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PLASMASPHERIC EFFECTS ON ONE-WAY SATELLITE TIMING SIGNALS

F. J. Gorman, Jr. and H. Soicher
Communications/Automatic Data Processing Laboratory
U. S. Army Electronics Command

ABSTRACT

At the 1973 PTTI Planning Meeting, the effects of the ionospheric retardation of satellite-emitted timing signals was presented. The retardation at the navigation frequencies, which is proportional to the total ionospheric electron content (TEC), was determined by Faraday polarization measurements of VHF emissions of a geostationary satellite. The polarization data yielded TEC up to ∿1200 km only, since the measurement technique is based on the Faraday effect which is weighted by the terrestrial magnetic field.

The radio beacon experiment aboard the recently launched geostationary ATS-6 offers the unique opportunity to determine TEC, or equivalently, the signal propagation delay, to geostationary altitudes. The beacon package provides the opportunity to conduct two relevant experiments. The first utilizes the Faraday rotation technique for determination of TEC. The second utilizes the dispersive group delay technique which is independent of the magnetic field and determines TEC to geostationary altitudes. The difference between the values of the integrated electron content obtained by the two techniques yields the content from ∿1200 km to geostationary altitudes, i.e., the plasmaspheric electron content.

Faraday rotation and dispersive group delay observations have been conducted at Fort Monmouth since the launch of ATS-6 in late May, 1974. The plasmaspheric content exhibited diurnal as well as day-to-day variations. Its absolute magnitude varied from 1 to ∿8 TEC units (10^{16} e/m^2). At night the plasmaspheric content was nearly always above 50% of the ionospheric content and on occasion exceeded 100%. During the day, this ratio averaged ∿35%.

INTRODUCTION

At the 1973 Precise Time and Time Interval (PTTI) Symposium, the effects of the ionospheric total electron content on the accuracy of transionospheric satellite navigation systems were discussed [1]. It was shown that in traversing the ionosphere, a propagating navigation signal is slowed by an amount which is directly proportional to the total electron content (TEC) along its path. This gives an apparent range that is larger than the equivalent free-space range. If the TEC is known, or is measured, a correction to the ranging may be applied. The TEC may be measured in real time, provided the user has dual-frequency capabilities. However, substantial reduction in the cost of user equipment could be realized if the navigation system used only one frequency. In such a case, the ionospheric time-delay will have to be determined through empirical modeling techniques based on existing and future global electron content data, and will be transmitted to the user for correction via the navigating signal.

Most TEC data to date has been obtained by the Faraday polarization rotation technique. The Faraday rotation is a terrestrial-magnetic-field-dependent phenomenon, and its magnitude is heavily weighted near the earth. It is therefore considered to provide electron content values at altitudes below ∿1200 km. The navigation system will utilize satellites at considerably higher altitudes. The navigating signal will be slowed by free electrons in the ionosphere as well as in the plasmasphere (i.e., at altitudes > 1200 km). The corrections for TEC supplied by a model based on the Faraday technique will not adequately compensate for the total signal delay since the free electrons in the plasmasphere will not be accounted for. The radio beacon experiment (RBE) aboard the geostationary Applied Technology Satellite (ATS-6 launched in May 1974) permits the accumulation of TEC data which includes the plasmaspheric content. The technique utilized is the dispersive-group-delay technique which is independent of the terrestrial-magnetic-field and hence yields the integrated electron content from observer to satellite.

