Measuring Plasma Density of the Magnetosphere

Electron-density and temperature profiles are measured by the incoherent-scatter technique of radar.

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The wide range of physical measurements being conducted in the "space" environment is by now well known. Most of these measurements are carried out *in situ* with equipment borne by earth satellites or by rockets. Strictly speaking, the word *space* is a misnomer inasmuch as even the interplanetary medium is occupied by a tenuous ionized gas or "plasma." Studies of this plasma are of great interest because of its strong interaction with electromagnetic waves, and with magnetic fields. We have measured the density of the plasma in the near vicinity of the earth by means of earth-borne radar. The technique makes use of weak backscattered echoes from the plasma.

For several decades the term *ionosphere* has been used to describe the ionized portion of the earth's atmosphere extending upward from a height of roughly 60 kilometers. Radars of moderate sensitivity have been used since the early 1930's to obtain echoes reflected from the ionsphere and from heights up to perhaps 500 kilometers. The echoes bear information about the variations of electron density with height. Thus, in current terminology, radar "sounding" of the ionsphere was one of the earliest forms of space research.

In conventional ionsphere sounding, the vertically incident radio wave is reflected at the height where the local plasma frequency f_p first reaches the operating frequency of the radar, f. In terms of density of the free electrons in the plasma, N_e (electrons per cubic centimeter), $f_p^2 = 0.81 \times 10^8 N_e$. N_e generally rises to a maximum at a height of between 300 and 400 kilometers; this is known as the F-region maximum. The maximum value of N_e is typically between 10^5 and 3×10^6, corresponding to f_p between 3×10^6 cycles per second (3 Mcy/sec) and about 16×10^6 cycles per second. At higher frequencies the radar sounding wave simply penetrates the ionospheric layer and most of the energy is lost. This technique has been widely used to study ionization below the F-layer maximum, but it has been useless for studies above the F-layer maximum.

At operating frequencies well above the maximum plasma frequency the free electrons exhibit a weak scattering of incident radio energy (Thomson scattering). It was presumed that the free electrons would scatter "incoherently" at such high frequencies, much as particles of a neutral gas exhibit Rayleigh scattering (*1*). The term *incoherent* implies that each electron moves about in the plasma independently of the motions of the other electrons and of the ions. However, early observations of the scattering demonstrated the need to consider the Coulomb interactions among the various particles (*2*). The theory of the scattering has now been thoroughly worked out (*3*), from various facets of the theory of plasma density fluctuations.

Characteristics of the Scatter

The characteristics of this quasi-incoherent scattering make it useful as a means of measuring the plasma density and the kinetic temperatures. The radio wave resolves a particular spatial Fourier component of the plasma-density fluctuations. This component, in turn, is approximately proportional to the ionization density in the region where the scattering occurs. Since the scattering is very weak, echoes may be obtained from all parts of a volume filled with plasma without mutual interference. Thus, by using pulsed radar, one can measure electron density as a function of distance, or range, from the radar. The range resolution of the measurement is proportional to the length of the pulse. No limitation is imposed by the F-region maximum, and measurements can be made simultaneously above and below that height.

The thermal fluctuations of plasma density are continually changing. Consequently, the scattered energy is Doppler-broadened into a spectrum surrounding the transmission frequency. Two important limiting cases define the observable spectra; these depend upon the ratio of the radio wavelength λ and the Debye shielding distance λ_D, which equals $0.69\ (T/N_e)^{\frac{1}{2}}$ centimeter, where T is the kinetic temperature of the particles. λ_D is roughly 0.2 centimeter in the F-region of the ionosphere. Most radar experiments satisfy the criterion $\lambda/4\pi\lambda_D >> 1$. This we call the limiting case of "long wavelength." In this case the ions dominate the appropriate Fourier component of the density fluctuations. Therefore the Doppler broadening of the spectrum is approximately equal to the broadening which would be obtained if the Thomson scattering arose from neutral particles having the mass of the ions. Of course, most of the scattering arises from the free electrons, since their Thomson-scattering cross section is much greater than that of the ions. On the other hand the distribution of electron density is largely determined by the ions, which have much greater momentum than the electrons. The shape of the spectrum profile is not completely independent of the electrons but depends upon the ratio (T_e/T_i) of electron temperature to ion temperature. Thus, spectrum measurements afford a means of estimating T_e/T_i as well as T_i alone.

