IONOSPHERIC EFFECTS ON ONE-WAY TIMING SIGNALS

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ABSTRACT

A proposed navigation concept requires that a user measure the time-delay that satellite-emitted signals experience in traversing the distance between satellite and user. Simultaneous measurement of the propagation time from four different satellites permits the user to determine his position and clock bias if satellite ephemerides and signal propagation velocity are known. A pulse propagating through the ionosphere is slowed down somewhat, giving an apparent range that is larger than the equivalent free space range. The difference between the apparent range and the true range, or the free space velocity and the true velocity, is the quantity of interest. This quantity is directly proportional to the total electron content along the path of the propagating signal. Thus, if the total electron content is known, or is measured, a perfect correction to ranging could be performed.

Faraday polarization measurements are continuously being taken at Fort Monmouth, N. J., using beacon emissions of the ATS-3 (137.35 MHz) satellite, which is in a geostationary orbit. The polarization data yield electron content values up to ~1500 km since the measurement technique is based on the Faraday effect which is weighted by the geomagnetic field. Day-to-day variability of the diurnal variation of total electron content values is present with differences of up to 50% or more not being uncommon. In addition, superposed on the overall diurnal variation are smaller scale variations of ~ 5 to 10% of the total content which are attributed to ionospheric density irregularities.

Future experiments planned for the emissions of the forthcoming ATS-F will permit Faraday rotation, dispersive phase, and dispersive group delay measurements. The latter two will give the integrated electron density to geostationary altitudes while the first will give the density integrated to ~ 1500 km. The difference—referred to as the exospheric content—will yield the currently unknown propagation time delay from ground to geostationary altitudes.

INTRODUCTION

A space-based radio navigation system could provide military and civilian users with precise three-dimensional position and velocity data.

The navigation signals contain data such as satellite identity, real-time ephemerides information, system time and other data. To determine his position and velocity, the user cross-correlates the coded time signal received from the satellite with the same coded time signal generated in his receiver. The relative phase, or equivalently the time displacement between the user's receiver and the incoming code, determines the range to the satellite. Simultaneous measurment of such relative phases from four different satellites permits the user to determine his range and his clock bias with respect to the satellite's position and clock respectively. In addition to such range measurements, corresponding range-rates are measured by the carrier frequency Doppler shift of each signal and the corresponding motion of the particular satellite as described by the ephemerides data.

The range from user to the various satellites is, of course, not the correct geometric range. A propagating navigation signal is slowed down by the ionosphere by an amount proportional to the total electron content along its path. The electron content 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 uses only one frequency. In such a case, the ionospheric time delay will have to be determined through empirical modelling techniques, based on existing and future global electron content data, and will be transmitted to the user for correction via the navigating signal. To calculate the true range, one must determine the group velocity of the signal along the path.

The transit time of a transionospheric signal from a satellite to a ground observer is:

$$t = \int_O^S \frac{ds}{v_g} = \frac{1}{c} \int_O^S n_g \, ds, \qquad (1)$$

where ds is an element of distance along the signal's path and v_g and n_g are the group velocity of the signal and the group refraction index respectively, c is the speed of light, and O and S are the observer and satellite position respectively. In the high-frequency approximation, the group index of refraction is:

$$n_g = 1 + \frac{40.3\ N}{f^2}, \qquad (2)$$

where N is the electron density per meter cubed, and f is the operating frequency in Hz. Equation 1 becomes:

$$t = \frac{1}{c} \int_0^S ds + \frac{40.3}{cf^2} \int_0^S N\, ds. \tag{3}$$

The first term in Equation 3 represents the free space signal transit time, while the second term represents the signal's excess time delay in the ionosphere. The excess time delay is inversely proportional to the frequency squared so that in the L band (the proposed navigation frequency is in the 1600 MHz band) it is very small. However, the precision required by the system is such that the ionospheric time-delay has to be accounted for.

The variation of the time delay with electron content for 1.6 GHz, 400 MHz, and 150 MHz is shown in Figure 1. At 1.6 GHz, the excess delay times are 0.524 nanoseconds and 52.4 nanoseconds for a total content of 10^{16} el/m^2 and 10^{18} el/m^2 respectively, which are the lower and upper bounds of the normal vertical ionospheric electron content. For an oblique signal path, the total content increases by an amount proportional to the additional path length (assuming spherical stratification of the ionospheric density distribution). At low elevations, i.e. below 10°, the slant total content exceeds the vertical content (i.e. elevation angle = 90°) by a factor of 3; while at 40° elevation, the slant content exceeds the vertical content by a factor of 1.5. Thus, for the vertical content at the upper bound and a low-elevation signal path, the total time delay introduced by the ionosphere is ~150 nanoseconds at 1.6 GHz.

