AIAA 80-1384R

Measurements of *D*-Region Electron Densities Utilizing the Partial Reflection Technique

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The partial reflection technique measures *D*-region electron densities as a function of height by transmitting rf pulses vertically and receiving the partially reflected echoes. The rf frequency is approximately 2 MHz, and right- and left-hand circular polarization is employed. Electron densities are derived from the ratio of the amplitudes of the extraordinary and ordinary echoes. Results from a partial reflection experiment conducted in New Mexico are presented, and comparisons are made with in-situ probe measurements and with theoretical predictions from an atmospheric model. The good agreement obtained in these comparisons provides evidence to support the validity of the partial reflection technique.

Introduction

THE ionospheric *D* region encompasses that portion of the atmosphere from approximately 60 to 90 km. It is a complex region because of the dynamic interaction between the neutral atmosphere and a weakly ionized plasma. Electron densities vary from less than 10^2 electrons/cm^3 at the base of the *D* region to 10^4 electrons/cm^3 or more at the higher altitudes during midday. The electron densities vary diurnally as a function of solar input, with the maximum occurring near noon and minimums occurring during the night. In addition to the normal variation, electron density can become greatly enhanced under disturbed solar conditions when additional ionization becomes available, creating more free electrons. These factors point to dynamic conditions under which the electron density can vary significantly in a relatively short period of time.

Electron densities in the *D* region are difficult to measure accurately because of the small fraction of ionized particles, about one part in from 10^9 to 10^{13}. The region has often been probed directly by rocketborne sensors which provide detailed measurements of electron density vs altitude, but do not show how electron densities vary continuously with time. A remote technique such as partial reflections cannot obtain the detailed structure revealed by the in-situ probe, but can provide a time history of electron density variations. Both the in-situ and the remote measurement techniques are useful, and they complement each other; ideally, they should be used together.

The objective of this paper is to describe the partial reflection technique, and the data we have obtained using it. Results are compared with other measurements and with theoretical predictions made using an atmospheric model.

Partial Reflection System

The partial reflection technique for deriving electron densities was first proposed by Gardner and Pawsey.[1] Since that time the method has been utilized by a number of investigators to measure electron densities.[2-4] The basic assumptions proposed by Gardner and Pawsey have been questioned and improved upon by researchers in formulating a proper model for the physical source of *D*-region partial reflections.

The partial reflection system measures *D*-region electron densities as a function of height. A short pulse of electromagnetic radiation is transmitted vertically, and echoes are partially reflected from the free electrons in the lower ionosphere. In our equipment, the reflected signals vs time (with time a measure of altitude) are digitized and recorded on magnetic tape. Circular polarization of the electromagnetic radiation, both right- and left-hand polarization, is utilized. Because of the Earth's magnetic field, the index of refraction of the ionosphere is different for the two polarization modes. This difference leads to different coefficients of reflection and absorption of the radio waves which provides the key to deriving electron densities.[4]

It is assumed that the amplitude A_m (m is an index to identify polarization mode) of an echo partially reflected from the ionosphere, from altitude h above the station, is related to an ionospheric reflection coefficient R_m and absorption coefficient K_m as follows.

$$A_m(h) \propto R_m(h)\exp\left[-2\int_o^h K_m(s)\,\mathrm{d}s\right]$$

At any altitude, K_m is proportional to the density N_e of free electrons at that altitude, i.e., $K_m = F_m N_e$, where F_m is a proportionality factor. When circularly polarized waves of both the ordinary (o) mode and the extraordinary (x) mode are transmitted at equal power, then

$$\left[\frac{A_x}{A_o}\right] = \left[\frac{R_x}{R_o}\right]\exp\left[-2\int_o^h [F_x - F_o]_s N_e(s)\,\mathrm{d}s\right] \qquad (1)$$

Equation (1) can be solved for N_e

$$N_e(h) = \frac{1}{G(h)}\frac{\mathrm{d}}{\mathrm{d}h}\left[\ln\frac{R(h)}{A_x/A_o}\right] \qquad (2)$$

where

$$G(h) = 2[F_x - F_o]_h$$

and

$$R(h) = [R_x/R_o]_h$$

Presented as Paper 80-1384 at the AIAA 13th Fluid and Plasma Dynamics Conference, Snowmass, Colo., July 14-16, 1980; submitted Sept. 18, 1980; revision received April 28, 1981.

