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SATELLITE OBSERVATIONS OF THE EQUATORIAL IONOSPHERE

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SUMMARY

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A method is presented for measuring total electron content by observing the Faraday effect on satellite beacon transmitters at a station located on the magnetic equator. This method is applied to data observed at Huancayo, Peru, between September 1961 and February 1962. The total electron content at the magnetic equator was found to have nearly a 10 to 1 diurnal variation with a maximum of 4×10^{17} electrons/m^2 near 1500 hours. Values of the thickness parameter $(\int N dh)/N_{max}$ for the observational period show an anomalous increase around layer sunrise which is attributed to a departure from thermal equilibrium.

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INTRODUCTION

Faraday rotation techniques have been used in conjunction with lunar radar investigations by other workers (References 1 and 2) to measure the total electron content of the ionosphere at mid-latitudes. The ambiguity in the number of polarization rotations was resolved by using two closely spaced frequencies. More recently beacon satellites have been used to determine total electron content with the dispersive Doppler (also called differential Doppler) and Faraday rotation techniques (References 3 to 6). The total number of rotations has been estimated with reasonable accuracy by estimating the small number of rotations along a ray path that approaches transverse conditions (References 3 and 7). For a station located on the geomagnetic equator, there is a time during each satellite pass when the ray path and geomagnetic field are perpendicular and there are essentially no rotations.

FARADAY ROTATION

If it is assumed that both magneto-ionic modes follow a common ray path determined by the isotropic indices, the total rotation, in radians, is given by:

$$\Omega = \frac{\pi}{\lambda} \int (\mu_+ - \mu_-) \, ds \, . \tag{1}$$

Assume an index of refraction of the form (Reference 8):

$$\mu^2 = 1 - \frac{X}{1 \pm Y_L} \, , \tag{2}$$

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†A similar paper was published in *J. Geophys. Res.* 67(12):4601-4605, November 1962.

where

$$X = \frac{f_N^2}{f^2} ,$$

$$Y_L = \frac{f_L}{f} ,$$

in which

f = wave frequency,

f_N = plasma frequency, and

f_L = the component of the gyro frequency along the ray path.

A binomial expansion of Equation 2 neglecting all but first order terms yield the result

$$\Omega = \frac{\pi}{\lambda} \int_{\substack{\text{RAY}\\\text{PATH}}} \frac{XY_L}{1 - Y_L^2} \, ds \; . \tag{3}$$

For a spherically stratified ionosphere, Equation 3 becomes, upon substitution for X and Y_L:

$$\Omega = 2.36 \times 10^4 \frac{\overline{B_L \sec \chi} \int N \, dh}{f^2} , \tag{4}$$

where

B_L = component of the magnetic field along the ray path in webers/m^2,

χ = zenith angle of the ray path,

N = electron density in electrons/m^3,

h = height, and

$\overline{B_L \sec \chi}$ = a weighted mean for the range of integration.

When the second-order terms of the binomial expansion of Equation 2 and refraction (Reference 9) are considered, the correct second-order expression is:

$$\Omega = \frac{\pi}{\lambda} \sec \chi_0 \int_{\substack{\text{RAY}\\\text{PATH}}} XY_L \left(1 + \frac{X}{2} + \frac{X \tan^2 \chi_0}{2}\right) dh \; , \tag{5}$$

where χ_0 is the zenith angle of the ray at the ground (Reference 5).

At 54 Mc the refraction correction may be neglected for small zenith angles ($\chi_0 < 50$ degrees). Furthermore, the integration may be carried out along a straight-line ray path without appreciable loss of accuracy. If a reasonable distribution of ionization is assumed and refraction is neglected, Equation 5 becomes

$$\Omega = 2.36 \times 10^4 \frac{\overline{B_L \sec} \int N\,dh}{f^2 \left[1 - 0.35 \left(\frac{f_0 F_2}{f}\right)^2\right]}, \tag{6}$$

where f_0F2 is the critical frequency of the F region of the ionosphere.

It is important to bear in mind the assumptions made in the derivation of Equations 3 through 6:

1. The propagation path satisfies the quasi-longitudinal (QL) approximation of the Appleton-Hartree formula (Reference 8).
2. In the region where the index of refraction differs from unity, the wave frequency is much greater than the electron gyro-frequency, the plasma frequency, and the electron collision frequency.

