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RADAR MEASUREMENTS OF GRAVITY WAVES IN THE LOWER IONOSPHERE

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Some characteristic parameters of gravity waves at D and E region heights such as amplitude, frequency spectrum and spatial properties can and have been measured by means of VHF radars. One of the techniques makes use of ionization trails produced by meteors as tracers of the neutral atmosphere motions in the region from 80 to 100 km. A recently developed technique at the Jicamarca Radio Observatory uses background enhanced fluctuations in the dielectric properties of the medium as tracers of the neutral motions in the region between 60 and 85 km. Profiles of the velocity field can be obtained continuously with a time resolution of the order of a minute allowing observations of gravity waves from its lowest periods, of the order of a few minutes, to tidal periods. Gravity waves in the lower F region have also been detected using incoherent scatter techniques. The methods, potential and limitations of the above mentioned techniques are reviewed as well as some of the results obtained.

1. Introduction

We briefly review existing radar techniques capable of observing gravity waves at the D and E region heights of the earth's upper atmosphere, and include some of the results obtained using these techniques.

Free electrons existing at D and E region heights can be used as tracers of neutral atmospheric phenomena. The electrons are strongly coupled to the neutral gas, either directly through electron-neutral collisions, or, indirectly, through Coulomb interaction with the ions, the ions in turn being coupled to the neutral background through ion-neutral collisions. These free electrons are capable of producing radar echoes as reflections or from scattering of the illuminating electromagnetic wave. Reflections are produced whenever the electron density is sufficiently high to have a plasma frequency equal to or higher than the frequency of the radar wave. This is the case with dense meteor trails. Scattering is produced by fluctuations in the electron density. If we consider these fluctuations as the Fourier superposition of sinusoidal variations in electron density with different wavelengths, it can be shown that only one of the Fourier components contributes to the scattering of the electromagnetic wave in a given direction. The Fourier component responsible for the scattering is that which has a wave vector $\boldsymbol{k}$ equal to the wave vector of the illuminating wave $\boldsymbol{k}_\mathrm{i}$ minus the wave vector of the scattered wave $\boldsymbol{k}_\mathrm{s}$, i.e. $\boldsymbol{k} = \boldsymbol{k}_\mathrm{i} - \boldsymbol{k}_\mathrm{s}$. For the particular case of backscattering the fluctuation component responsible for scattering is in the direction of incidence and has a wavelength equal to half the wavelength of the illuminating wave. It can also be shown that the dynamical properties of the scattered wave, for instance its spectral shift and spectral width, depend on the dynamics of the above-mentioned fluctuation wave component responsible for the scattering, i.e. on the collective behaviour of the electrons, rather than on the dynamics of each independent scattering electron.

Electron density fluctuations will always exist in a plasma because of the discrete nature of the electrons and ions. These fluctuations are at a minimum level when the plasma is in thermodynamic equilibrium. The incoherent scatter technique, which has been used so successfully for the study of ionospheric plasmas, is based on the existence of these fluctuations and on the fact that its magnitude and dynamics can be predicted very precisely by equilibrium statistical mechanics.

Fluctuations in electron density can at times be found to be very much enhanced over the thermal level (i.e. over the minimum level) either as a consequence of external action (neutral turbulence, meteor ionization, etc.) or as a consequence of internal unstable processes. In such cases one usually cannot fully predict the behaviour of the fluctuations or that of the scattered signals; thus one cannot obtain as much information on the characteristic parameters of the medium as in the case of incoherent scatter. Nevertheless, at D and E region heights, because of the strong collisional coupling, the fluctuations can still be used as tracers of the dynamics of the neutral background in which they are embedded. In fact, enhanced fluctuations present some advantages over thermal fluctuations as they will produce enhanced scattered signals which are easier to detect.

Four different radar techniques are described which have been used for the observation and study of gravity waves at E and D region heights; each is characterized by the nature or source of the electron density fluctuations responsible for the reflection or scattering of the radar waves. They are: meteor trail radar technique, non-thermal scattering techniques, incoherent scattering techniques, the second title comprising two techniques, both developed and used at the Jicamarca Radio Observatory, which, although they use an incoherent scatter facility, are not classified as incoherent scatter techniques since they do not depend on the thermal electron density fluctuations for the scattering.

It should be pointed out that gravity wave observations at higher altitudes, i.e. at F region heights, with the help of the gravity wave theory and neutral atmosphere models, can be used to infer information about the amplitude and other characteristics of the same wave at the altitudes of interest in this review. Radio and radar techniques used at these altitudes and the results obtained have been recently reviewed by Vasseur et al. [1] and will not be discussed here.

