Reports

Ionosphere Explorer I Satellite: First Observations from the Fixed-Frequency Topside Sounder

Abstract. *The satellite has yielded new information on the arrangement of irregularities in sheets and the structure of plasma resonances in the ionosphere. Studies of the geographical distributions of the different kinds of spread F, sporadic E, and other phenomena will be facilitated by the satellite. More phenomena will undoubtedly be recognized as the records are studied.*

The Ionosphere Explorer I satellite (IE-I) was successfully launched into orbit from the Pacific Missile Range on 25 August 1964. Its orbit is approximately circular at an altitude of about 950 km and is inclined 80° to the equatorial plane. The satellite carries two experiments: a pulsed radio sounder operating on six fixed frequencies (1.50 to 7.22 Mcy/sec) to study the electron distribution of the topside of the ionosphere, and a plasma probe to measure the ion composition and temperature.

The new satellite is one of a series of rockets and satellites being launched as part of the international topside sounder program sponsored by the National Aeronautics and Space Administration (*1*). Previously, two rockets carrying fixed-frequency sounders were launched, one on 24 June 1961 (*2*), and the other on 13 October 1961 (*3*). Alouette I satellite, carrying a swept-frequency sounder as well as other experiments, was launched on 29 September 1962 (*4*).

Like the two previous rocket experiments, the new satellite is under the scientific direction of the Central Radio Propagation Laboratory of the National Bureau of Standards. However, the plasma probe experiment is the responsibility of the University College of the University of London (*5*). Alouette I was a project of the Defence Research Telecommunications Establishment of Canada in cooperation with NASA. The international topside sounder program is managed by the Goddard Space Flight Center of NASA. It and the Radio Research Station of the Department of Scientific and Industrial Research of the United Kingdom are also major scientific participants. Within 1 year after reception the film records of IE-I will be deposited in World Data Center A, Boulder, Colorado, where they will be available to the scientific community.

We now present some preliminary observations of the phenomena being recorded by the topside sounder experiment on the new satellite.

Background

The ionosphere, which is that part of the earth's atmosphere where an appreciable concentration of free electrons exists, has long been observed by pulsed radio sounding (*6*). In this technique pulses of radio energy of a given frequency are transmitted. As the pulse proceeds into the ionosphere, the free electrons there slow it down. When a sufficiently great electron density is reached, the pulse is reflected back to the sounder, where its travel time is recorded. The electron density at the point of reflection is simply related to the sounding frequency and thus is measured by this technique. A network of over 100 ground-based sounders (ionosondes) has been established throughout the world to make such measurements of electron density for studies of radio propagation.

However, ground-based ionosondes cannot measure the electron density above the height of its maximum (roughly 300 km). Sounding pulses which can penetrate above this height are not reflected, but continue into space. With the advent of artificial earth satellites, several groups proposed a satellite ionosonde to sound the "topside" of the ionosphere, the region above the maximum. Out of these proposals grew the international topside sounder program and the current experiment.

The first topside sounder satellite of the program was the Canadian Alouette I. Its primary experiment is a swept-frequency sounder covering 0.5 to 12 Mcy/sec in approximately 18 seconds. Since its launch Alouette I has provided a great deal of unique data on the topside of the ionosphere. These data have significantly advanced our understanding of the topside electron-density distribution, the structure and distribution of ionospheric irregularities, and the phenomenon of plasma resonances in the ionosphere.

However, because Alouette requires 18 seconds per sweep, during which time it moves about 130 km, it is not well suited for studies of ionospheric irregularities. Also, observation of the detailed structure of the plasma resonances is obscured by the simultaneous motion of the satellite and sweep in frequency.

The fixed-frequency sounder on the new satellite will thus complement Alouette I by providing a more rapid sampling rate at constant frequencies. It cycles through all six of its sounding frequencies in 0.105 second. Between successive soundings on the same frequency it moves only about 800 meters, and hence it is well suited for studies of irregularities down to that size. In addition, the constancy of the sounding frequencies permits detailed observation of the resonances.

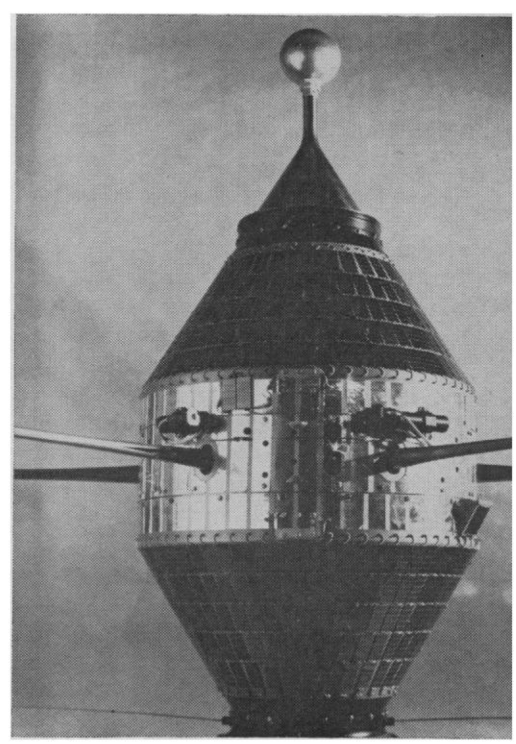

Fig. 1. The Ionosphere Explorer I satellite. The spherical plasma probe is mounted on top, the sounder antennas on the cylindrical mid-section, and the telemetry antennas on the bottom.