In the limiting case of "short wavelength," $\lambda/4\pi\lambda_D << 1$, the electron density fluctuations are largely independent of the ions. This independence results from the phenomenon of short-range Debye shielding in the plasma. The electrons appear to be distributed essentially independently in this case. Thus, the spectrum profile expected is simply a Doppler transformation of the probability distribution of the electron velocity components parallel to the

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propagation path of the radio wave. In this case the scatter is truly incoherent, and the intensity of the scatter is obtained by multiplying the Thomson cross section by the number of free electrons within the scattering volume.

In the limiting case of long wavelength the intensity of the scattering is complicated by the ratio T_e/T_i. For relatively low values of this ratio the echo power P obtained in the long-wavelength limiting case is related to the echo power P_s obtained in the short-wavelength limiting case by the following formula

$$\frac{P}{P_s} \approx \frac{1}{1 + T_e/T_i}$$

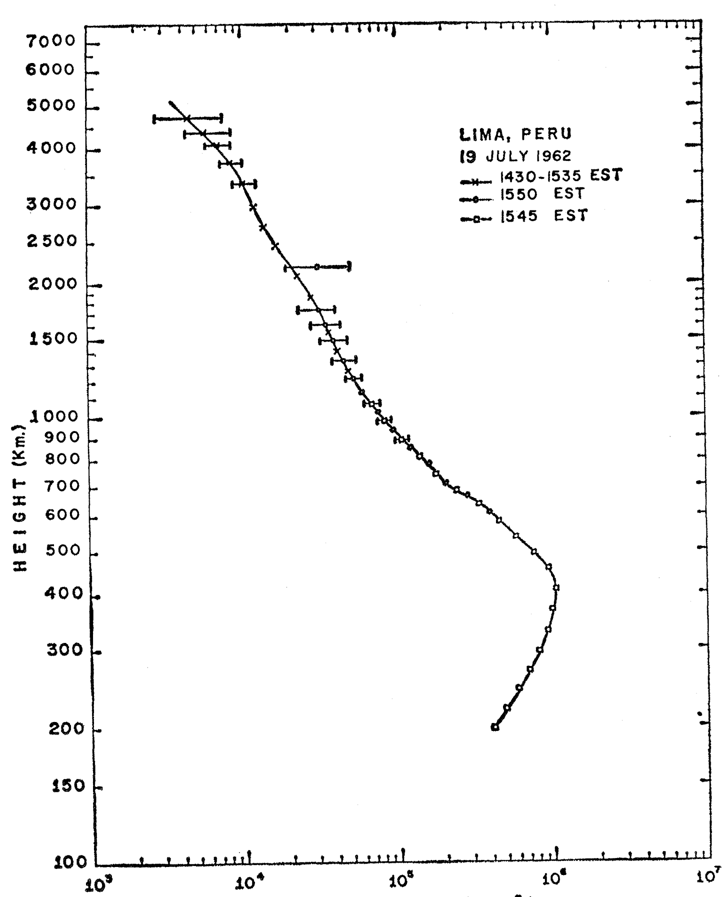
The predictions of the theory have been checked experimentally, and excellent agreement has been obtained. The echo intensity has been found to be as predicted (*4*). The experimental spectra agree almost precisely with the theoretical profiles (*5*). Thus, the way appears to be open for the use of this technique to measure the variation in electron density with height, and to measure the variation in T_i and T_e/T_i. These variations in height are also referred to as "profiles."

Jicamarca Radar Observatory

We now have in final stages of construction a large radar station, the Jicamarca Radar Observatory (*6*), near Lima, Peru. The observatory was established primarily to make incoherent scatter studies of the earth's upper atmosphere, as described in this article. The equatorial location was chosen partly because the equatorial ionosphere and exosphere have received far less experimental attention than the ionosphere and exosphere in either the temperate or the arctic regions. Thus it was hoped that the contribution would be more meaningful if the observatory was near the equator, since the Jicamarca results would complement results obtained by other methods elsewhere. Another reason for the choice of location was the hope that the incoherent scatter technique could be used to identify the ion species existing in the magnetosphere. Such identification is thought to be more likely with radars located near the magnetic equator. No successful observations of this kind have yet been made, but further attempts will be made shortly, now that the installation is complete.