2. Meteor Trail Radar Technique

Meteor trail radars have been used for more than 20 years for the study of neutral winds in the region between 80 and 120 km [2—7], but it has not been until recently that the full potential of the technique for the study of gravity waves at meteor heights has been exploited. A radar technique has been developed for this purpose by Spizzichino and co-workers [8] and a special radar has been constructed in Garchy, France (47°N 3°E). Here we shall only describe briefly the latter technique and present some of the results obtained.

The French system is a bi-static continuous wave radar and is shown schematically in Fig. 1. It consists of a 5 kW transmitter operating at a nominal frequency of 29.8 MHz. The transmitter antenna is a corner reflector pointing east at an elevation of 45° with a beamwidth of 20° in elevation and 25° in azimuth. The receiver site is located at Sens-Beaujeu, 30 km to the west of the transmitter site at Garchy. It consists of three receiving antennas of construction similar to the transmitter antenna and arranged in an interferometer fashion with a baseline of 30 m in the E—W direction and 20 m in the N—S direction.

When a meteor enters the common volume seen by the transmitter and receiving antenna, and if the path of the meteor is perpendicular to the line of sight from the center of the transmitter-receiving system, an echo from that portion of the trail which presents the proper angle (within a Fresnel zone) is received. The position of this portion of the trail is determined in azimuth, elevation and range, and the velocity of the neutral medium in which it is embedded is obtained from the Doppler shift of the received signal.

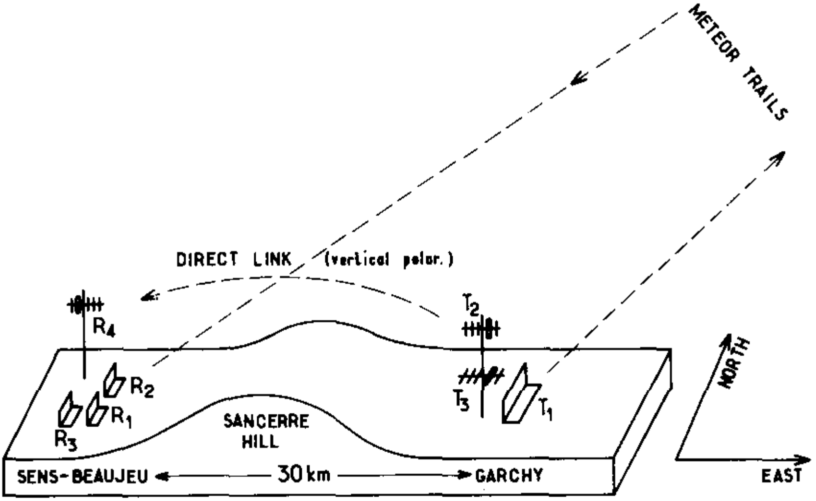

Fig. 1. The Meteor Radar at Garchy. T_1, main transmitting antenna; R_1, R_2, R_3, receiving antennas; T_2R_4, vertically polarized link for reference signals; T_3, transmitting antenna to cancel direct field at receiving site (after Spizzichino [8]).

The azimuth and elevation of the echoing region are determined by measuring the difference in phase of the signals arriving to the three receiving antennas. The range is obtained using three closely separated frequencies. The lowest separation is 600 Hz and the highest 5400 Hz which essentially modulate the radio wave with these frequencies. The phases, at reception, of the 600 Hz and the 5400 Hz "modulating" signals with respect to their phases at emission, are directly proportional to range. The 600 Hz modulation gives the range unambiguously but not with sufficient accuracy. The 5400 Hz modulation gives the necessary accuracy but in an ambiguous way. The ambiguity of the latter is resolved using the approximate range obtained from the 600 Hz signal.

In order to be able to measure the range and Doppler shift (range rate) it is essential to have the transmitted signals at the reception site for reference. The reference is needed for the coherent detection of phase and phase rate of the re-

