RADIO WAVE PROPAGATION EXPERIMENTS TO PROBE THE IONOSPHERE

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The Earth's ionosphere biases all measurements associated with radio tracking of spacecraft because the velocity of radio waves in the ionosphere differs from that in free space. The integrated effect of this velocity difference is directly proportional to the total number of electrons in a unit cross-section tube along the ray path connecting spacecraft and tracking station. All tracking measurement ionospheric biases can be shown to be directly proportional to this "integrated electron content" and inversely proportional to the square of transmission frequency. This paper briefly discusses three techniques which have proved highly successful in measuring integrated electron content.

The three techniques are

1. Faraday rotation measurements from an Earth synchronous satellite.

2. Ranging measurements at two frequencies.

3. Group and phase velocity measurements obtained from tracking data.

The third scheme (see Reference 1) is the most desirable because measured corrections pertain directly to the spacecraft whose orbit or trajectory is being determined. Similar work has been performed for deep space applications at the Jet Propulsion Laboratory (JPL) where group and phase velocity differences through ionized media are used in their so-called "charged particle calibrations" (Reference 2).

Such ionospheric corrections are of special importance in the case of VHF tracking. From the standpoint of spacecraft and ground antenna simplicity and the related ease of signal acquisition (because of antenna beamwidth relationships), 136 to 148 MHz is still a highly desirable frequency range for tracking and subsequent orbit computation of low-power, low-data-rate, Earth and near-Earth orbiting spacecraft. Such approved future VHF missions include the Radio Astronomy Explorer B (RAE B), the Synchronous Meteorological Satellite (SMS), and the continuing Explorer series of spacecraft.

Figure 1 shows Faraday rotation data recorded at Goddard Space Flight Center from an Earth synchronous satellite, ATS 3, during the March 7, 1970, solar eclipse. The measured polarization twist is a function of both the integrated electron content and the Earth's magnetic field. Since the Earth's magnetic field is well established, the observed Faraday rotation from ATS 3 at 137.350 MHz is directly related to changes in integrated electron content and hence to changes in ionospheric biases in tracking data. By the use of ionosphere bottom sounding data from Wallops Island, the absolute (i.e., total unambiguous) number of polarization rotations was noted during the eclipse. These data indicated that the content dropped from 6×10^{17} to 4.5×10^{17} electron/m^2 as the lunar shadow passed through the ionosphere. This corresponds to a range bias change of approximately 500 m at 140 MHz.

The lower portion of Figure 1 shows a normal buildup in ionization peaking at approximately 3:15 p.m. local time at a level on the order of 10^{18} electron/m^2. The upper portion of Figure 1 shows the same type of display with the exception of the abrupt decrease in electron content (phase reversal at approximately 12 noon), which then recovered to the normal diurnal cycle at 2:20 p.m. to reach the afternoon peak integrated density at 3:30 p.m. All times are local (i.e., Eastern Standard Time).

Figure 2 shows a comparison of range bias determined by Faraday rotation from ATS 3 and that determined by ranging to ATS 3 at two widely separated frequencies. In this case, the frequencies are nominally 140 MHz and 6000 MHz. The range bias is given by

$$\Delta R = \frac{40.3I}{f^2} \doteq \frac{40.3I_v}{f^2 \sin E} \quad \text{(m)}, \qquad (1)$$

where

I = total integrated electron content along ray path (electron/m^2),

f = frequency (Hz),

E = local elevation angle of ray intercept point at 300-km height (i.e., height of maximum ionization),

I_v = vertical integrated content in column intersecting 300-km intercept point (electron/m^2).

For elevation angles above 45 deg, E can usually be taken as the ground-measured elevation angle to the spacecraft. For lower angles, Earth curvature should be taken into account:

$$E = \arccos\left(\frac{a}{a+h}\cos E'\right), \qquad (2)$$

where

a = Earth radius,

h = 300 km (or height of maximum electron density if known more accurately),

E' = elevation angle as measured by tracking station.

Figure 2 shows clearly the diurnal variation in electron content at Rosman, North Carolina, with the typical midafternoon peak occurring at approximately 2:00 p.m. local time. The difference between Faraday data and range difference data in this preliminary test is attributed primarily to the ATS 3 VHF transponder time delay uncertainty. Further tests are being conducted to improve calibration techniques.

The most desirable way to obtain group and phase velocity information, from an operational standpoint, is to extract integrated electron content information and hence ionospheric bias corrections directly from the tracking data. Figure 3 shows that this can be achieved by the comparison of range-rate measurements based on carrier Doppler shift with differentiated range measurements based on tone delay.