THE FARADAY AND DISPERSIVE-GROUP DELAY METHODS

The Faraday polarization rotation technique has long been used in measurement of TEC. In the high-frequency and quasi-longitudinal approximations, the two magneto-ionic modes are nearly circularly polarized in opposite senses; thus a plane polarized wave traversing the ionosphere may be regarded as the vector sum of the ordinary and extraordinary components. Since these two components travel at different phase velocities, the plane of polarization rotates continually along the signal's path. The total rotation from the signal source to the observer is related to the total electron content by the expression:

$$a = \frac{k}{f^2}\int_0^S B\cos\theta N ds = \frac{k}{f^2}\int_0^S (B\cos\theta\sec\chi)N dh, \qquad (1)$$

where $k = 2.36 \times 10^{-5}$, B is the local magnetic field flux density in gammas, θ is the angle between the radio wave normal and the magnetic field direction, and χ is the angle between the wave normal and the vertical. Since B decreases inversely with the cube of the geocentric distance, and since the electron density decreases exponentially with altitude above F_2 max (∿ 300 km), the integral is heavily weighted near the earth and is considered to provide electron content values at altitudes below ∿1200 km.

The term $M = B\cos\theta\sec\chi$ in Eq. (1) may be taken out of the integral sign and replaced by its value at a "mean" ionospheric altitude (420 km). Equation (1) then becomes:

$$a = \frac{k}{f^2}\bar{M}\cdot\int_{\text{Ionosphere}} N dh = \frac{k}{f^2}\bar{M}N_I, \qquad (2)$$

where N_I is the ionospheric total electron content measured by the Faraday rotation technique. At Fort Monmouth, where the numerical value for $\bar{M}$ is 56292 γ, for $N_I = 10^{16}$ e/m^2 defined as 1 TEC unit, we calculate a = 38.83° (for f = 140 MHz).

Using the dispersive-group-delay technique, the phase of the modulation envelope between a carrier and its sideband is compared at two frequencies (nominally f = 140 and 360 MHz with sideband displacements of $\Delta f = +1$ MHz). Since the phase is insensitive to the earth's magnetic-field, this technique yields the number of electrons along the entire path from satellite to observer (N_T).

The time delay of a signal propagated through a medium containing free electrons with a group velocity v_g is:

$$t = \int_0^S \frac{ds}{v_g} = \frac{1}{c}\int_0^S \mu_g \, ds = \frac{1}{c}\int_0^S \left(1 + \frac{kN}{f^2}\right) ds, \qquad (3)$$

where μ_g is the group refractive index and c is the velocity of light in vacuum. For two signals at frequencies f_1 and f_2, the differential time delay is:

$$\Delta t = \frac{40.3}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \int_0^S N ds. \qquad (4)$$

If the two signals are modulated by a sideband separated by an equal Δf, then the modulation time delay Δt_m is equal to the differential group time delay, i.e.,

$$\Delta t = \Delta t_m = \frac{\Delta\phi}{360} \frac{1}{\Delta f} = \frac{40.3}{c} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \int_0^S N ds, \qquad (5)$$

where $\Delta\phi$ is the differential modulation phase shift in degrees. It follows that

$$\int_{\text{Total}} N dh = N_T = \frac{\Delta\phi}{360} \frac{1}{\Delta f} \frac{c(\sec\chi)^{-1}}{40.3} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)^{-1}. \qquad (6)$$

At Fort Monmouth for $N_T = 10^{16}$, a phase difference of 30.55° is measured.

THE DATA

The variation of the total electron contents measured by the Faraday and group delay techniques is shown in Fig. 1 at 15-minute intervals for the time period 1600 EDT on 3 July to 0800 EDT on 8 July. The temporal variations of N_I and N_T were nearly parallel with most density variations observed on both curves.

Prominent during the time period covered were the large increases of total electron content in response to two large solar flares (see Fig. 1). Between 0945 EDT and 1000 EDT on 4 July, N_I increased by $\sim 1.5 \times 10^{16}$ e/m^2, while N_T increased by $\sim 2 \times 10^{16}$ e/m^2. Since the content values in Fig. 1 are given for every 15 minutes, the full increase of N_I and N_T is not indicated there. Starting at ∿0953 EDT, N_I increased by $\sim 3.3 \times 10^{16}$ e/m^2 in 3 minutes and then decayed to its value at 1000 EDT. At the same time, N_T increased by approximately the same amount. On 5 July between 1730 and 1745, N_I increased by $\sim 1.9 \times 10^{16}$, while N_T increased by $\sim 2.3 \times 10^{16}$. The rapid increases started at 1740 EDT with N_I increasing by $\sim 2.1 \times 10^{16}$ in 6 minutes; N_T increased similarly.