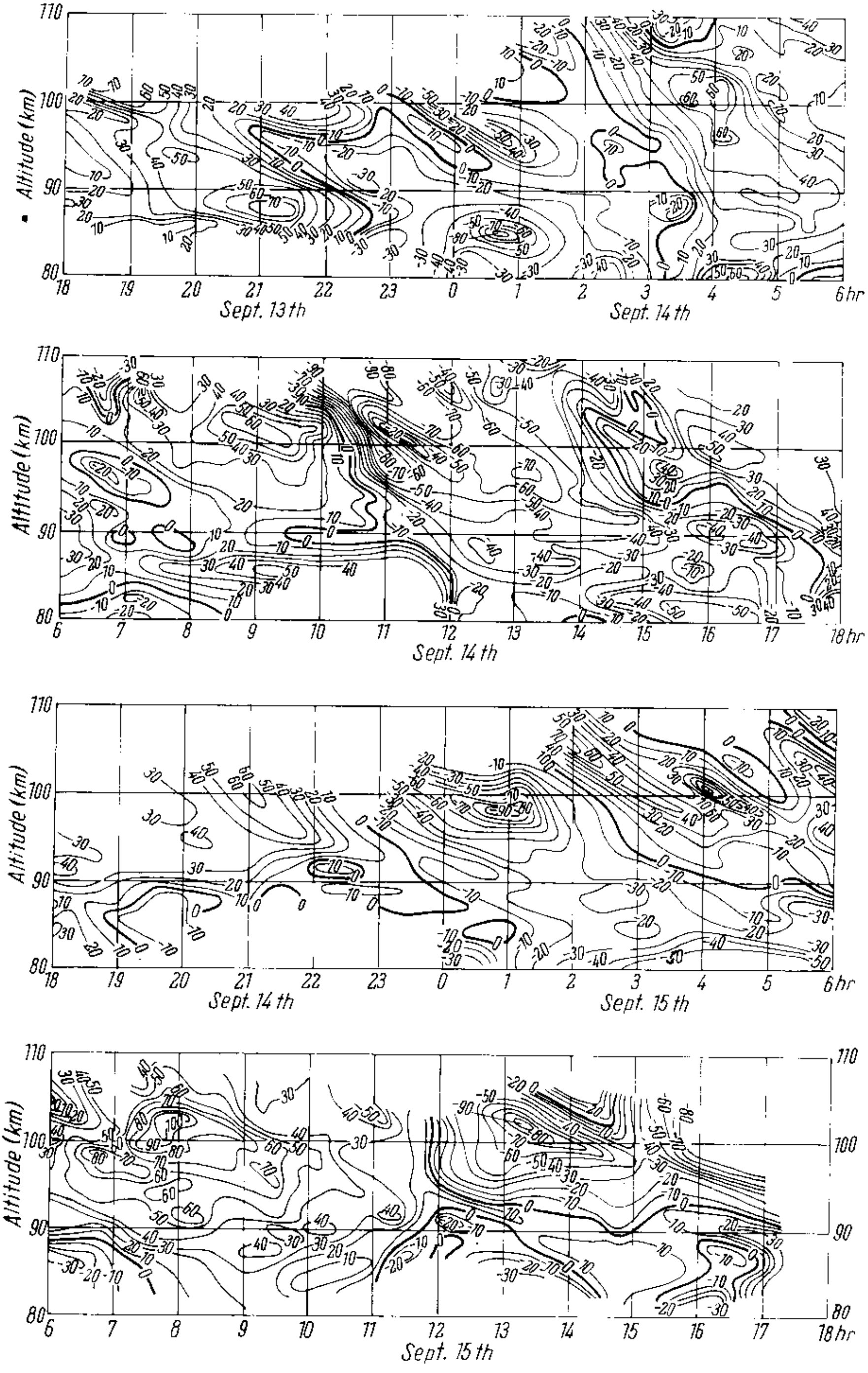

Fig. 2. An example of interpolated wind pattern at Garchy, 13–15 Sept. 1966 (after Spizzichino [9]).

ceived signals. This is accomplished by a low power direct communication link of the radar frequencies but using a vertical polarization orthogonal to the radar polarization. It is also essential for the precision of the measurements that the three receiving antennas receive only the signal echoing back from the meteors. They should not receive the ground wave or the reference signal. This is accomplished by transmitting the radar frequencies through a horizontally polarized Yagi antenna with an amplitude and phase which exactly cancel the interfering signals mentioned above.

The system is able to measure the height of the meteor echoing region with an accuracy of 500 to 1000 meters for signals with a signal-to-noise ratio better than 20 dB. The velocities obtained are the projection of the total velocity along the line of sight. The E—W velocities are derived by assuming no vertical component and neglecting the contributions from the N—S component of the wind. The second assumption limits the accuracy of the velocity measurements to 10 m s^{-1} for each individual measurement. This error is reduced by averaging in the processing of the data (see Spizzichino [9] for the error analysis).