Satellite System

Ionosphere Explorer I (Fig. 1) has also been known as Ionosphere Explorer A (before launch), S-48, Fixed Frequency Topside Sounder Satellite, TOPSI, 1964 51A (after launch), and Explorer XX (after launch). Mechanical, electrical, and orbital data appear in the accompanying box.

Because the satellite has no information storage capability, data can be obtained only when it is within range of a ground telemetry station. At present, the following telemetry stations are participating in the program: Resolute Bay, North West Territories, Canada; College, Alaska; St. Johns, Newfoundland; East Grand Forks, North Dakota; Boulder, Colorado; Fort Myers, Florida; Quito, Ecuador; Santiago, Chile; South Atlantic Station (U.K.); Winkfield, England; and Singapore, Malaysia. This network of telemetry stations allows continuous data acquisition in the Western Hemisphere from high northern latitudes to high southern latitudes.

During the first 3 weeks, while the orbit was entirely sunlit, the satellite could operate 7 to 8 hours per day. When the orbit is least sunlit (67 percent), the available sounding time will decrease to 3 to 4 hours per day.

Preliminary Observations

Some examples of the phenomena observed by IE-I during its first few passes over Boulder, Colorado, and South Point, Hawaii, are presented in Figs. 2 through 7. For these figures a single frequency has been separated from the sounding sequence and displayed alone. The delay after the transmitted sounding pulses increases downward and is given in terms of "virtual depth," half the delay between transmission and reception multiplied by the radio-wave velocity in free space. The horizontal axes are labeled with the geographical position of the satellite as the soundings were recorded. Radio echoes appear on these diagrams as darkened areas.

Echoes from a smooth ionosphere in middle latitudes are shown in Fig. 2. The two echo traces correspond to the two magnetoionic polarizations, ordinary and extraordinary, for which the pulses travel at different speeds and are reflected from different electron density levels. The constancy of the virtual depths in this case indicates that the reflection surfaces, which are also surfaces of constant electron density, are smooth and at nearly constant altitudes.

However, the electron density distribution beneath the satellite is not always constant, as in Fig. 2. In Fig. 3 the electron density throughout the topside decreases toward the right, that is, with increasing latitude. On the left-hand side of the figure, the echoes come from the topside of the ionosphere. But, as the electron density decreases, the reflection levels move lower, and the virtual depths increase, until each magnetoionic mode separately penetrates the ionosphere. To the right of the penetrations the echoes come from the ground. The virtual depth of the ground echoes is greater than the true range of the ground (960 km) because of retardation in the intervening ionosphere. Near penetration, the ground and ionospheric echoes often become complex, because of oblique propagation. An example of this is the recurvature of the o-mode ground trace at 30° latitude in Fig. 3.

Figure 3 also shows echoes from sporadic E, a reflecting structure in the lower ionosphere. In this case the height of the sporadic E is about 110 km, so that its virtual depth is 110 km less than the virtual depth of the ground echoes. This patch of sporadic E was of the order of 100 km long. Over part of its extent it suppressed the ground echoes.

In previous radio studies of the ionosphere, diffuse echoes, called "spread F," have been commonly observed (*7*). These spread-F echoes have been attributed to irregularities in the electron-density distribution, which are elongated along the earth's magnetic field (*8*). The topside sounder rockets and Alouette I have confirmed that these irregularities extend far into the topside of the ionosphere (*3; 9–11*). Their widths may range from a few meters to tens of kilometers, and they may be thousands of kilometers long.

The previous topside sounder studies have established that two distinct echo mechanisms give rise to topside spread F (*11*). Irregularities thin compared with the radio wavelength may efficiently scatter radio energy back toward the sounder. Irregularities somewhat broader than the wavelength may guide radio energy in a duct (or wave-guide) mode down toward the normal reflection level and back. On the basis of these two mechanisms, spread-F echoes may be classified into "scatter spread F" and "ducted spread F." Both kinds are observed by the new satellite.