THE FARADAY ROTATION

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 the 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:

$$a = \frac{k}{f^2} \int_0^S B \cos\theta \, N ds = \frac{k}{f^2} \int_0^S (B \cos\theta \sec\chi)\, N\, dh, \tag{4}$$

where k = 2.36 x 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

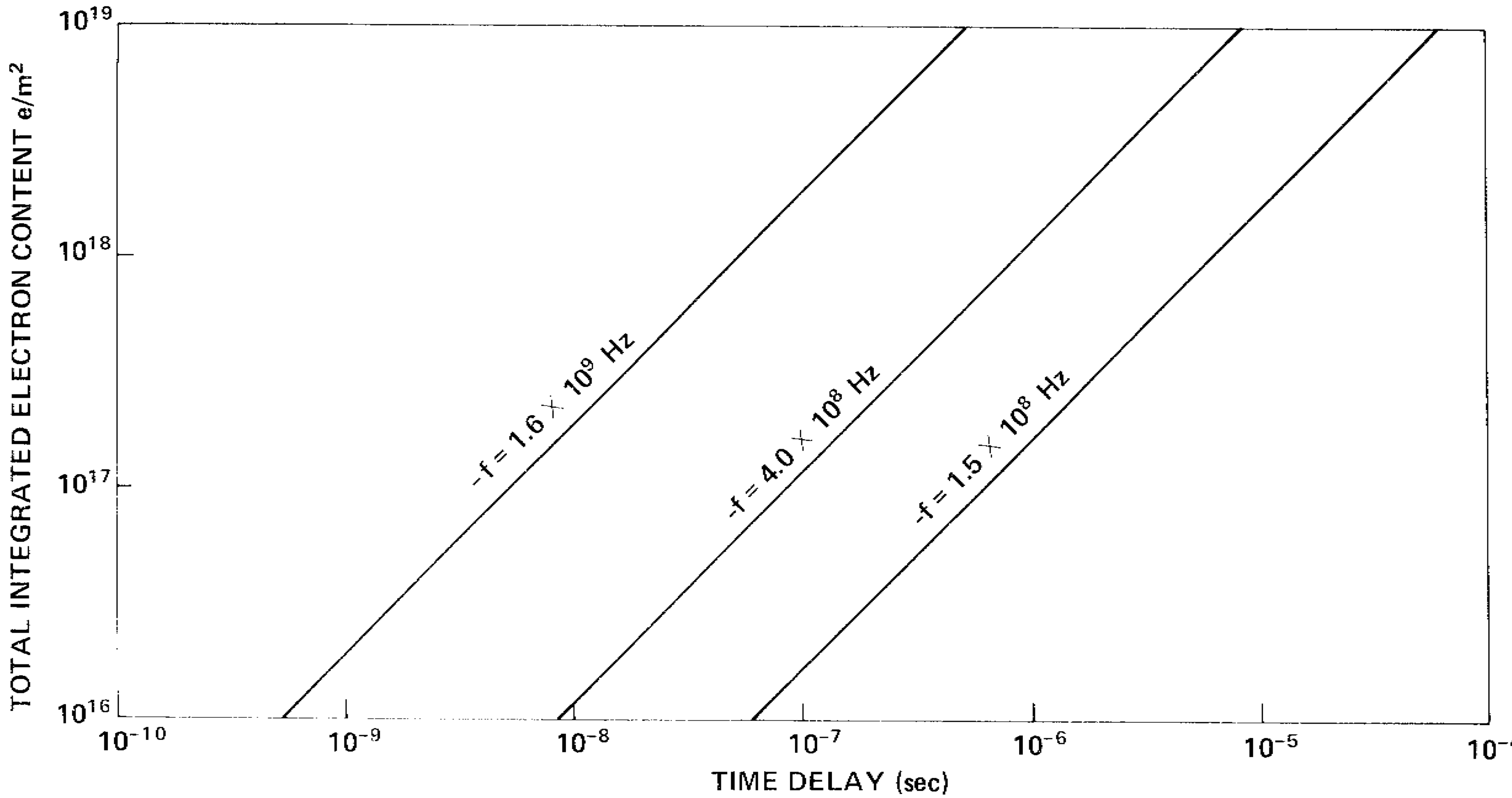

Figure 1. Ionospheric Excess Time Delay vs. Integrated Electron Content for 150 MHz, 400 MHz, and 1600 MHz Signals

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 ($\sim$300 km), the integral is heavily weighted near the earth and is considered to provide electron content values below ~1500 km.