The height at which $\overline{B_L \sec \chi}$ is the weighted mean for the range of integration can be determined if the N-h profile is known. A study of published N-h profiles indicates that the mean height is 400 ± 25 km for integration to 1000 km (Reference 10). For the results reported here, $\overline{B_L \sec \chi}$ has been evaluated by using a spherical harmonic analysis of the main field. The coefficients used in this analysis were obtained from Reference 11.

TRANSVERSE PROPAGATION REGION

It is important to consider the behavior of the polarization through the quasi-transverse (QT) region. Figure 1 illustrates the mode behavior in the QT region and is calculated for a wave frequency of 54 Mc with a typical daytime ionosphere model. Under QL conditions, the two magneto-ionic modes are circularly polarized and the phase path difference between modes, expressed in wavelengths, is the total number of half-rotations of the plane of polarization.

As the transverse region is approached, the mode polarizations become elliptical and their respective indices depart from the QL approximation. The QT region may then be identified from the resulting elliptical wave polarization. Because of this resulting elliptical wave polarization, the phase path difference cannot be simply interpreted as rotation of the plane of polarization (Reference 12). The typical time scale for the 54-Mc ray path from an earth satellite in a 1000-km circular orbit to sweep through this transverse region indicates that the QL approximation (Equation 6) may be applied accurately at 54 Mc to deduce total rotation unambiguously throughout a satellite pass except for about 6 seconds on each side of the transverse point.

OBSERVATIONS

The satellite, Transit 4A (1961 o1), was launched into an approximately circular orbit inclined 67 degrees to the equator. The satellite is oriented along the local geomagnetic field. The 54-Mc radiation pattern is such that linear polarization with stable orientation is radiated near the magnetic equator.

Since September 1960 this satellite has been observed by a station located on the magnetic equator near Huancayo, Peru (Reference 13). The signals are received on fixed folded-dipole antennas by fixed-gain crystal controlled receivers, the outputs of which are recorded on magnetic tape along with timing marks from a clock.

Figure 2 is a pen record produced from the magnetic tape of a typical midday pass at Huancayo during local summer. The top channel displays the timing marks, and the other two

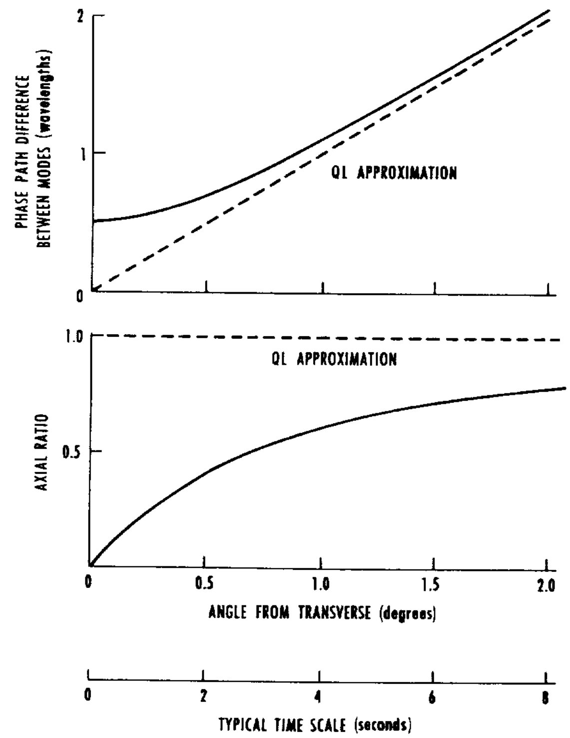

Figure 1—Parameters for 54-Mc propagation in a typical daytime ionosphere.

