the echo power and the signal correlation time reverses from positive to negative with increasing altitude. The reversal generally occurs around 75 km, although individual data show a considerable scatter there. The standard deviation of individual data around the mean values plotted in Figure 8 is fairly large, their correlation coefficient being less than 0.5 in most cases. Despite this limitation, the general sense of correlation seems to be significant, since the 3 days data, which are independent of each other, show quite the same altitude variation.

Our ability to interpret these results is greatly limited by the poor height resolution of the Jicamarca radar. It should be noted that the altitude of the reversal coincides with the altitude below which a marked aspect sensitivity is seen in the scattering and above which isotropic scattering occurs. Above 75 km, a negative correlation is generally observed between the echo power and the signal correlation time. This could mean that more intense echo power is due to stronger velocity fluctuations. Hence this negative correlation suggests that the velocity fluctuations could be due to the atmospheric turbulence with a spatial scale of one half the radar wavelength.

Rastogi and Bowhill [1976*a*] have argued that the scattering cross section is independent of the intensity of turbulence in the inertial subrange but depends strongly on the turbulent intensity in the dissipative regime. Thus the observations appear to be consistent with Jicamarca's wavelength being in the dissipative regime at 75 km.

The mean echo power decreases above 75 km, until by 85 km it is roughly of the order of the incoherent scatter level due to 2.5×10^3 e/cm^3. The signal correlation time is also roughly equal to the expected incoherent scatter correlation time for this height. Thus it appears to us that turbulent enhanced electron density fluctuations are highly damped above 85 km, although the signal power we observe still fluctuates occasionally in a way which suggests nonthermal echoes. However, *Miller et al.* [1978] and *Czechowsky et al.* [1979] have observed strong thick scattering layers above 85 km at the Illinois and SOUSY radars, respectively.

Below 75 km, on the other hand, the increase in signal correlation time is observed to occur along with increased echo power. *Rastogi and Bowhill* [1976*b*] showed that the positive correlation could be explained if stronger turbulence were occurring in narrower layers. The turbulent layers had to be

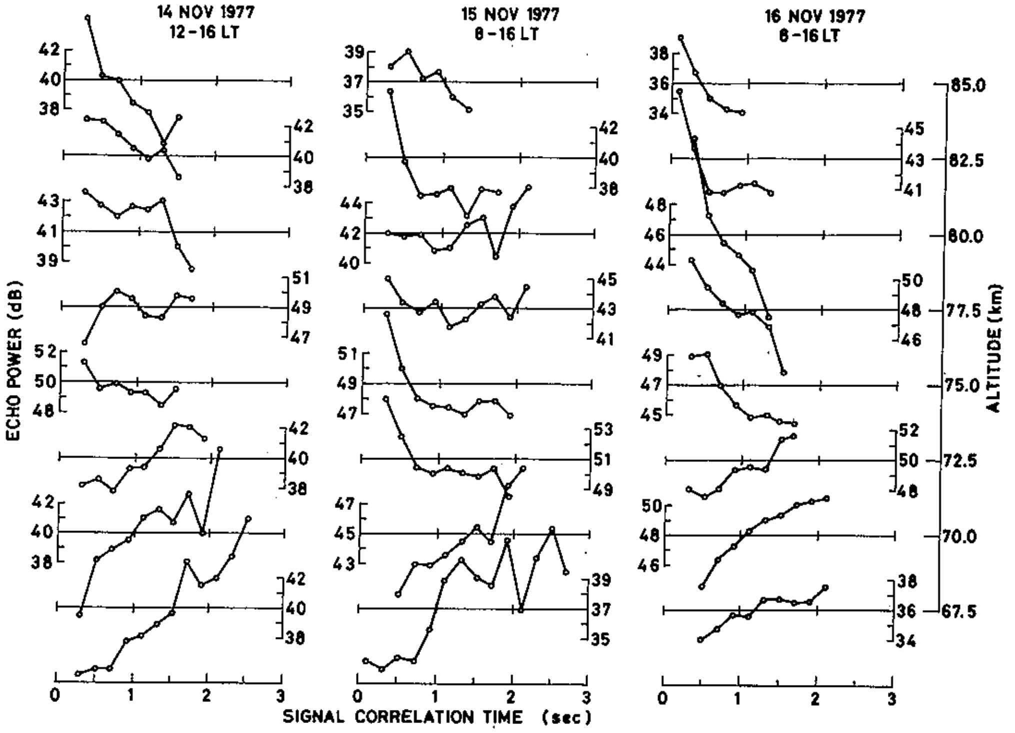

Fig. 8. Altitude variation of a relationship between the echo power and the signal correlation time. Each curve is an average value for each daytime period shown at the top of the diagram. See text for details.

of the order of a few tens of meters thick so that a range of wave number, with the turbulent enhancements strongly wave number dependent at Jicamarca's frequency, could contribute to the scattering.