The term $M = B \cos \theta \sec \chi$ in Equation 4 may be taken out of the integral sign and replaced by its value at a "mean" ionospheric altitude. Equation 4 then becomes:

$$a = \frac{k}{f^2} \bar{M} \int N\, dh. \qquad (5)$$

The correct conversion of polarization rotation data to electron content data depends on the altitude chosen for the calculation of $\bar{M}$. A method for arriving at such an altitude is shown in Figure 2. The height distribution of the electron density was obtained by converting the topside and bottomside ionograms recorded at close geographic proximity to Fort Monmouth into electron density profiles. Polarization-rotation data on 40 MHz was obtained from an overhead orbit of the S-66 satellite (nominal altitude = 100 km). The vertical component of the geomagnetic field (curve B) was derived from the spikes in the topside ionogram which measure the gyrofrequency at the satellite altitude. At lower altitudes, the field intensity was calculated from the reference at the satellite using the magnetic dipole approximation. Numerical, successive integration of the product $N \cdot B$ produced the curve of the polarization angle rotation Σa which ends with the total polarization angle observed at the ground ("measured" in Figure 2). The next procedure was integration of the bottomside and topside profiles to obtain $\int N\, dh$. Next, the magnetic field component, $\bar{M}$, was obtained from Equation 5 by inserting the measured total polarization angle Σa, and $\int N\, dh$ of the integrated profiles. The figure indicates that for the above example $\bar{M}$ corresponds to a local field value about 60 km above h_{max}. Figure 2 indicates further that 90% of the total polarization-angle rotation took place below 550 km.

THE DATA

The need for an empirical model of the global distribution of the ionospheric electron content for prediction purposes has focussed attention on the availability of such data on a global basis and on future requirements. The advent of beacon emissions from geostationary satellites has clearly facilitated data gathering at wide geographic areas, with the diurnal variation of content being obtained without contamination by satellite orbital changes. With low flying satellites, months of data from a particular station are necessary to obtain a diurnal variation. The

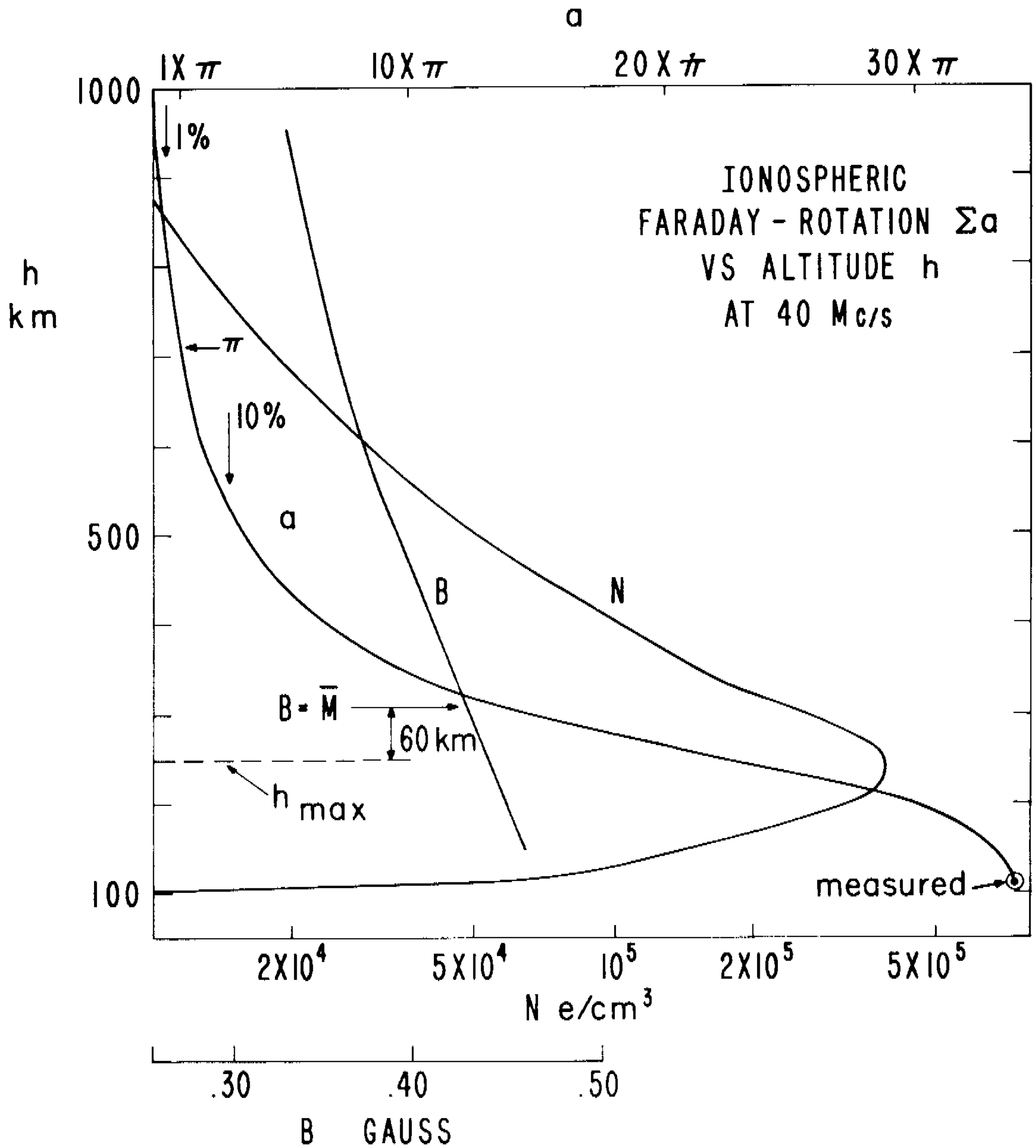

Figure 2. Calculation of the Faraday Polarization Rotation Angle Σa as a Function of Altitude Using the Actually Measured Electron Density Profile N(h), and the Geomagnetic Field Component B Obtained from Gyrofrequency Spikes in the Topside Ionogram.