The equivalent signal-delay time at 1.6 GHz (in the navigation frequency band) corresponding to the vertical electron content distribution was always below 15 nanoseconds for the time period reported. On different days, the time delay varied by as much as 60%. Between maximum and minimum on any one day, the largest factor was 12. Superimposed on the normal diurnal variations of the content were quasi-sinusoidal variations which usually occur near the time period of maximum content of the daily cycle. These variations are caused by ionospheric irregularities.

The dispersive-group-delay technique measures the total electron content from observer to satellite, whereas the Faraday technique yields the content only in the vicinity of the earth (i.e., up to ∿1200 km). The difference between the two yields the content above ∿1200 km, which is referred to as the plasmaspheric content, N_P.

It follows that

$$N_P = N_T - N_I. \tag{8}$$

N_P is plotted in Fig. 2 for the same time intervals and for the same time period as that of Fig. 1. The plasmaspheric content ranged from 1 to ∿8 TEC units, or equivalently from ∿0.5 to over 4 nanoseconds for a 1.6 GHz signal. Generally, the minimum of the plasmaspheric content occurred near ionospheric sunrise while its maximum occurred near ionospheric sunset. During any one day, the diurnal variation was not as pronounced as the corresponding variation of the total or ionospheric electron contents. The maximum variation (by a factor of ∿3.4) was observed on 5 July. This is compared to a total content variation by a factor of 12 for the same day. The day-to-day variability exhibited changes of up to 300% during comparable local time periods (e.g., on 4 and 7 July during nighttime hours).

Of great importance to the applicability of global time-delay models based on TEC data obtained by the Faraday rotation technique, is the magnitude and variation of the ratio of plasmaspheric to the ionospheric time delays, or equivalently (N_P/N_I). This ratio (see Fig. 3) shows a diurnal as well as a day-to-day variability. Between 0100 and 0700 EDT, the ratio was nearly always above 50% and on occasions exceeded 100%. After this time-period, the ratio decreased to its minimum at ∿1100 EDT, after which time it increased with the time of day. From 0700-0100 EDT, the ratio average increased from ∿30 % to ∿40 %.

The ratio of the plasmaspheric to the total time-delays due to free electrons along the signal's path, or equivalently N_P/N_T, is shown in Fig. 4. The diurnal and day-to-day variability of this ratio is similar to that of N_P/N_I. During the night the ratio was high, reaching a value up to 70%. During the day, the ratio was lower, averaging from ∿25% to 30%.

CONCLUSIONS

Preliminary results of the radio beacon experiment of the ATS-6 indicate the magnitude and variation of the plasmaspheric electron content. The group path delay of a navigation signal due to free electrons in the plasmasphere cannot be neglected when it is compared to the delay due to the ionosphere. Group path delay prediction models based on Faraday data do not adequately compensate for the total delay; at night, they may be off by more than 50%, and during the day by an average of ∿35%. This is in addition to other prediction errors, i.e., differences between observed and predicted values of the delay times. Furthermore, ionospheric (Faraday) prediction models cannot be corrected by adding a constant offset to account for the plasmaspheric delay, since the plasmaspheric content exhibited a diurnal and day-to-day variation. Fortunately, the highest ratio of plasmaspheric-to-ionospheric delay time occurs at night, when the total delay time is relatively small.

The data reported here was taken at a mid-latitude station during the quiet phase of the solar cycle. During such a phase at such a location, the group delay is generally small and modeling schemes yield corrections within the accuracy requirements of the proposed navigation systems. It remains to be seen if the observed ratios of plasmaspheric-to-ionospheric delays will be maintained at other geographic locations, and when delay times will be large, such as during the maximum phase of the solar cycle. If such ratios are maintained during the maximum of the cycle, neglecting the plasmaspheric content will cause errors exceeding the accuracy requirement of the system.