All measurements within the observed volume are projected into a vertical line in the center of the volume. The data from all meteors in a given campaign form a time and altitude random sampling of the winds in the altitude range between 80 and 110 km. From this array of randomly space samples two-dimen-

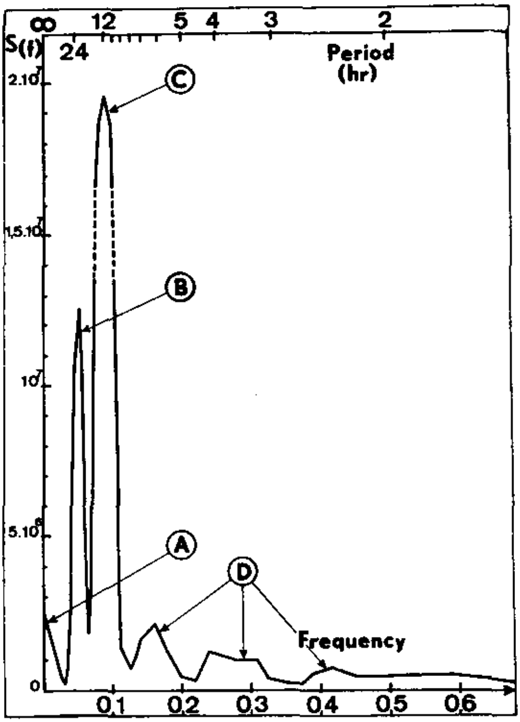

Fig. 3. Power spectrum (in $m^2 s^{-1}$) of the zonal wind at Garchy, 29 March—1 April 1966. A, prevailing wind; B, diurnal tide; C, semidiurnal tide; D, gravity waves (after Spizzichino [9]).

sional smooth contours of velocity as a function of height and time are obtained by means of a smoothing and interpolating numerical process. Fig. 2 shows an example of an interpolated wind pattern taken from Spizzichino [9]. Typical values and the structure of the winds at this altitude are apparent from this figure.

Power spectrum analysis has been performed by Revah [10] and by Spizzichino [11]. A power spectrum plot obtained for a particular campaign is shown in Fig. 3; in addition to the prevailing wind, the diurnal and the semidiurnal components, one can observe the presence of peaks at periods of 8, 4 and 2.5 hours. The interpolation in the processing of the data filters out waves with periods shorter than two hours. Whenever a wave of a particular frequency is identified, its phase as a function of altitude is found to vary linearly with time [10] corresponding to a downward propagating phase which corresponds to waves excited from below, in accordance with the gravity wave theory [12]. The amplitude of the waves varies as a function of height in a sinusoidal way, strongly suggesting the existence of partially reflecting waves.

The vertical wavelength can be obtained from the slope of the phase dependence, height curve or from a direct two-dimensional (frequency and vertical wavelength) Fourier spectrum analysis [10, 11]. Fig. 4 summarizes the distribution

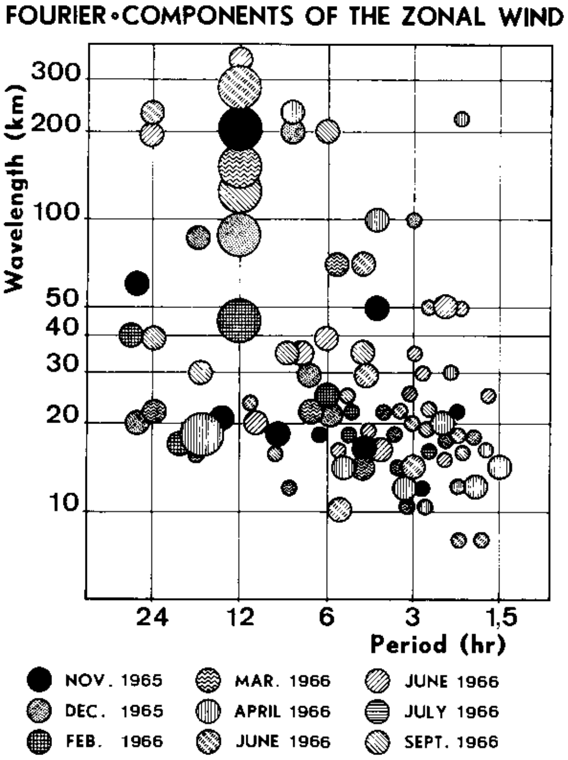

Fig. 4. Frequencies and vertical wavelength of spectral components observed at Garchy from November 1965 to September 1966 (after Spizzichino [11]).

of waves according to their frequency and vertical wave number. Gravity wave vertical wavelengths are found to be mainly in the 10 to 50 km range.

If all the spectra in the gravity wave range are averaged over many days of observation, it is found [10, 11] that the peaks at a given frequency disappear. The resultant frequency power spectrum follows a power law with a coefficient n equal to 0.82 for the 90 km waves and 0.47 at 100 km as shown in Fig. 5.