We would like to call attention to the possibility that the scattering is occurring off of sharp gradients in the electron density over distances of the order of 1 wavelength, or 6 m. The aspect sensitivity that we observe either could be from very narrow regions of at least 1 km horizontal extent, possibly occurring at the nonturbulent/turbulent interfaces that are implied in the Rastogi-Bowhill model, or could be from smaller irregularities which have to be elongated by about a factor of 5 in the horizontal direction over the vertical direction. Each of these mechanisms has been invoked to explain the partial reflection observation at much lower frequencies [*Belrose,* 1970; *Vincent,* 1973], but at a scale size of 6 m the difficulties of sustaining a narrow interface against small-scale turbulence are much greater [*Röttger et al.,* 1979; *Fukao et al.,* 1979]. Röttger et al. suggest the possibility of diffuse reflection due to narrow turbulence structures of a medium horizontal scale of the order of 100 m, based upon the direct observation of the geometry of high-reflectivity regions.

The signal correlation time is observed to increase with echo power. This could possibly indicate that a relatively more stable nonturbulent/turbulent interface allows larger gradients to exist, as is seen in the lower stratosphere [*Gage and Green,* 1978; *Röttger and Liu,* 1978]. Thus the marked aspect sensitivity as well as positive correlation between the echo power and the signal correlation time below 75 km appears to be directly related to the static stability of the atmosphere [*Eskinazi,* 1975]. It could be concluded from the present observation that the lower mesosphere below about 75 km is, on the average, horizontally stratified without large vertical scale turbulent mixing that appears to predominate in the upper mesosphere above 75 km.

5. CONCLUSIONS

A 60-hour continuous observation of the tropical mesosphere was made with the VHF radar at Jicamarca on November 14–16, 1977. Statistical features of the echo power and signal correlation time (or spectral width) are presented in order to discuss the mesospheric scattering. The echo power generally maximizes around 70–80 km, and there is appreciable day-to-day change in its vertical structure. A marked aspect sensitivity of the echo power is noted in the region below about 75 km, where the echo power becomes 5–10 times larger in the vertical than in the off-vertical beam direction. No aspect sensitivity is observed above 75 km. The main conclusions are summarized as follows.

1. The correlation between the echo power and the signal correlation time generally reverses its sign from positive to negative at an altitude around 75 km. This altitude just coincides with the altitude below which a marked aspect sensitivity of the scattering is noticed. This suggests the presence of several scattering structures whose distribution or frequency of occurrence is a function of height.

2. The marked aspect sensitivity of the echo power as well as the positive correlation between the echo power and the signal correlation time noted below about 75 km seems to suggest a Fresnel or diffuse scattering mechanism and that the lower mesosphere below 75 km is, on the average, in static stability without kilometer-scale vertical turbulent mixing that appears to predominate in the upper mesosphere above 75 km.

3. Considering the altitude and aspect dependences of the signal correlation time, the rms turbulent velocity fluctuations generally increase with increasing altitude. The data suggest a change in the geometry of high-reflectivity regions, or turbulence structures, from narrow-sheet structures below 75 km to more diffusive layered structures above it. The mean echo power and correlation times above 85 km are near those expected from incoherent scatter.

Finally, the basic features reported in this paper agree with other observations, especially those made with the SOUSY radar at the same 50-MHz range [e.g., *Röttger et al.*, 1979]. The poor height resolution of the Jicamarca radar places severe limitations on the interpretation of the data. SOUSY measurements will not suffer from this limitation. An upgraded Jicamarca transmitter would allow Jicamarca to give important clues to the dynamics and structure of the tropical mesosphere.

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REFERENCES

Balsley, B. B., and K. S. Gage (1980), The MST radar technique: Potential for middle atmospheric studies, *Pure Appl. Geophys.*, in press.