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In summary, the reduction of partial reflection data utilizes Eq. (2) to convert the ratios (vs altitude) of the measured amplitudes of extraordinary and ordinary echoes, A_x/A_o, into a profile of electron density vs altitude. Equation (2) requires, in the addition to the amplitude ratios, precomputed functions $R(h)$ and $G(h)$. These functions are evaluated using either experimental or theoretical values of gyromagnetic frequency and collision frequency vs altitude. A study of partial reflection accuracies by Coyne and Belrose[5] estimates the accuracy of the mean electron density at a given altitude to be within 50% when integration times of 10 min or more are used. For a discussion of errors associated with the partial reflection and other measuring techniques the reader is referred to a review by Thrane.[6]

In practice, the amplitudes A_x and A_o of the extraordinary and ordinary echoes that are used in Eq. (2) are average values. Using echo amplitudes from single measurements, the result would not be statistically significant. The time of a typical "run" of the experiment is 10 min, and the averages extend over such a time interval. Electron densities in the lower ionosphere are generally a function of solar zenith angle, and the change in this angle over a 10-min period is negligible. Our partial reflection transmitter operates at a pulse repetition frequency of 17 pulses/s, so a great deal of data is accumulated in the course of a run.

Eight consecutive pulses from the transmitter form the basic pattern of the system's operation, which is under computer control. During the first four pulses, transmission and reception is done in the ordinary mode, and during the second four, in the extraordinary mode. For each group of four pulses, receiver attenuation is increased in steps. This insures that some echoes from the altitude region of interest are always in the range of receiver sensitivity, above the noise level but below saturation level.

The transmitted pulse has a time duration of 20 μs, and so echoes received at one instant may have been reflected from anywhere within a layer 3-km thick. Variations in electron density with altitude that occur on a scale smaller than this will not be detected. Accordingly, each echo is digitized at a sample rate corresponding to an altitude increment Δh of 2 km, and 30 samples per echo are recorded. Thus, echo information from an altitude interval of 60-90 km is recorded. The base of this interval is selected by the operator so that the lowest-altitude echoes are always sampled. The base altitude is set typically at between 50 and 60 km. Results from the partial reflection experiment are generally not reliable above 90 km because of losses at the lower altitudes, especially in the extraordinary mode. Table 1 contains information on the more important operating parameters of the partial reflection sounder station.

D-Region Electron Densities

Using the partial reflection sounder system, 682 electron density profiles have been produced since 1975. Most of the data were taken at the White Sands Missile Range (WSMR) in southern New Mexico. Figure 1 shows a typical profile obtained from one run. Electron density vs altitude is plotted semilogarithmically, and the data processing provides a value at 1-km intervals.

Figure 2 contains averages of results for WSMR data during December 1977. In forming the averages, we used only data recorded during the midday hours from 1000 to 1400 MST. Within the plots the circles mark the average value, while the dots are separated from the average by one standard deviation.

Table 1 Operating parameters

rf frequency	2.2375 or 2.6667 MHz
Transmitted power	135 kW (peak)
Pulse width	20 μs
Pulse repetition frequency	17 pps
Height sample interval	2 km
Antenna polarization	*o* and *x* mode
Antenna arrays	5 turnstiles (horizontal half-wave dipoles at right angles)

Electron Densities Intercomparisons

Hoock and Heaps have developed a computer code entitled DAIRCHEM that models the time varying chemistry and charge distribution of the *D*-region.[7] The code considers all ionizing sources of solar and terrestrial origin. These sources, coupled with reaction rates of the various atmospheric constituents, yield the number density as a function of time at any specified *D*-region altitude for a number of charged and neutral species.