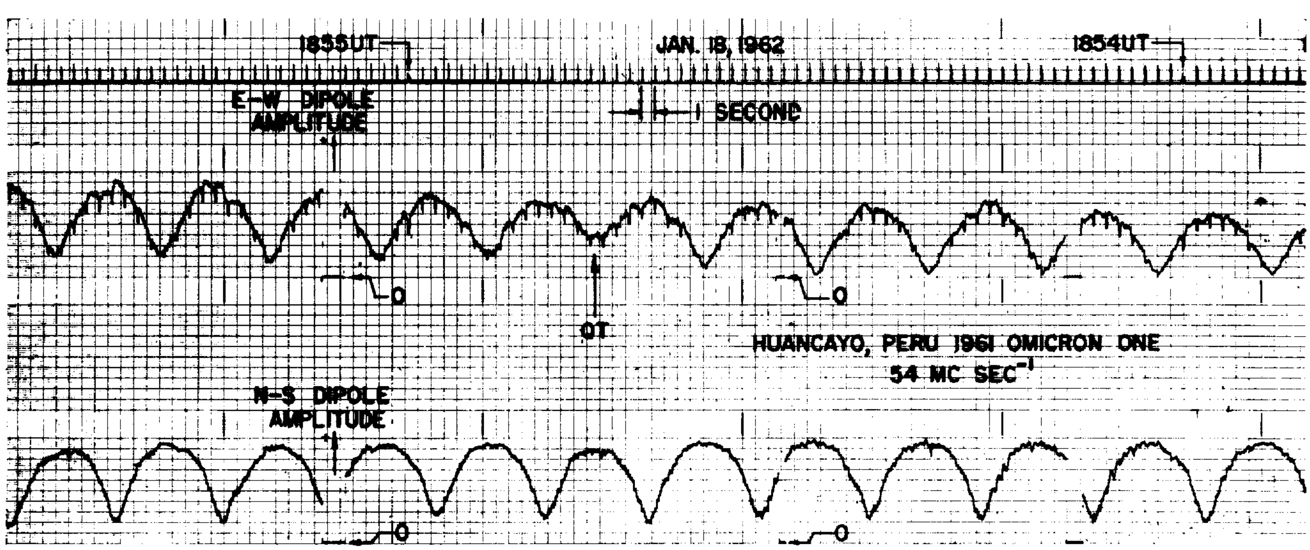

Figure 2—Typical satellite Faraday rotation record. Taken at 54 Mc from Satellite 1961 o1 at Huancayo, Peru, on January 18, 1962.

channels are linear displays of the amplitude received on two oriented dipole antennas. The spacing between nulls on each channel corresponds to a rotation of the plane of polarization of π radians; for the northbound pass shown here the rotation is from north into west.

At 1854 UT, the satellite is in the southern magnetic hemisphere and the propagation is QL. Near 1854:45 UT, the wave polarization is elliptical, and this is identified as the transverse region QT. This elliptical polarization is observed for several seconds during each daytime pass, as Figure 1 indicates.

TOTAL ELECTRON CONTENT

Total electron content is measured by simply counting the number of rotations observed between the transverse point QT and some later time when the satellite is in the QL region. The satellite location at this time is obtained from the orbital ephemeris and used to compute the term $\overline{B_L \sec \chi}$ entering in Equation 6. From Equation 6 it is possible to obtain values of total electron content with better than 10 percent accuracy.

The values obtained from several applications of this technique to each satellite pass are then averaged (standard deviation less than 5 percent) and plotted as a function of local mean time (Figure 3). The nodal precession of this satellite results in passes over the station occurring, on the average, earlier each day so the diurnal variation in total electron content could be measured over a six-week interval. The data plotted in Figure 3, observed from September 1960 through January 1962, correspond to several cycles of quiet-day observations.

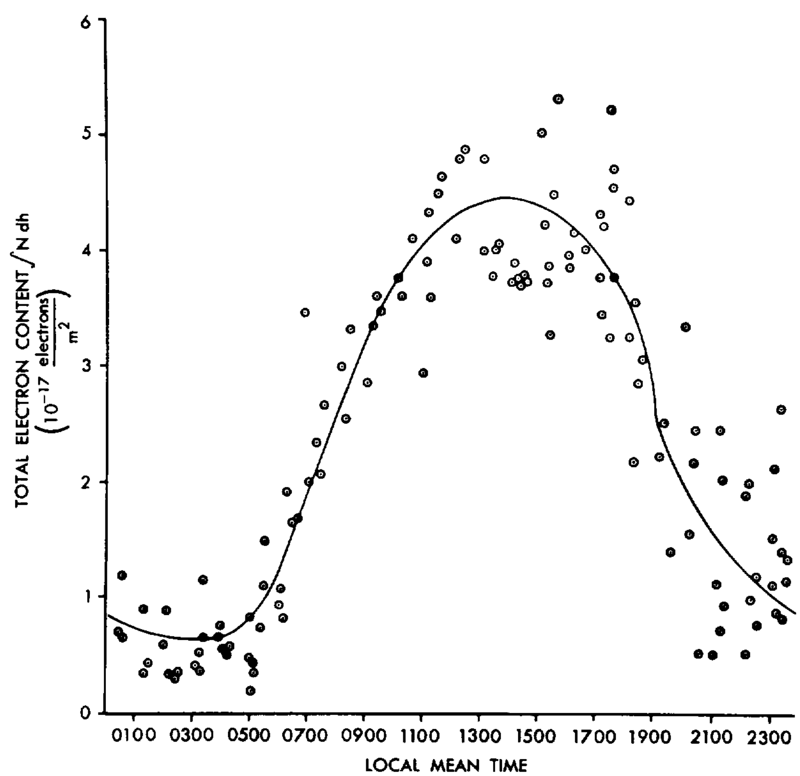

Figure 3—Diurnal variation of total electron content at the magnetic equator, September 1961-January 1962.