Belrose, J. S. (1970), Radio wave probing of the ionosphere by the partial reflection of radio waves (from heights below 100 km), *J. Atmos. Terr. Phys.*, *32*, 567–596.

Cunnold, D. M. (1975), Vertical transport coefficients in the mesosphere obtained from radar observations, *J. Atmos. Sci.*, *32*, 2191–2200.

Czechowsky, P., R. Rüster, and G. Schmidt (1979), Variations of mesospheric structures in different seasons, *Geophys. Res. Lett.*, *6*, 459–462.

Eskinazi, S. (1975), *Fluid Mechanics and Thermodynamics of Our Environment*, 422 pp., Academic, New York.

Fleisch, D. A. (1976), Stratospheric scattering of radio waves and the Jicamarca radio telescope, M.S. dissertation, Rice Univ., Houston, Tex.

Fukao, S., S. Kato, S. Yokoi, R. M. Harper, R. F. Woodman, and W. E. Gordon (1978), One full-day radar measurement of lower stratospheric winds over Jicamarca, *J. Atmos. Terr. Phys.*, *40*, 1331–1337.

Fukao, S., T. Sato, S. Kato, R. M. Harper, R. F. Woodman, and W. E. Gordon (1979), Mesospheric winds and waves over Jicamarca on May 23–24, 1974, *J. Geophys. Res.*, *84*, 4379–4386.

Fukao, S., T. Sato, I. Hirota, and S. Kato (1980), A preliminary radar observation of long-period waves in the tropical mesosphere over Jicamarca, *J. Geophys. Res.*, *85*, 1955–1957.

Gage, K. S., and B. B. Balsley (1978), Doppler radar probing of the clear atmosphere, *Bull. Amer. Meteorol. Soc.*, *59*, 1074–1093.

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.

Harper, R. M., and R. F. Woodman (1977), Preliminary multiheight radar observations of waves and winds in the mesosphere over Jicamarca, *J. Atmos. Terr. Phys.*, *39*, 959–963.

Hocking, W. K. (1979), Angular and temporal characteristics of partial reflections from the *D* region of the ionosphere, *J. Geophys. Res.*, *84*, 845–851.

Miller, K. L., S. A. Bowhill, K. P. Gibbs, and I. D. Countryman (1978), First measurements of mesospheric vertical velocities by VHF radar at temperate latitudes, *Geophys. Res. Lett.*, *5*, 939–942.

Nathanson, F. E. (1969), *Radar Design Principles*, 626 pp., McGraw-Hill, New York.

Rastogi, P. K., and S. A. Bowhill (1976*a*), Scattering of radio waves from the mesosphere, 1, Theory and observations, *J. Atmos. Terr. Phys.*, *38*, 399–411.

Rastogi, P. K., and S. A. Bowhill (1976*b*), Scattering of radio waves from the mesosphere, 2, Evidence for intermittent mesospheric turbulence, *J. Atmos. Terr. Phys.*, *38*, 449–462.

Rastogi, P. K., and R. F. Woodman (1974), Mesospheric studies using the Jicamarca incoherent-scatter radar, *J. Atmos. Terr. Phys.*, *36*, 1217–1231.

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

Röttger, J., J. Klostermeyer, P. Czechowsky, R. Rüster, and G. Schmidt (1978), Remote sensing of the atmosphere by VHF radar experiments, *Naturwiss.*, *65*, 285–296.

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

Singleton, R. C. (1969), An algorithm for computing the mixed radix fast Fourier transform, *IEEE Trans. Audio Electroacoust.*, *AU-17*, 93–103.

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

Vincent, R. A. (1973), The interpretation of some observations of radio waves scattered from the lower ionosphere, *Aust. J. Phys.*, *26*, 815–827.

Vincent, R. A., and J. S. Belrose (1978), The angular distribution of radio waves partially reflected from the lower atmosphere, *J. Atmos. Terr. Phys.*, *40*, 35–47.

Woodman, R. F., and A. Guillen (1974), Radar observations of winds and turbulence in the stratosphere and mesosphere, *J. Atmos. Sci.*, *31*, 493–503.

Zimmerman, S. P., and E. A. Murphy (1977), Stratospheric and mesospheric turbulence, in *Dynamical and Chemical Coupling*, edited by B. Grandal and J. A. Holtet, pp. 35–47, D. Reidel, Hingham, Mass.