Simply stated, the ionosphere biases range-rate in one direction and biases the differentiated range an equal amount in the opposite direction. Thus, the true range rate is halfway between the two curves shown in Figure 3. The reason for this phenomenon is that the Doppler phase is altered by the phase velocity and the range delay is altered by the group velocity. In a dispersive media like the ionosphere, the group and phase velocities differ in a predictable manner.

The same technique is used by JPL in their charged particle calibration, with one important difference. In our work, the angle rate of near-Earth spacecraft is high, and an absolute measure of integrated electron content is possible over the roughly 50-second observation-time arc. The deep space angle rates are primarily Earth rotation ($\sim 7 \times 10^{-3}$ rad/s), and integration over long periods of time (hours) are used to obtain changes in integrated electron content rather than absolute content.

The measurability of the electron content can be seen from the following relation:

$$I_\nu = \left(\frac{1}{80.6}\right)\left(\frac{f^2}{\dot{E}}\right)\left(\frac{\sin^2 E}{\cos E}\right)\left(\dot{r} - k_s - \frac{dR}{dt}\right) \qquad \text{(electron/m}^2\text{)}, \qquad (3)$$

where

I_ν, f, and E are as defined previously and

$\dot{r}$ = range-rate from tracking data (m/s),

$\frac{dR}{dt}$ = differentiated range from tracking data (m/s),

k_s = spacecraft range-rate bias due to spacecraft spin* (m/s),

$\mathring{E}$ = rate of change of local elevation angle at ray intercept point at 300-km height (rad/s).

The angle rate $\dot{E}$ is linked to the tracking station measurements of elevation E' and elevation rate E' by

$$\dot{E} = \left\{ \frac{\sin E'}{\left[1 - \left(\frac{a}{a+h}\right)^2 \cos^2 E'\right]^{1/2}} \right\} \left(\frac{a}{a+h}\right) \dot{E}' \qquad (4)$$

*If spin stabilized, see Marini, J. W., "The Effect of Satellite Spin on Two-Way Doppler Range Rate Measurements", Goddard Space Flight Center Document X-551-69-104, March 1969, Goddard Space Flight Center, Greenbelt, Maryland.

As seen in Figure 3, the results show excellent agreement between the vertical content extracted from Explorer 41 tracking data, $I_v = (2.4 \pm 0.1) \times 10^{17}$ electron/m^2, and that based on ESSA f_0F_2 data, $I_v = 2.45 \times 10^{17}$ electron/m^2. This happened to be during a stable period (local night) with no solar disturbance. However, daytime estimates based on average monthly f_0F_2 predictions are often in error by a factor of 2 to 4 throughout the month.

This particular scheme for extracting integrated electron content directly from tracking data is therefore shown to be both feasible and highly desirable for corrections to near-Earth as well as deep space tracking data. In some cases, simultaneous range and range-rate data may not be available or elevation angle rates may be too small for determining corrections in the desired observation time. In such cases, measurements involving synchronous spacecraft such as ATS 1 and ATS 3 can be used to update the presently used ionospheric profiles, which are based on monthly predictions that are available three months in advance.

REFERENCES

1. Schmid, P. E., Rangaswamy, S., and Murray, C. W., "Ionospheric Corrections Based on VHF Range and Range Rate Measurements", Proceedings of the GEOS-2 Program Review Meeting 22-24 June 1970, Vol. II, November 1970.

2. Mulhall, B. D. "Charged-Particle Calibration System Analysis", JPL Space Programs Summary 37-64, Vol. II, pp. 13-21, August 31, 1970, Jet Propulsion Laboratory, Pasadena, California.