During the period of November 4-5, 1977, the partial-reflection sounder was operated for a 24-h period. Results from this series of measurements, and model values, are given in Figs. 3 and 4. Figure 3 shows the diurnal variability at altitude 85 km. It is seen that the data and model values follow the same trend, though the measured values are less than the model values. Similar results are shown in Fig. 4 for the variability at 75 km. Here again the measured values are less than the model values. The gap in measurements in Fig. 4 occurs because at 75 km, night-time electron density fell below the sensitivity threshold of the partial-reflection station.

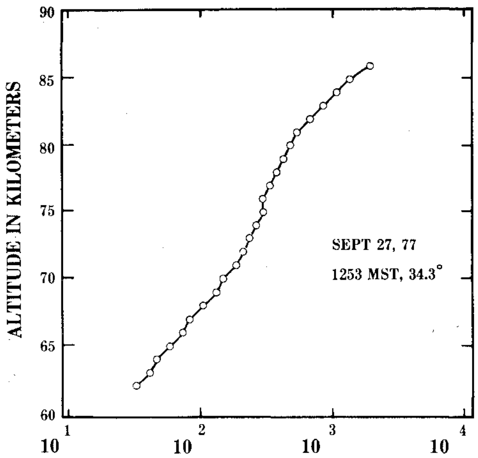

Fig. 1 A typical midday electron density profile at a solar zenith angle of 34.3 deg.

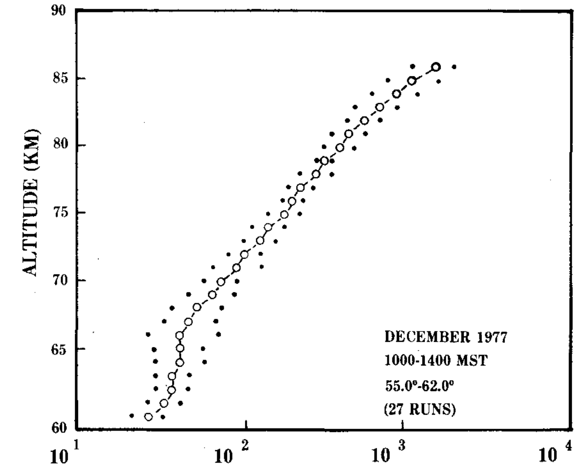

Fig. 2 A mean electron density profile with one standard deviation for December 1977.

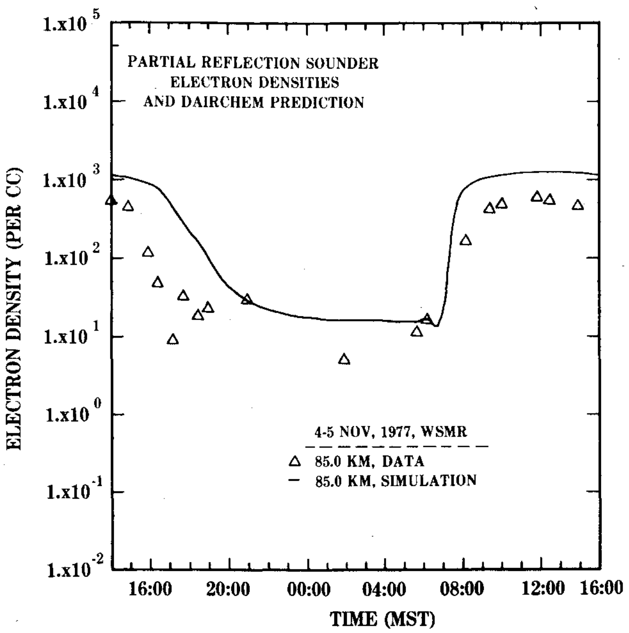

Fig. 3 Diurnal variability of electron densities at 85 km from the DAIRCHEM model and sounder measurements.