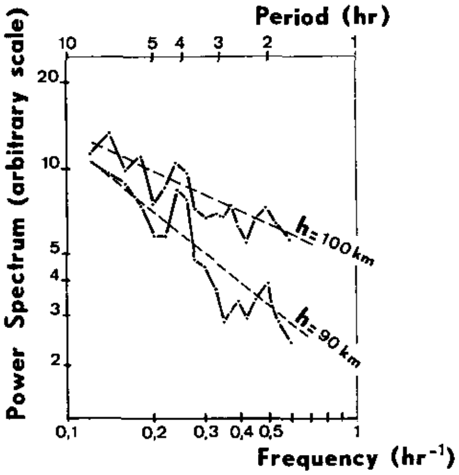

Fig. 5. Mean power spectrum (in $m^2 s^{-1}$) of the zonal wind at Garchy (1965—1966) (after Spizzichino [11]).

The wave behave, in general, very much according to the gravity wave theory. An important discrepancy has been found with respect to the amplitude of the wave as a function of height. Conservation of energy calls for an exponential growth of the amplitude of the wave as a function of height; it has been found that the growth is faster than predicted; Spizzichino has explained this discrepancy by a nonlinear interaction between the gravity and tidal waves [13].

3. Non-Thermal Scattering Techniques

Several powerful radars have been designed and built for the study of the earth's ionosphere by means of incoherent scatter techniques (see Evans (14] for a review and references). One of them is the Jicamarca radar located near Lima, Peru (12°S 76°W). It consists of a very large antenna built as an array of dipoles (9216 half-wavelength cross dipoles) covering an area of 84000 m^2 (Fig. 6) and a powerful transmitter with four modular units each of 1 MW peak power. It operates at a frequency of 49.920 MHz. The Jicamarca radar has been mainly used to study ionospheric parameters and motions in the altitude range 200 to 700 km for most of these parameters, and up to 10000 km for electron density studies. The top range is limited by the system sensitivity. The bottom range is determined by the incoherent scatter theory requirement that the ionosphere be in thermodynamic equilibrium. This condition is not satisfied at E region heights at the latitude of Jicamarca (magnetic equator) where strong density fluctuations

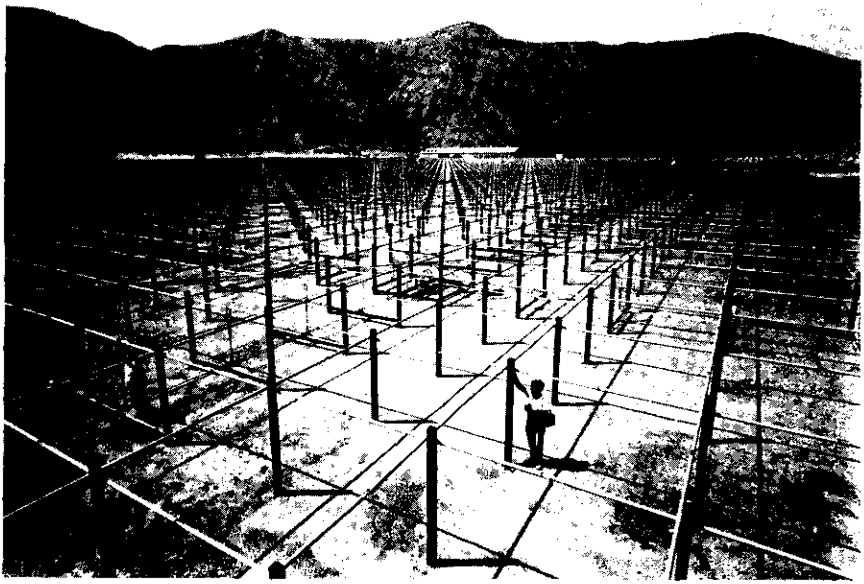

Fig. 6. A view of the antenna at the Jicamarca Radio Observatory.

exist as consequence of different electrodynamic unstable processes. Enhanced electron density fluctuations are also found at D region heights. This means that one cannot derive as many parameters from the spectral characteristics of the echoes obtained from D and E region heights as from those obtained from F region echoes; nevertheless, one can still derive many properties of the scattering medium, among them the velocity of the neutral background within the scattering volume. One can, therefore, study winds, tides and gravity waves using the electron density fluctuations as tracers of the neutral air motions.

A technique has been recently developed by Woodman and Guillén [15] for the observation of winds and waves as well as turbulence parameters at stratospheric and D region heights with the Jicamarca radar. The technique consists mainly of the real time determination of the three first moments of the frequency power spectrum of the backscatter signal, i.e. the power, the Doppler shift and the width of the spectrum. The power is a direct indication of the magnitude of the 3 m ($\lambda/2$ at 50 MHz) density fluctuations in the medium, the Doppler shift is a measure of the mean velocity of the neutral background within the scattering volume, and the spectral width gives information about the distribution of random velocities within the medium. The first and third parameters are of interest for the observation of the turbulent processes responsible for the enhancements in the electron density fluctuations. The second, i.e. the Doppler shift, gives information about winds, tides and gravity waves at the altitude under observation.