day-to-day as well as the geographic and seasonal variability of the ionosphere is superimposed on the diurnal variation thus obtained.

Polarization rotation measurements are performed continuously at Fort Monmouth, N. J. (40.25°N, 74.025°W) utilizing beacon emissions of the ATS-3 (137.35 MHz). The subionospheric point (below 350 km along the path from Fort Monmouth to ATS-3) is located at 37.1°N, 73.6°W. For the purpose of this report, data observations for time periods between the 123rd and 178th days of 1973, i.e., May 3 to June 27, 1973, are presented. The data have been normalized to the vertical direction and, hence, represent the vertical total electron content. Representative diurnal variations are shown in Figures 3 through 5. The following observations are made with respect to the absolute values of the content (and, equivalently, of the ionospheric time delay):

1. The diurnal variation as well as the day-to-day variability of the total vertical content is evident. The lower and upper limits of the content are $\sim 0.2 \times 10^{17}$ and $\sim 3.0 \times 10^{17}$ respectively and correspondingly the ionospheric time delay is ~1 nanosecond and 15.7 nanoseconds. Differences of up to 100% can be observed in the figures.

2. For the reported data, buildup of ionospheric ionization started daily at ~0400 EST. For the time of year considered, the dawn buildup begins when solar illumination is at ~100 km (solar zenith angle = ~98°). Topside ionospheric densities have been reported to decrease with increasing solar illumination until about ground sunrise.[1] The discrepancy between topside density and total content could be explained by thermally induced particle fluxes from the topside ionosphere to the bottomside ionosphere during ionospheric sunrise and by the quicker buildup of the bottomside ionosphere.

3. The buildup phase of the diurnal variation is smooth, and its time slope is nearly constant. On most days, the sustained buildup phase ends prior to noontime, although the diurnal maximum is not reached until later.

4. The maximum of the content is variable in absolute value as well as in the time of occurrence. Such maxima usually occur after 1600 EST, and sometimes much later.

5. In terms of absolute values of the electron content, magnetic activity does not have a consistent effect on the content. Figures 3 through 5 show cases when magnetically disturbed days show depressed content values with respect to quiet days, and vice versa. Even data taken on consecutive disturbed days have totally different characters.