Most of the diffuse echoes on Fig. 4 are attributed to scatter spread F. The normal ionospheric traces are obscured by the exceptionally strong scattering near the reflection levels. Moreover, the slanted, diffuse traces may be

Mechanical Data

Diameter	26 inches
Length	32 inches
Weight	97 pounds
Spin axis	Axis of cylindrical symmetry
Sounding antennas	Two dipoles, 62 feet tip-to-tip, and one dipole, 122 feet tip-to-tip (tubular strap antennas constructed in orbit), all in the plane perpendicular to the spin axis
Telemetry antenna	Turnstile configuration

Electrical Data

Sounder frequencies	7.22, 5.47, 3.72, 2.85, 2.00, and 1.50 Mcy/sec (in the order of the sounding sequence)
RF pulse length	100 microseconds
Sounding cycle	105 milliseconds (one 15-msec period is allotted to a calibration pulse and the ion probe together, and one to each of the six sounding frequencies)
Sounder peak pulse power	8 to 45 watts
Power supply	2,400 *P/N* solar cells and 23 nickel-cadmium storage batteries
Telemetry	136 Mcy/sec: 2-watt FM transmitter (sounder video), 200 milliwatts, phase-modulated transmitter (house-keeping data)
Beacon	137 Mcy/sec, 75 milliwatts, continuous-wave transmitter
Data acquisition	10-minute direct read-out on command from ground station

Orbital Data (Epoch 25 August 1964, $13^h\ 55^m\ 23^s$)

Time of launch	$13^h\ 43^m\ 17^s$ UT, 25 August 1964
Anomalistic period	103.797 minutes
Inclination	79.903 degrees
Right ascension of ascending node	247.86 degrees
Rate of precession	−1.080 deg/day
Eccentricity	0.00981
Perigee	866 km
Apogee	1010 km
Mean height above ellipsoid	approx. 952 km
Spin rate	approx. 1.5 rev/min
Inclination of spin axis to ecliptic plane	approx. 85 degrees

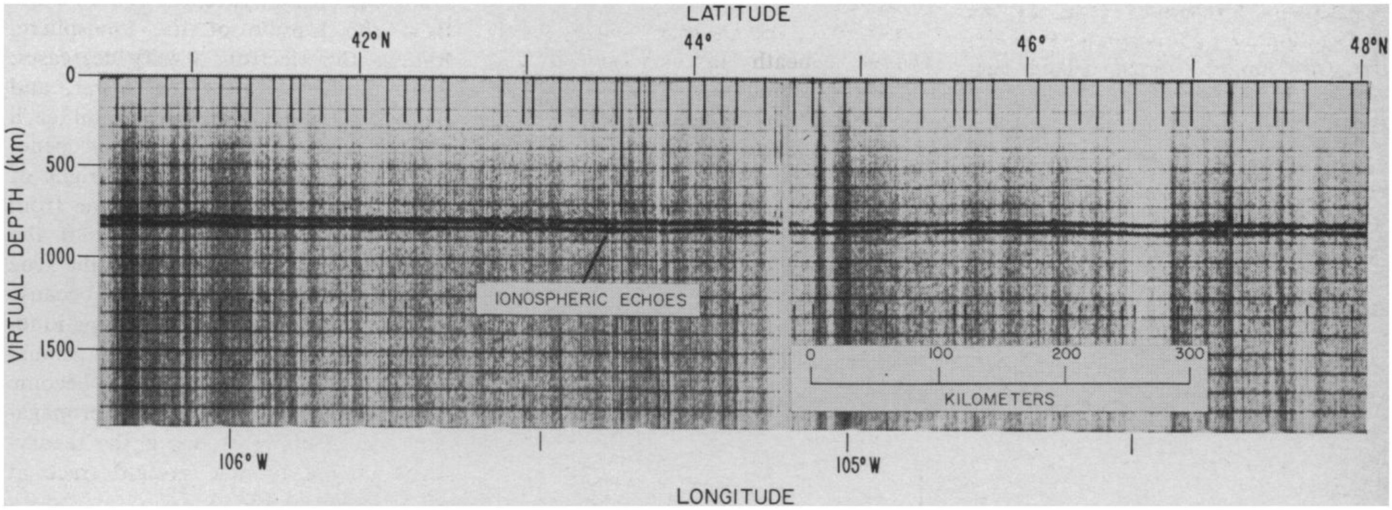

Fig. 2. Normal ionospheric echoes. 3.72 Mcy/sec, 27 August 1964, 0142 UT (1845 LMT).