REFERENCE

[1] H. Soicher and F. J. Gorman, Jr., "Ionospheric effects on one-way satellite timing signals," Proc. Fifth Annual PTTI Planning Meeting (Greenbelt, Maryland; December 4-6, 1973), NASA Report X-814-74-225, December 4-6, 1973.

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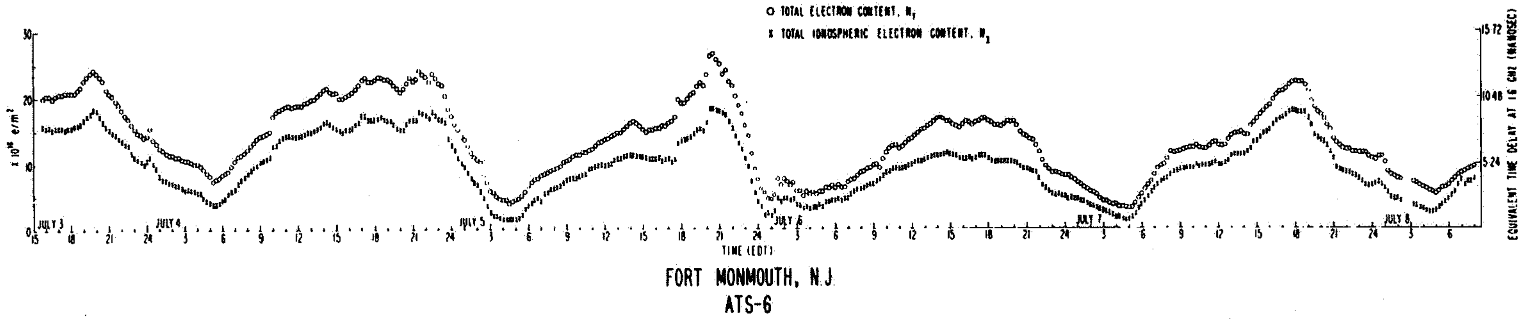

Fig. 1. Variation of total electron content, $N_T^{(\odot)}$, and ionospheric electron content, $N_I^{(x)}$, at 15-minute intervals from 1600 EDT, 3 July 1974, to 0800 EDT, 8 July 1974, at Fort Monmouth, N. J. (equivalent time-delay for 1.6 GHz signals are also indicated).