The three spectrum parameters mentioned above are obtained every minute, at a given height, with a resolution of 5 km for two independent antenna channels. The two linear polarizations of the antenna are independent and they can be pointed, by proper phasing of their elements, in two different directions 3° off the physical axis of the antenna. The simultaneous observations at two different directions allow a determination of the vertical and horizontal components of the instantaneous winds in the plane formed by the two antenna directions. The velocity is obtained with an accuracy of 10 cm s^{-1} for the vertical and 1 m s^{-1} for the horizontal component with only one minute of integration (for a S/N > 10 dB).

The signal-to-noise ratio is considerably improved by a coherent integration scheme. Because of the relatively slow dynamics of the 3 m fluctuations, the radar echoes are highly correlated from one pulse to the other. The measured coherence time [15] (inverse of the frequency spectrum width) is of the order of one second, and the pulse repetition rate is of the order of 1200 pulses s^{-1}. As many as 300 pulse echoes are averaged coherently to make a single sample point giving a signal-to-noise ratio 25 dB better than that obtained from a single radar pulse echo.

The three characterizing parameters of the frequency spectrum are obtained from a few points of the autocorrelation function of the series of coherently integrated samples. Woodman and Guillén [15] have shown that the first three moments can be obtained from only two points of the complex autocorrelation function, one point evaluated at zero delay, the other at a sufficiently small delay for a truncated second order Taylor series expansion to be valid. The technique is based on the direct relationship existing between the first three moments of the frequency spectrum and the first three derivatives of the autocorrelation function evaluated at the origin. This is a property of any Fourier transform pair. This scheme is considerably faster than a conventional evaluation of the full frequency power spectrum.

Fig. 7 shows a power profile obtained at Jicamarca from 15 to 85 km. The profile was taken at a randomly selected time. The power from mesospheric heights varies considerably during the day and from one day to the next: in that sense the profile shown should not be considered typical. The profile was taken using 314 coherent integrations. The dotted line shows the noise level for a single radar pulse. Echoes are received from 15 to 35 km and from 55 km and above. Echoes beyond 85 km were not processed: they come from a region where electric fields are important and need a different interpretation (they were excluded from [15]). The predicted incoherent scatter power level for an altitude of 80 km and an electron density of 10^3 elect cm^{-3} is shown for reference.

The 15–35 km echoes do not concern us here, but we should mention in passing that they give important information about winds, waves and clear air turbulence at these altitudes. They are produced by fluctuations in the index of refraction of the neutral atmosphere. There are no echoes between 35 and 55 km for lack of efficient scatterers. The echoes from the 55–85 km region are believed to be caused by electron density fluctuations produced by neutral turbulence in a region of electron density gradients. At certain times the echoes are 10–15 dB higher than shown in Fig. 7, at a particular narrow range, anywhere between 60 and 85 km. These narrow and strong echoes, we believe, are caused by the coincidence of a layer of turbulence with a region of strong density gradients. Strong density gradients at D region heights have been observed at the equator by means of rockets [16].

Fig. 8 shows two time series corresponding to the continuous observations of the vertical and E–W component of the winds at 80 km. Fluctuations larger

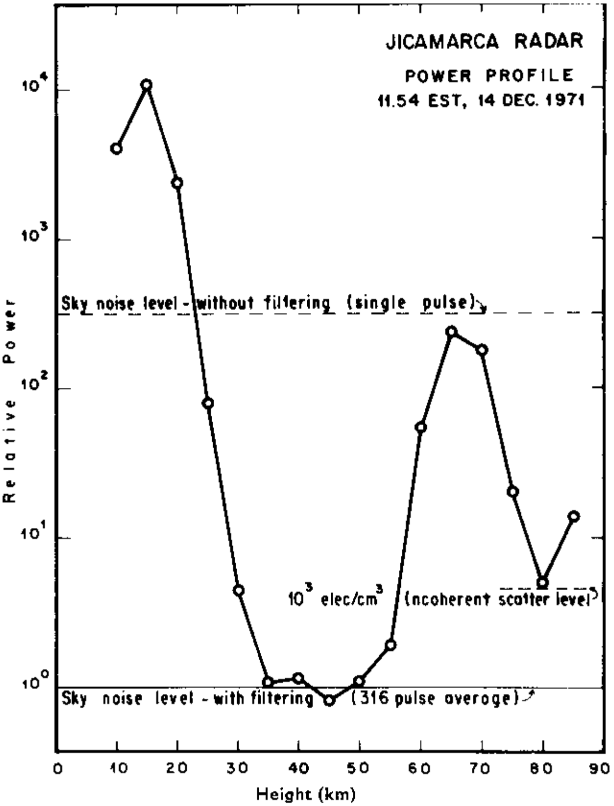

Fig. 7. Backscatter power profile obtained at Jicamarca (after Woodman and Guillén [15])