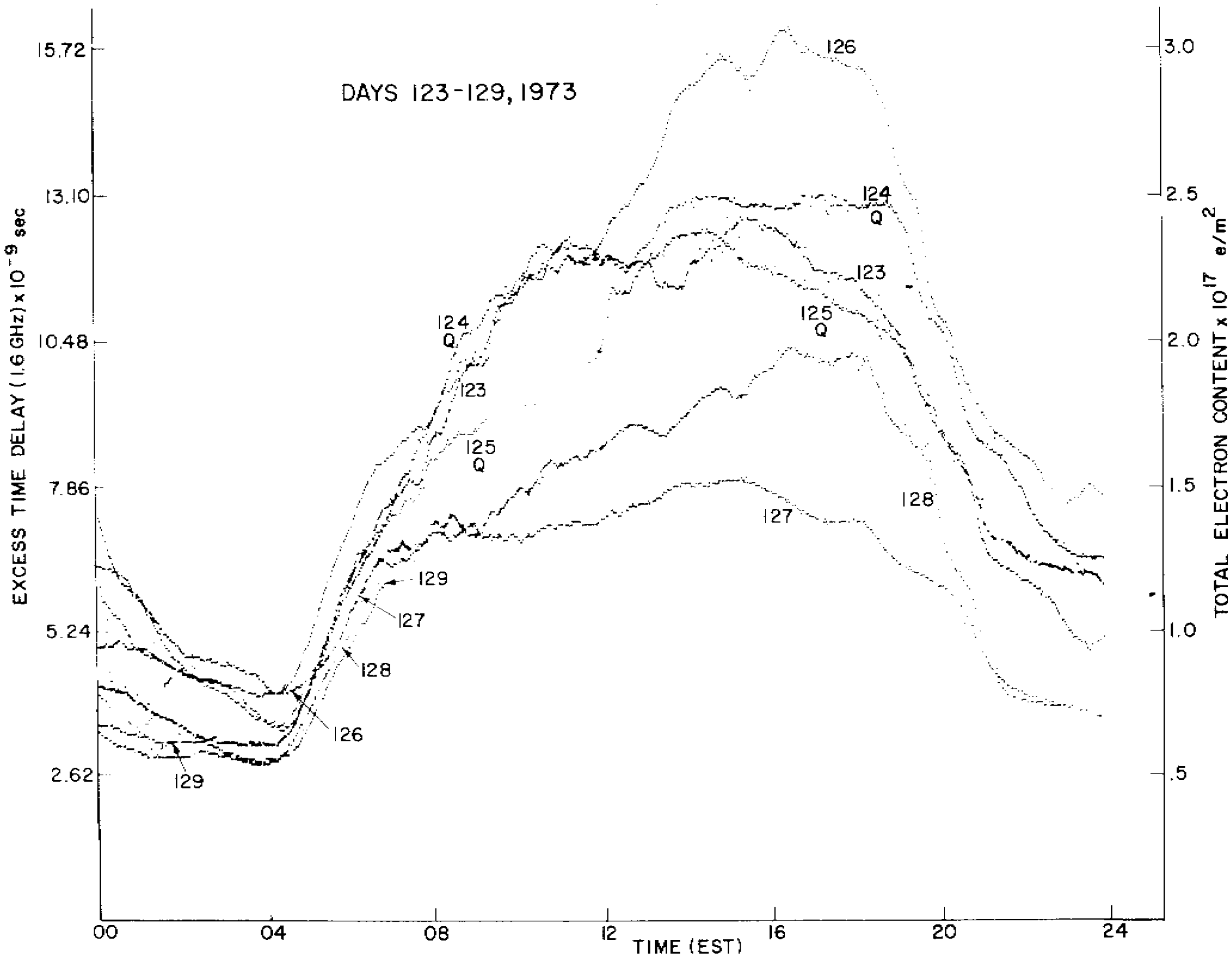

Figure 3. Total Integrated Electron Content Diurnal Variation for the Days 123 Through 129, 1973. (QQ, Q, D refer to Magnetically Extremely Quiet, Quiet, or Disturbed Days, Respectively).