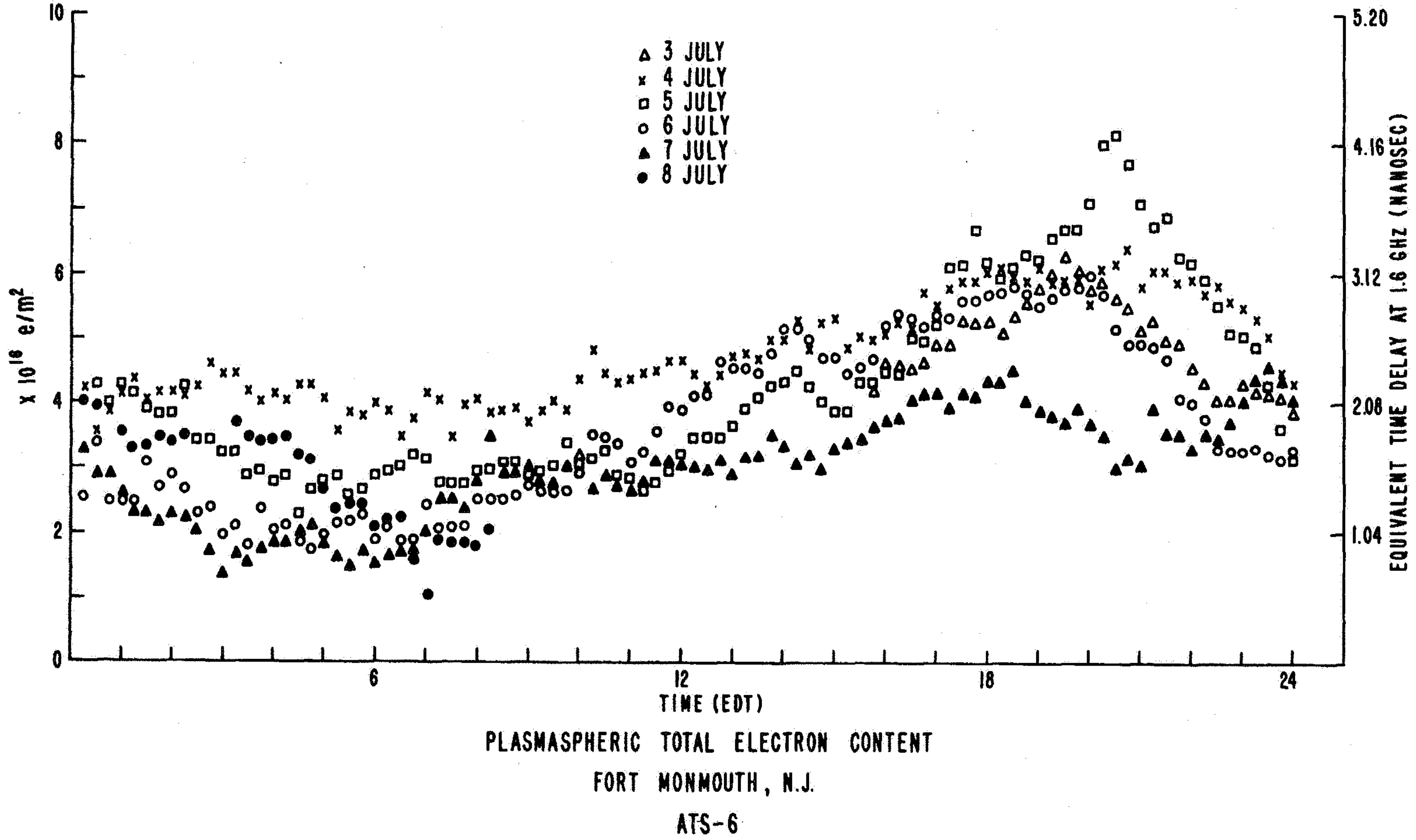

Fig. 2. Variation of the plasmaspheric electron content at 15-minute intervals for same time period as in Fig. 1.