The Jicamarca facility is used for a variety of other radar and radio-based experiments. The intense beam of radio energy, emitted when the transmitter is on the air, causes a transient increase of ionospheric absorption. Early observations show that the increase is not nearly as serious as had been conjectured from theoretical considerations. Measurements of absorption by means of the Luxembourg effect are continuing.

Another experimental area is the study of aspect-sensitive radar reflections from ionospheric irregularities aligned with lines of the earth's magnetic field. The Jicamarca group have found that these irregularities exist because of the flow of a strong electric current in the ionosphere. Similar irregularities cause strong radar *clutter* reflections in the polar regions during displays of aurora, and the cause appears to be the flow of electric currents generated during the aurora. The mechanism for the generation of the irregularities seems to be a two-stream instability similar to the instabilities found in laboratory plasmas. The Jicamarca group are actively cooperating with several groups interested in plasma physics to



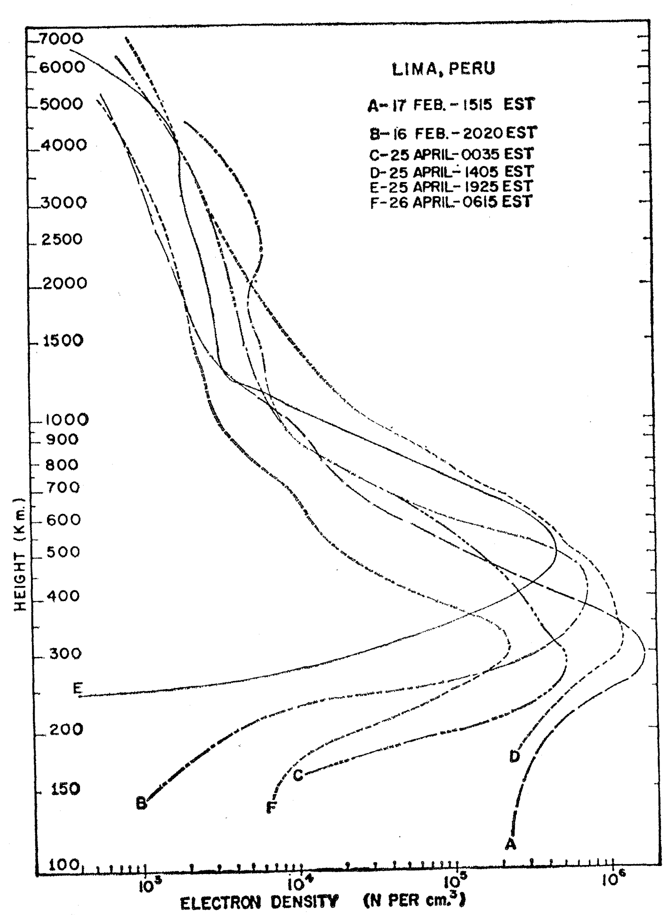


Fig. 1 (left). Electron density profile. Fig. 2 (right). A composite of six electron density profiles.

determine whether the ionospheric observations can be of benefit in the more general study of plasma instabilities.

Still another area of investigation is radio and radar astronomy. Recently radar echoes were obtained from the planet Venus, and the fading of the echoes is being studied for clues to the surface properties of the planet. In passive radio astronomy the huge collecting area of the Jicamarca antenna is being used to advantage to study extremely faint radio stars.

During the radio noise observations, a strong increase was noted as a result of the 9 July 1962 explosion over Johnston Island. The increased radio noise was identified with synchrotron radiation from a belt of particles emitted by the blast.

Construction of the Jicamarca Observatory was begun in January 1961. The site is a deep valley in the foothills of the Peruvian Andes. Nevertheless, the terrain is flat, as a result of infrequent flash flooding of the area because of rainfall in the higher foothills. Such floods occur perhaps one year in 25, during the summer season when the Pacific Ocean temperature reaches its yearly maximum. A diversion dam protects the observatory from flood damage. An early demonstration of its effectiveness occurred during the period January through March 1961, when the first floods since 1932 occurred.

The staff of the Jicamarca station consists of six North Americans and about 40 Peruvians. During its brief existence there have been several gratifying examples of international cooperation and friendship.

Electron Density Profiles

Preliminary measurements have been made with parts of the Jicamarca radar prior to completion of the station. In this article we present several of the electron density profiles we have obtained.