No seasonal variation was evident on the data and this is not unusual when we consider that the solar noon zenith angle was less than 12 degrees over this observational period.

The nearly 10 to 1 diurnal variation is the outstanding feature of the values of total electron content. A minimum of about 0.5×10^{17} electrons/m^2 at 0300 hours and a maximum greater than 4×10^{17} electrons/m^2 near 1500 hours may be contrasted with mid-latitude values for the same period which show a broad maximum of about 2×10^{17} electrons/m^2 near 1600 hours and nearly a 2 to 1 diurnal variation (W. J. Ross, private communication).

THICKNESS PARAMETER

Since the major contribution to the total electron content is in the F region, the thickness parameter $\left(\int N\,dh\right)/N_{max}$ is closely associated with the scale height of the F region. If the N-h profile is a Chapman function with constant scale height, the total content is given by

$$\int N\,dh = 4.13\,N_{max}\,H\ , \tag{7}$$

where

$$H = \frac{k\,(T_e + T_i)}{mg} \tag{8}$$

in which

K = Boltzmann's constant, 1.38×10^{-23} joule/°K,

T_e = electron temperature

T_i = ion temperature

m = molecular mass, and

g = acceleration of gravity.

For N-h profiles other than that of the familiar Chapman expression, Equation 7 will be modified by a different constant.

The thickness parameter $\left(\int N\,dh\right)/N_{max}$ is plotted as a function of local mean time in Figure 4 along with theoretical values of neutral gas temperature based on the value of the 10.7-cm solar flux appropriate to the observational period (Reference 14). Values of N_{max} were obtained from extrapolation in solar time of vertical incidence values observed at Huancayo (Instituto Geofisico del Peru, private correspondence). The hourly mean curve of the thickness parameter shows a distinct anomaly near sunrise. Measurements at Lima, Peru, of the effective scattering cross-section of free electrons by the radar backscatter technique (Reference 15) indicate that only during this sunrise period are departures from thermal equilibrium significant $\left(T_e/T_i = 2\right)$. It is suggested that the anomaly in the thickness parameter near sunrise is due to this departure from thermal equilibrium. Bauer

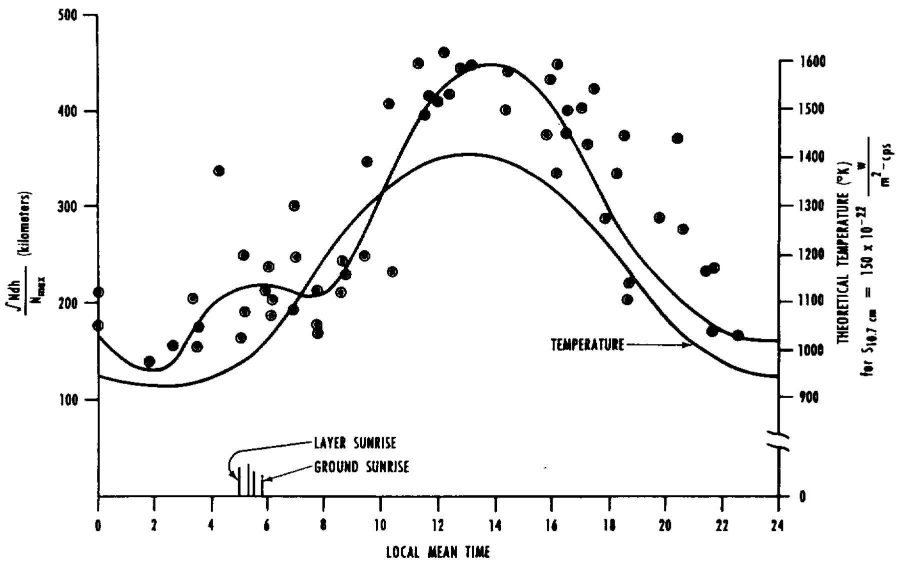

Figure 4—Diurnal variation of the equatorial thickness parameter$\left(\int N\,dh\right)/N_{max}$. September 1961-January 1962.

(Reference 16) and Evans and Taylor (Reference 2) have observed similar departures in the effective scale height during the sunrise period.

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