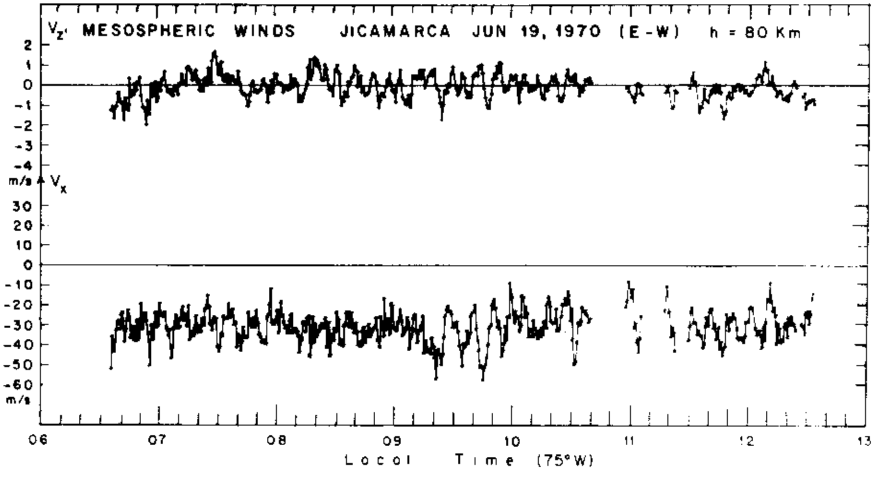

Fig. 8. Record of velocities at 80 km obtained at Jicamarca from the Doppler shift of backscatter echoes produced by enhanced dielectric fluctuations at D region heights. V_z, vertical component; V_x, horizontal component (after Woodman and Guillén [15]).

than ± 1 to $2\,\mathrm{m\,s^{-1}}$ in the E—W winds and ± 0.1 to $0.2\,\mathrm{m\,s^{-1}}$ in the vertical should be considered real. Fluctuations with periods of the order of $10\,\mathrm{m\,s^{-1}}$ predominate and are of the same order of magnitude as the mean zonal component. Fig. 9 shows a special event of unknown origin. A quasi-sinusoidal packet with a period of the order of 10 minutes is evident in the horizontal component from 1045 to 1120. The accuracy of the technique can be appreciated in the small scatter of the points following the oscillation.

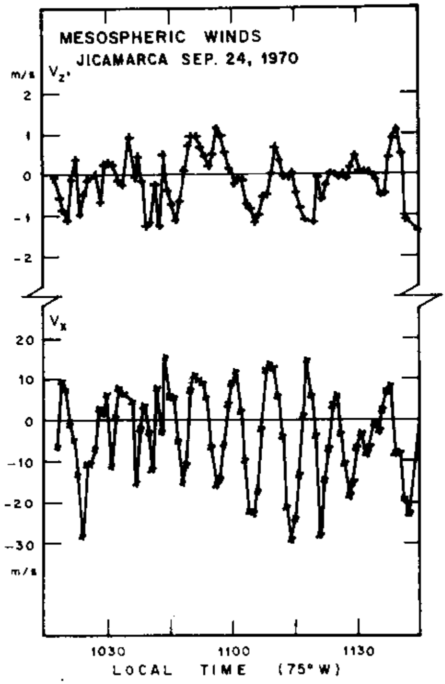

Fig. 9. Record of a special event obtained at Jicamarca showing clean sinusoidal fluctuations at gravity wave periods (after Woodman and Guillén [15]).

Spectral analysis of the velocity time series at D region heights by the Jicamarca technique has been reported by Rastogi and Woodman [17]; Fig. 10 shows a typical result. The cut-off at around 5 minute period is a fairly consistent feature of all the spectra that have been obtained so far. It corresponds approximately to the Brunt-Väisälä frequency cut-off beyond which no gravity waves should propagate. The random errors in the series caused by noise are independent from point to point; their contribution to the spectra is a constant as a function of frequency. The smallness of these errors is evident from the amplitude of the tail of the spectra beyond the 4 minute period.

The wind and wave observations at Jicamarca have been limited so far, because of computer speed limitations, to one particular altitude and to a 5 km resolution. A new system using a third generator computer has been developed which should allow the observation of the full velocity vector at 20 heights simultaneously with a resolution of 2 km and a time resolution of one minute. The new system will allow us to make gravity wave propagation studies and to determine the origin of these waves.