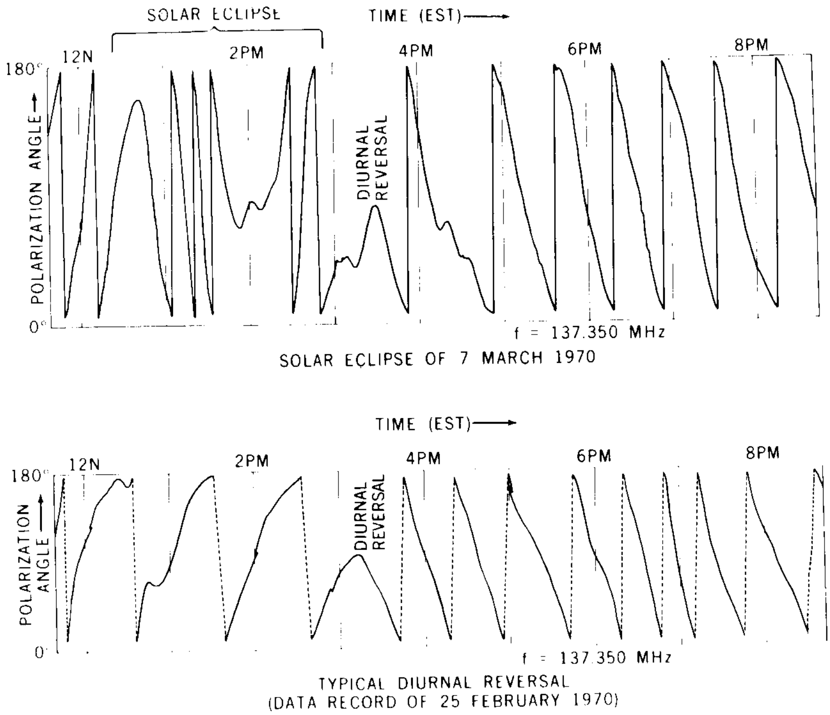

Figure 1–Faraday rotation data from ATS 3.

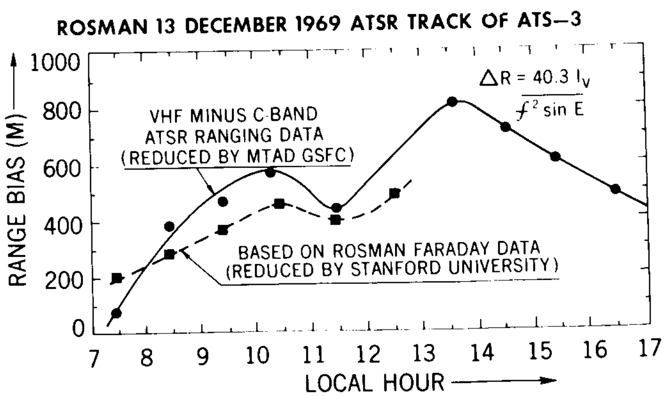

Figure 2–Zenith ionospheric range bias.

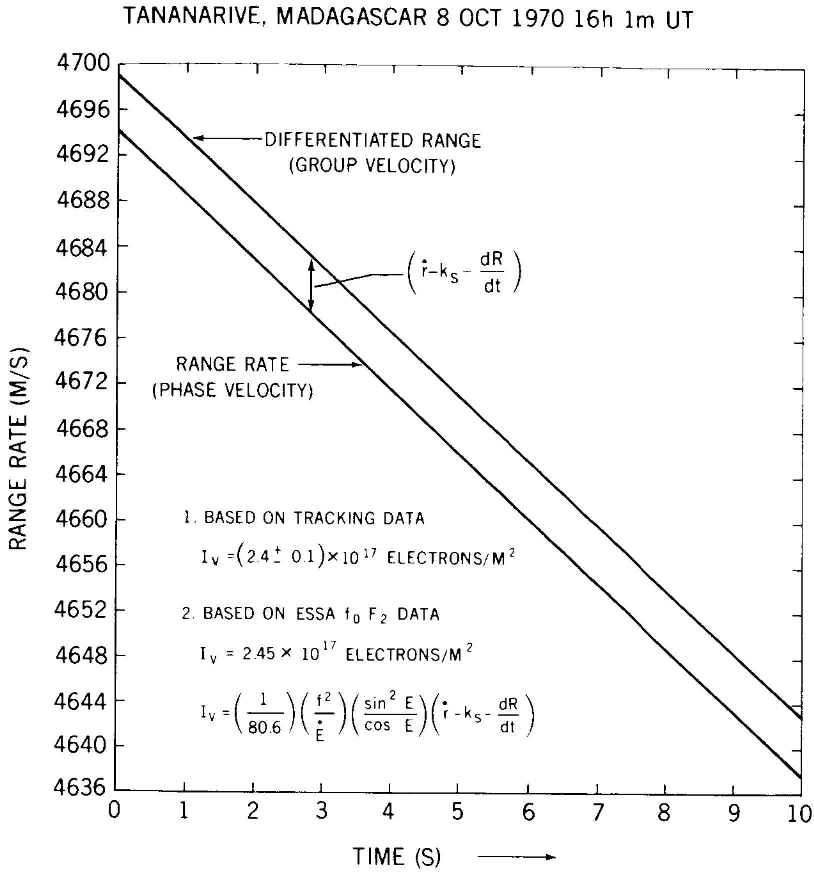

Figure 3—Explorer 41 track by VHF GSFC range and range-rate system.