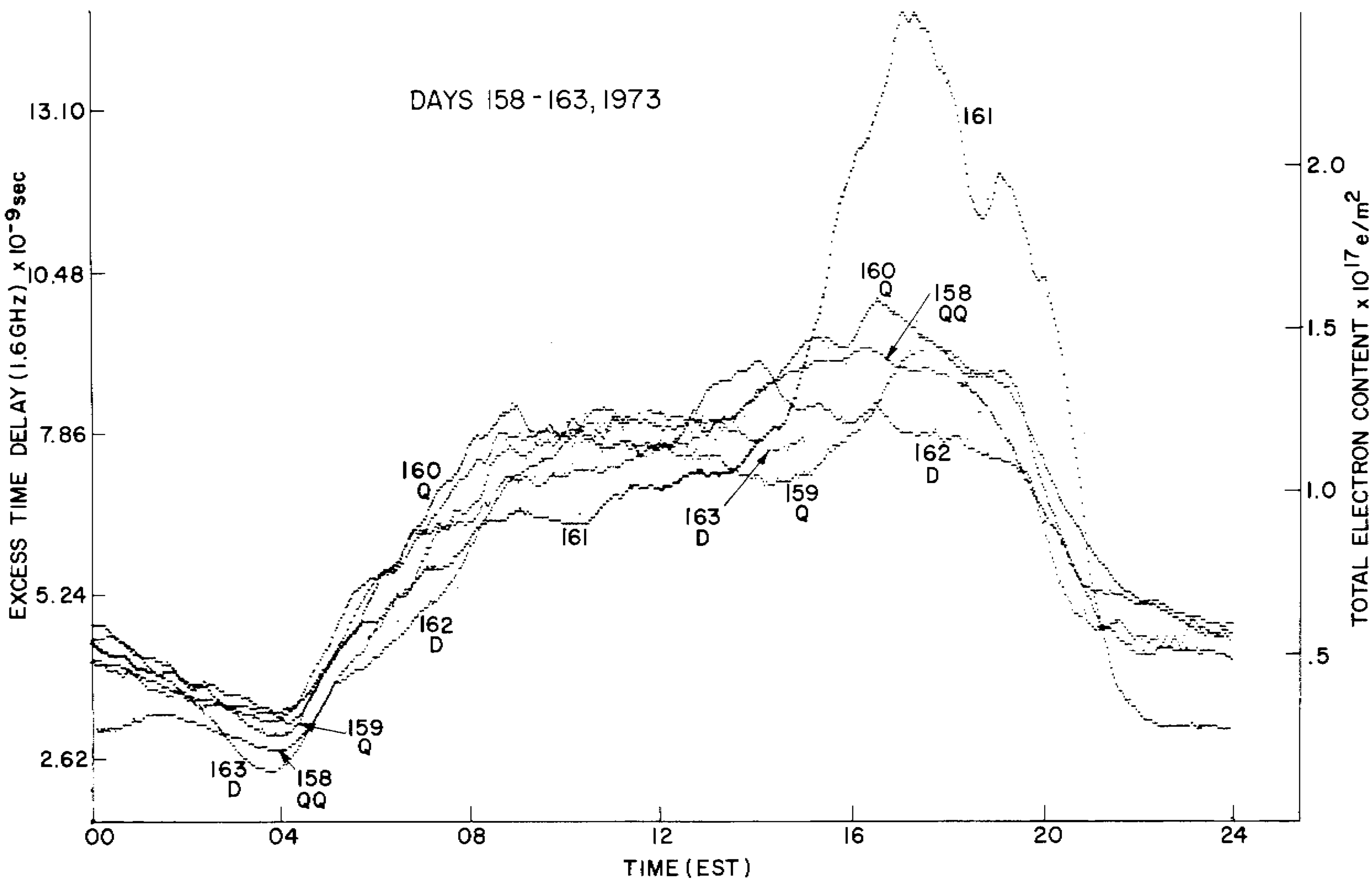

Figure 4. Same as 3, but for the Days 158 Through 163, 1973.

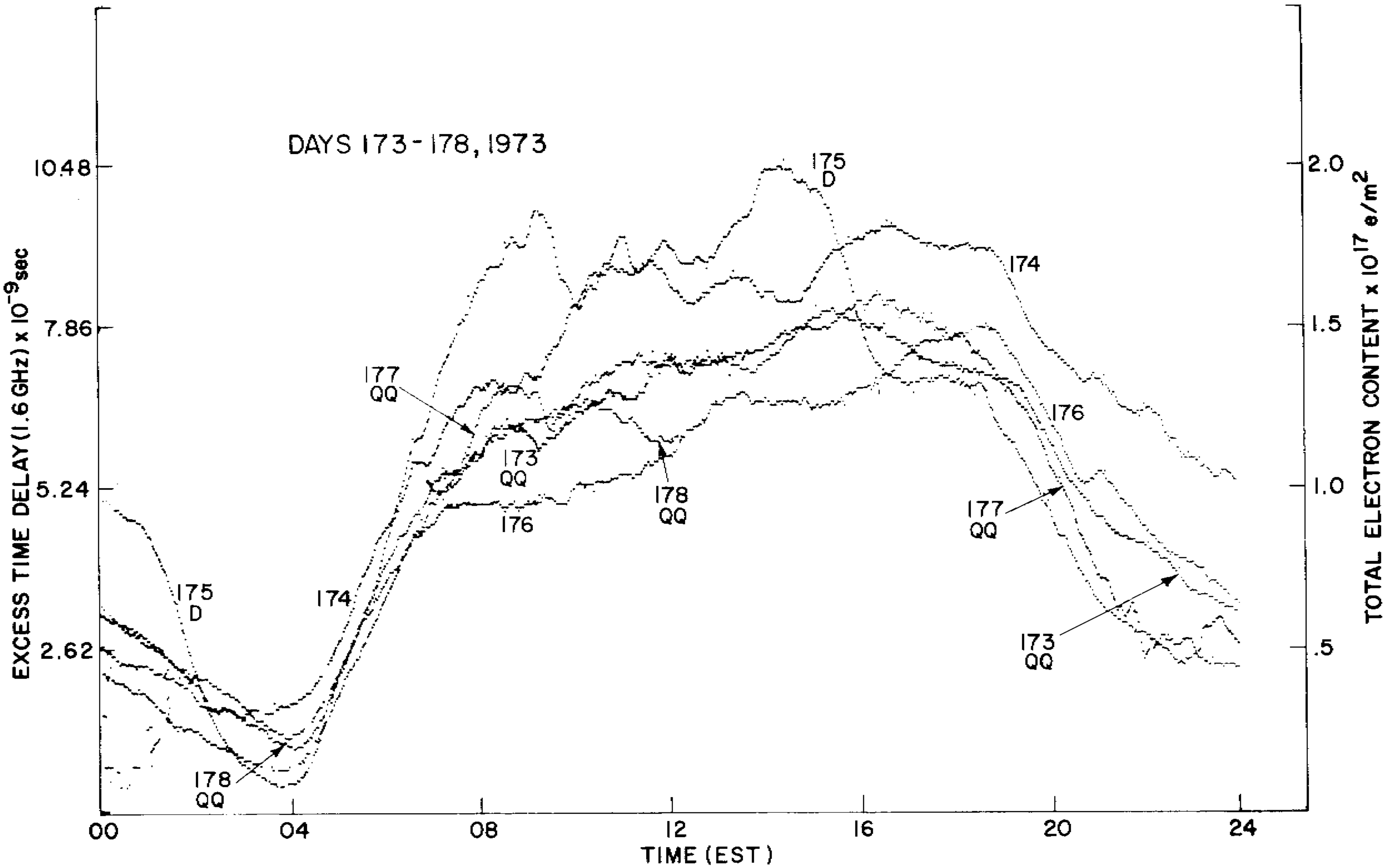

Figure 5. Same as 3, but for the Days 173 Through 178, 1973.