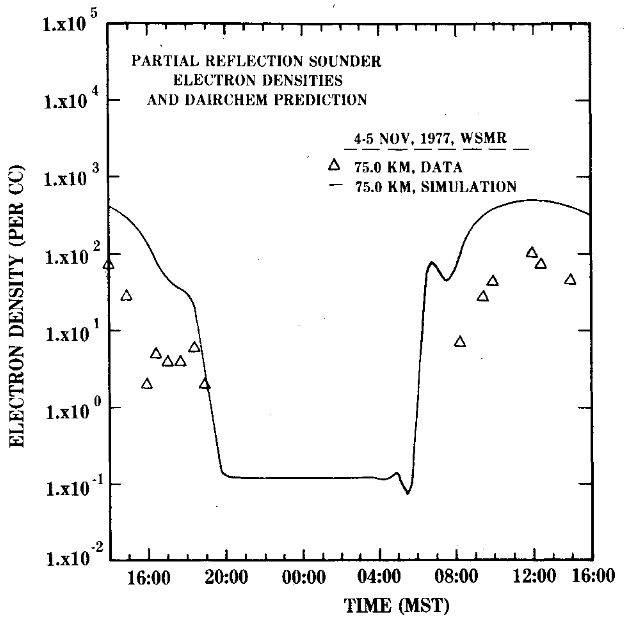

Fig. 4 Diurnal variability of electron densities at 75 km from the DAIRCHEM model and sounder measurements.

Figure 5 shows a comparison of measurements with the DAIRCHEM model for 1400 h on a day early in November. The data values are seen to be slightly smaller than the model values. Also included in the figure is an average of many midday measurements made throughout November. These data appear to be in good agreement with the model values, but again the greater number of values are generally on the low side. One reason could be that to obtain sufficient midday samples, the selected data covered the time span from 1000 to 1400 h, while the model values are solely for 1400 h. Another reason may be that the model does not aptly describe electron densities between 70 and 80 km due to the inadequacy of information on negatively charged distributions at these altitudes. The model normally indicates a decrease in the concentration of negative ions; however, if the negative ions do not decrease; there would be fewer free electrons since they would attach to the neutrals to form negative ions. Even with these discrepancies, however, the comparisons are felt to be

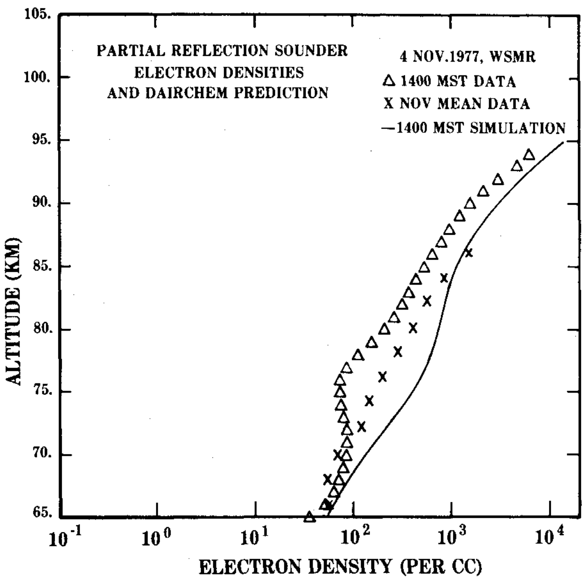

Fig. 5 Electron densities obtained from a November 4 sounding, a November mean, and the DAIRCHEM model.