An idea of the high radar sensitivity required for measurements of this kind may be obtained from the cover photograph on this issue, which shows part of the antenna at the station. The antenna is an array of dipoles with an aperture area of some 22 acres. Each dipole is approximately 10 feet long—a half wavelength at our operating frequency of 50 megacycles per second. The transmitter peak pulse power is about 5×10^6 watts.

For technical reasons we have not as yet been able to make spectrum measurements on the backscattered echoes obtained at our station. Therefore we have been unable to measure T_e/T_i. However, the error introduced over the electron density profile by assuming T_e/T_i to be constant is probably not large. The profiles of Figs. 1 and 2 were plotted on the basis of this assumption. Calibration of these profiles in terms of absolute electron density has been made at just one point—the point of maximum electron density. This point is obtained by using an auxiliary sweep-frequency radar, or ionosonde, to measure the maximum frequency at which reflections are obtained from the *F*-region. This frequency is the plasma frequency f_p at the *F*-region maximum, hence a direct measure of plasma density at that height. The remainder of the profile is measured relative to the maximum density.

At the greater heights it has been necessary to vary the radar sensitivity. Thus, the profiles given are really composites of several measurements in each case. Curves pertaining to each of three height ranges have been fitted together to form a single profile. The kinds of error to be expected from this fitting process are shown by the error flags in Fig. 1. For each individual section of the profile, the greatest error occurs at the greatest height. This is because the intensity of the scattered echo decreases rapidly with increasing range. Correction for the decrease in radar sensitivity with increase in range was made before these electron density profiles were plotted.

The scatter theory available at this time is strictly valid only for the regions where the plasma may be considered to be "collisionless." For heights below about 200 kilometers this approximation is probably not correct. Because of this, the fluctuations of electron density may reflect turbulence and other factors in addition to background thermal fluctuation. Therefore, the indicated values for electron density on the profiles of Figs. 1 and 2 for heights below about 200 kilometers are probably too large by a factor approaching 2. Efforts are being made to increase the accuracy of the observations at these heights.

In the title of this article we refer to these measurements as pertaining to the "magnetosphere." This term is applied to the region in which the atmospheric plasma is strongly affected by the presence of the static magnetic field of the earth. The magnetosphere encompasses both the ionosphere and the exosphere. The magnetic field of the earth is expected to have some influence on the spectrum of the backscattered echoes. When the radio wave propagates nearly perpendicularly to the lines of force of the earth's magnetic field, the spectrum should be divided into a series of side bands separated at intervals equal to the ion Larmor frequency. It should be possible to make observations of this effect with a vertically directed radar beam in the vicinity of the magnetic equator. Thus it is possible that radar can be used as a kind of mass spectrometer to identify the ion species. This is one reason why a site near the magnetic equator was chosen for our station. Thus far it has not been possible to make observations of this effect.

Currently we have available about 20 electron density profiles such as those of Figs. 1 and 2 (*7*).

References and Notes

1. W. E. Gordon, *Proc. I.R.E. (Inst. Radio Engrs.)* **46**, 1824 (1958).
2. K. L. Bowles, *Phys. Rev. Letters* **1**, 454 (1958); *J. Res. Natl. Bur. Std.* **D65**, 1 (1961).
3. J. P. Dougherty and D. T. Farley, *Proc. Roy. Soc. London* **A259**, 238 (1960); J. A. Fejer, *Can. J. Phys.* **38**, 1114 (1960); ———, *J. Geophys. Res.* **65**, 2635 (1960); ———, *Can. J. Phys.* **39**, 716 (1961); T. Hagsfors, *J. Geophys. Res.* **66**, 1699 (1961); J. Renau, H. Camnitz, W. Flood, *ibid.* **66**, 2703 (1961); M. N. Rosenbluth and N. Rostoker, *Phys. Fluids* **5**, 776 (1962); E. E. Salpeter, *J. Geophys. Res.* **65**, 1851 (1960); ———, *Phys. Rev.* **120**, 1528 (1960); ———, *J. Geophys. Res.* **65**, 982 (1961); ———, *Phys. Rev.* **122**, 1663 (1961).
4. K. L. Bowles, G. R. Ochs, J. L. Green, *J. Res. Natl. Bur. Std.* **D66**, 395 (1962).
5. J. V. Evans, in press.

6. The Jicamarca Radar Observatory is a joint venture of the National Bureau of Standards' Central Radio Propagation Laboratory, Boulder, Colorado, and the Instituto Geofísico del Perú, Lima.
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