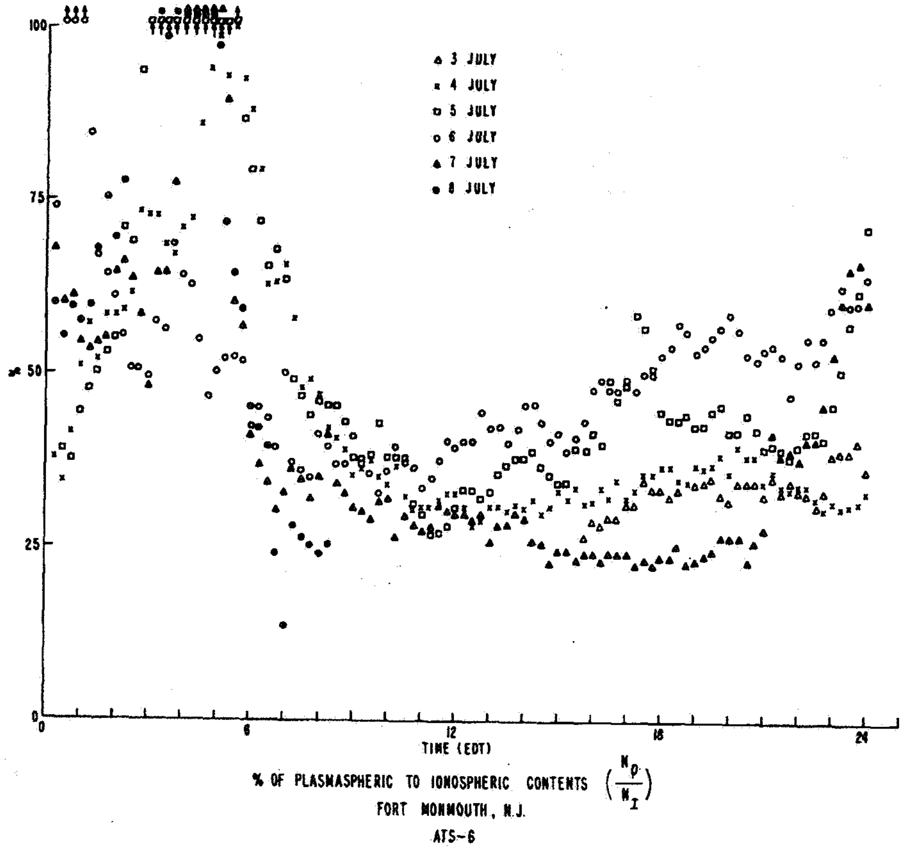

Fig. 3. Variation of the ratio of plasmaspheric to ionospheric electron contents (in percent) at 15-minute intervals for same time period as in Fig. 1.

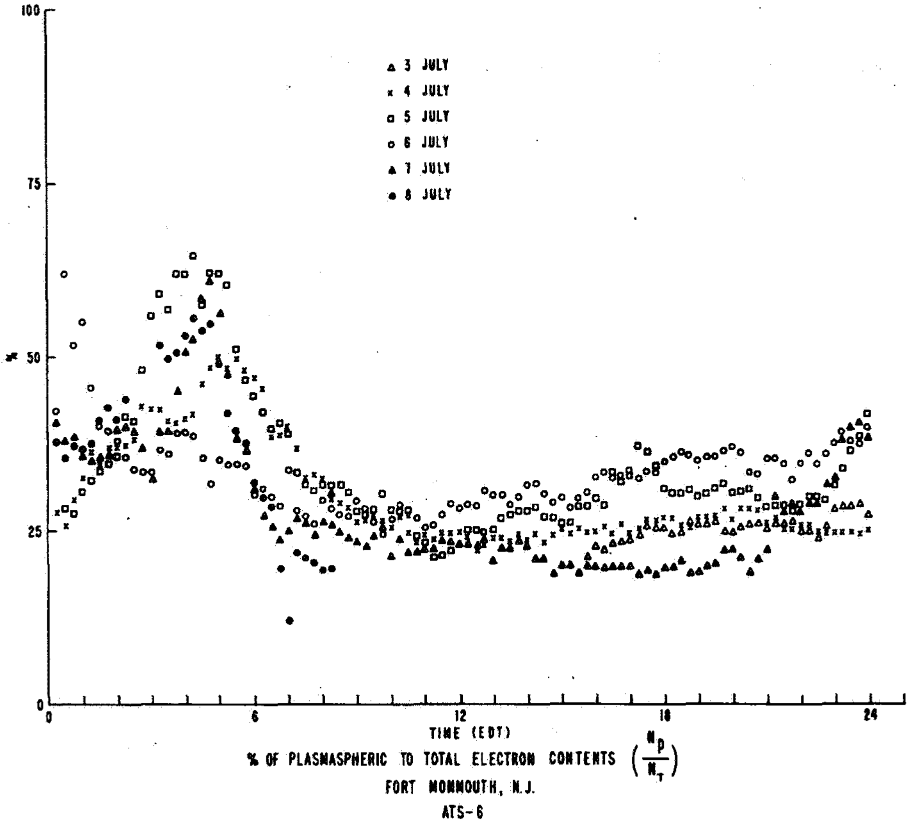

Fig. 4. Variation of the ratio of plasmaspheric to total electron contents (in percent) at 15-minute intervals for same time period as in Fig. 1.