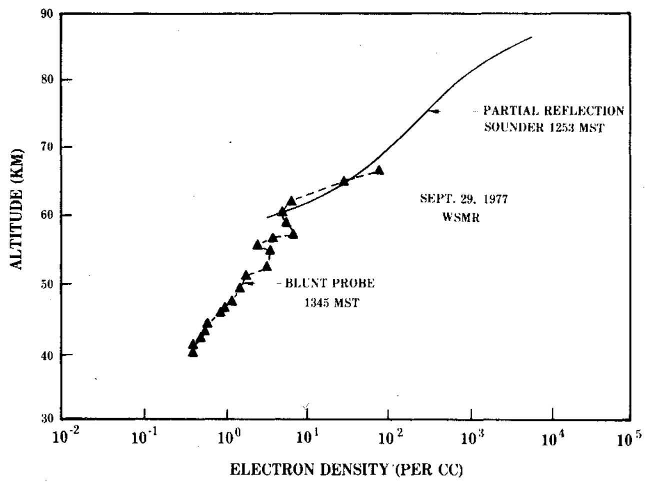

Fig. 6 Electron densities obtained from the partial-reflection sounder and blunt probe measurements.

satisfactory and support the validity of the partial reflection data.

Data from the partial reflection station were also used to make comparisons with data from in-situ probes. On September 29, 1977, a subsonic blunt probe was launched at WSMR. Partial-reflection data were obtained for a time near the launch of this probe. Results of this comparison are shown in Fig. 6, which indicates excellent agreement in the area where the measurements overlap.[8] The amount of agreement between these two techniques is significant. It provides a check on the partial reflection data as well as verifying York's technique for deriving electron densities from blunt probe data. Prior to the experimental work completed by York et al.,[9] the separation of the negative charge data obtained by the blunt probe did not yield electron density values appropriate for the particular altitudes.

Figure 7 contains median values of electron densities obtained by the University of Illinois experimenters, using Langmuir probes during quiet sun conditions.[10] These values are compared with the mean of electron density obtained from the partial reflection sounder at WSMR with comparable solar zenith angles. In general, there appears to be good agreement between both sets of data, considering the fact that the data were obtained at different locations using different techniques.

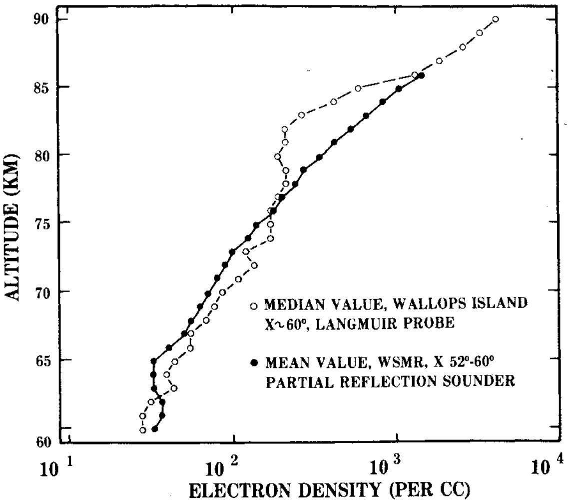

Fig. 7 Electron densities obtained from the partial-reflection sounder and Langmuir probe measurements.

Some of the differences noted in this comparison may be due to the number of data samples and the differences between the two techniques. The partial-reflection data indicate a relatively continuous slope of electron density with altitude, whereas the in-situ soundings indicate a change in slope at approximately 82 km. This feature appears in numerous in-situ probe soundings and has been classified as "the ledge" in electron densities. The partial reflection technique would tend to smooth over this ledge because of the lack of altitude resolution. The smallest altitude interval that the partial reflection experiment can resolve is 3 km, while much finer altitude detail can be obtained from the in-situ probe. Also, the partial-reflection data would tend to smooth the ledge if it varied in altitude because of the larger data sample used in computing the mean values. Considering these differences, there appears to be good agreement between the two techniques.

Summary

Partial reflection measurement is a technique for remotely sounding the ionospheric *D*-region. Comparisons with atmospheric models and in-situ probes indicate relatively good agreement between the different measurement and model values. The partial-reflection method lends itself to long-term studies of the *D*-region to determine seasonal and diurnal variability. It can also serve to provide background data on solar eclipse or special event studies; however, it is limited in providing fine-scale altitude and short-term varying structure. For special events, the ideal situation would be to utilize partial-reflections and in-situ probes simultaneously.

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