A second backscatter radar technique has been used at Jicamarca using enhanced fluctuations as tracers of neutral atmospheric motions at E region heights

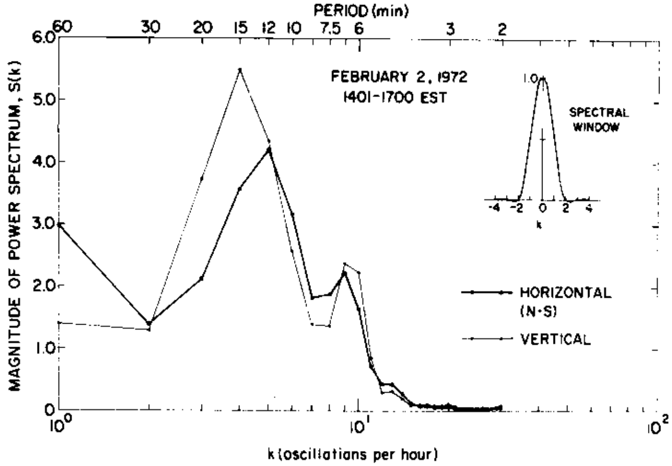

Fig. 10. Power spectrum of vertical and E—W winds at 70 km obtained at Jicamarca (after Rastogi and Woodman [17]).

and around 105 km. The technique is based on the spectral characteristics of echoes received from irregularities produced by the two-stream instability in the equatorial electrojet. The technique has been used and reported by Cohen [18] using the Jicamarca transmitter but with a smaller steerable antenna. The theory of the two-stream instability predicts that the irregularities should move at the ion-acoustic velocity with respect to the neutral background; therefore the spectrum of the backscatter signal should be Doppler shifted by an amount correspond-

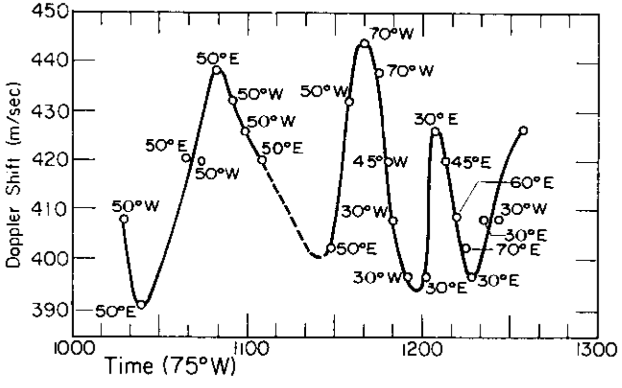

Fig. 11. Record of the Doppler shift of the spectral peak of backscatter echoes from two-stream E region equatorial instability showing gravity wave oscillations, 3 Jan. 1964 (after Cohen [18]).

ing to the ion-acoustic velocity plus the projection of the neutral velocity along the line of sight of the receiver. Fig. 11 shows a record of the time history of the center frequency of the backscatter frequency spectrum scaled in m s^{-1}. The fluctuations from the mean velocity are interpreted by Cohen [18] as neutral air motions produced by gravity waves. The periods are from 30 minutes to an hour and the velocities of the order of ± 25 m s^{-1}.

4. Incoherent Scatter Techniques

Gravity waves are essentially a neutral atmosphere phenomena and they manifest themselves as fluctuations of the velocity, the temperature and the density, as well as other thermodynamically related parameters of the neutral atmosphere. These fluctuations produce corresponding fluctuations in the velocity, temperature and collision frequencies of the ionized plasma, which are directly observable by incoherent scatter techniques. Gravity waves have been observed and studied using incoherent scatter techniques, but so far at F region heights [1, 19—25], with a few recent observations, limited to diurnal and semidiurnal tidal periods, at E region heights [26, 27]. The technique is nevertheless potentially capable of studying waves of shorter periods at E region heights and it is expected that this will shortly be done.

5. Conclusions

Radar techniques are capable of and have been used for, the detection and study of gravity waves in the lower ionosphere. Meteor radar techniques have been fully exploited for the study of gravity waves from periods of two hours to periods in the range of tidal waves. The French system at Garchy has shown the potential of the technique and many interesting properties of gravity waves at altitude ranges between 85 and 110 km have been reported. The potential of powerful radar at VHF, making use of turbulent fluctuations at D region heights, has been established with observations made with the Jicamarca radar. The technique has detected gravity waves with periods down to the Brunt-Väisälä frequency. Incoherent scatter techniques should be capable of detecting gravity waves at E region heights; so far only tidal wave observations have been reported.

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