6. The sustained decay of ionization with the setting of the sun starts, in most cases, from the maximum absolute value of the content. As during the buildup period, the decay with time is smooth and has a constant slope. The decay slope is sharper than the buildup slope.

7. At night the content continues to decline until it reaches an absolute minimun, from which the buildup phase starts at sunrise. The minimum may be reached just before sunrise or it may be sustained an hour or so before sunrise.

8. Smaller scale variations are superimposed on the overall diurnal variation of the electron content as is evident from Figures 3 through 5. These variations are caused by ionospheric ionization irregularities along the signals' path. The irregularities are finite in extent and are known to be moving. Some of the irregularities are caused by ionospherically traveling internal gravity waves.[2] Their finite size means that two relatively closely-spaced ground stations monitoring the same satellite may observe different vertically normalized electron content values since one's path to the satellite goes through the irregularity while the other's does not.

The traveling ionospheric disturbance which cannot be predicted, except possibly statistically, constitutes a natural limit to the accuracy of any real-time prediction of the total integrated electron content. To ascertain the extent of this limit and its possible diurnal variation, the following procedure was used. Each day was divided into 6 four-hour intervals and the maximum deviation from the ambient content at any of the intervals was recorded. The bounds of the deviation ranged from no deviation to an $\sim$20% deviation. The deviations were then averaged for all the days and plotted in Figure 6. The following conclusions may be drawn:

a. Electron content deviations occur, on the average, at all diurnal periods with a maximum of 5.4% and a minimum of 2.8%.

b. On the average, the deviations are smallest during the sustained ionospheric buildup period (0400-0800 EST) and during the sustained ionospheric decay period (1600-2000 EST).

c. The greatest deviations occur during the day between the buildup and the decay. Nighttime deviations are also large.

d. From the viewpoint of prediction schemes, the daytime deviations pose a greater problem to accuracy, since the daytime content is larger than the nighttime content by a factor of 3 or so.

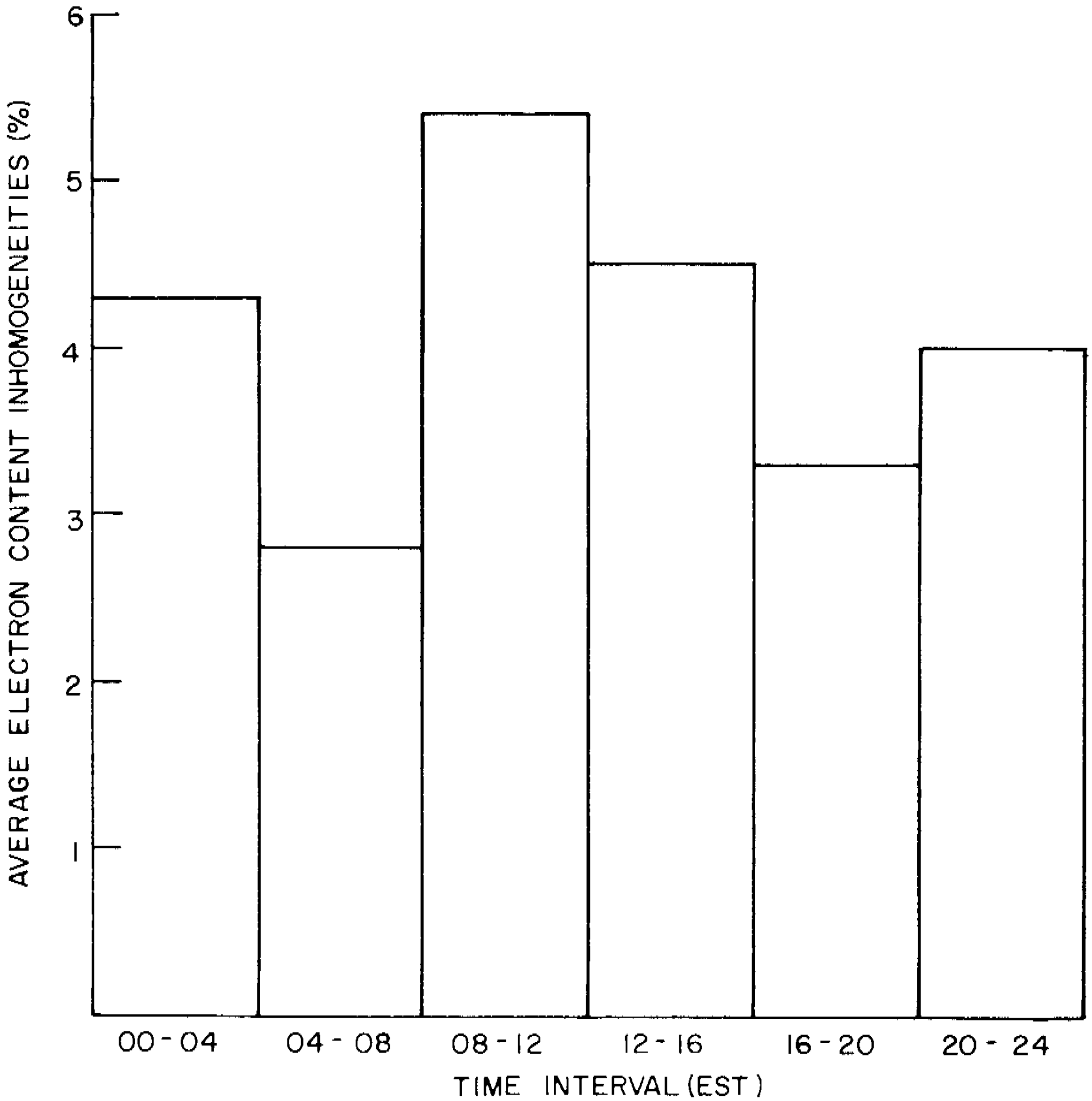

Figure 6. Ionization Irregularity in Percent of Ambient Content for Six Daily Time Periods

FUTURE EXPERIMENTS

The forthcoming launch of the geostationary ATS-F[3] will offer a unique and excellent opportunity to study the diurnal behavior of the total electron content at various geographic locations. Our group will perform two experiments. In one experiment, the polarization rotation of the 140 MHz beacon will be measured.

This will not be different from the experiments carried out to date utilizing other geostationary satellites. In a second experiment, continuous dispersive group delay measurements will be made on 140 MHz and 360 MHz, both of which will be complemented with ±1 MHz sideband emissions. With such a modulation on both frequencies, the distance between peaks of the modulation envelope is 300 meters in free space and very little different in the ionosphere. The modulation envelope travels at the group velocity and is retarded in phase by $\Delta P/300$ cycles at the modulation frequency where

$$\Delta P = \int_0^S ds - \int_0^S n_g \, ds = -\frac{40.3}{f^2} \int_0^S N \, ds. \qquad (6)$$

At night (assuming $\int N\, ds \approx 10^{17} el/m^2$), $\Delta P \sim 200$ meters for the 140 MHz frequency and $\Delta P \sim 30$ meters for the 360 MHz frequency, i.e., phase reduction is <1 cycle for both frequencies. The modulation phase difference is thus obtained unambiguously and yields the absolute value of the total electron content. For other times of the day when the total content is larger, the absolute value could easily be derived from the nighttime values since the total content varies continuously with time.

Since the phase effect is independent of the terrestrial magnetic field, it gives the true electron content along the entire propagation path, as opposed to the content given by the polarization rotation effect which pertains only to a signal path portion of 1500 km from the earth's surface. The difference between simultaneous polarization and group-delay data will yield the currently unknown exospheric electron content, i.e., the content between 1500 km and synchronous altitudes.

SUMMARY

With stringent precision requirements, a navigation system which measures signal propagation time between high-altitude satellites and users at or near the earth's surface must take into account the excess time delay of the signal owing to the existence of free electrons along its path. The excess signal time delay is proportional to the total electron content along the propagation path. The upper bound for non-anomalous ionospheric conditions is ~150 nanoseconds for a highly oblique propagation path at a frequency near 1600 MHz.

For dual-frequency user-capability, the excess time delay may be measured in real-time and a correction applied to the apparent range. For single-frequency user-capability, the ionospheric time delay must be arrived at through empirical global prediction techniques based on existing and future electron content data.

The pertinent information will be transmitted to the user via the navigating signal. To date no truly global coverage of the total electron content exists. Most existing data are based on Faraday rotation measurements of the electron content in the earth's immediate vicinity only (i.e., up to ~1500 km). Future experiments will yield content values up to geostationary altitudes.

A limit to the accuracy of the prediction is set by superposition of the variations of ionization irregularities on the diurnal variation of the total electron content. The greatest average percent variation was observed during the day between the buildup and decay phases of the diurnal variation and amounted to ~5.4% of the ambient total electron content. Since the content is at its highest during the day, such percentage deviations cause relatively high absolute time delay deviations. Of course the complexity of the ionospheric processes and their interrelationships with many other geophysical phenomena will introduce additional uncertainties into the predictions.

ACKNOWLEDGMENT

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QUESTION AND ANSWER PERIOD

MR. EASTON:

Any questions? No questions?

(No response.)

MR. EASTON:

Thank you very much, Mr. Soicher.