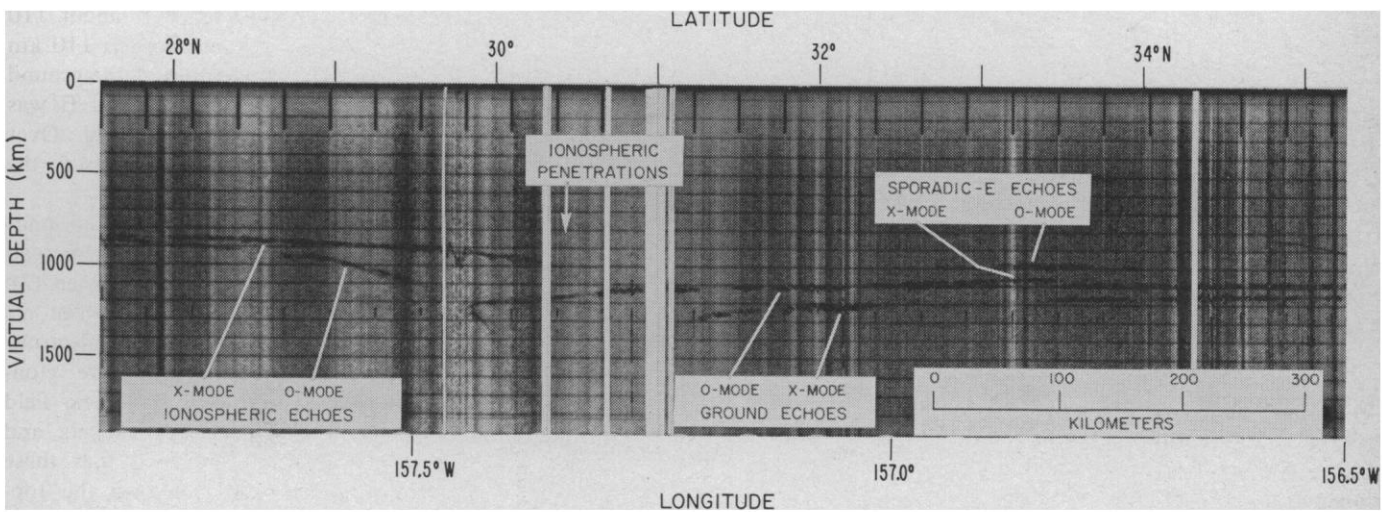

Fig. 3. Ionospheric F-layer penetrations, ground echoes, and sporadic-E echoes. 7.22 Mcy/sec, 31 August 1964, 0421 UT (1850 LMT).

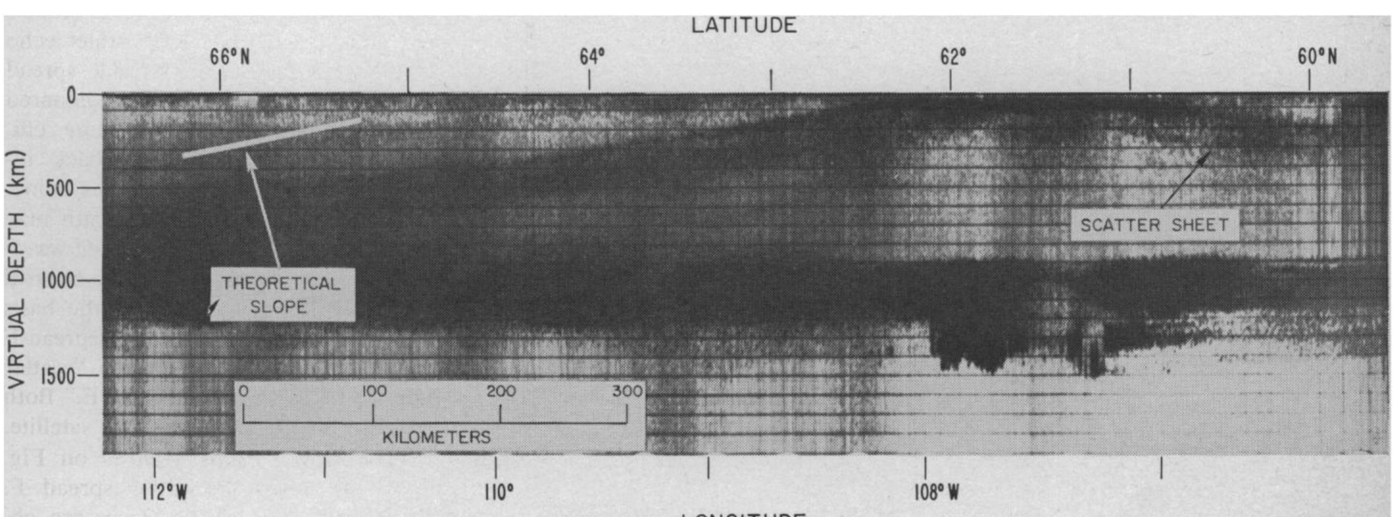

Fig. 4. Scatter spread F, including echoes from sheets of irregularities. The magnetic dip at the sheets is about 83°. 2.00 Mcy/sec, 30 August 1964, 1126 UT (0405 LMT).

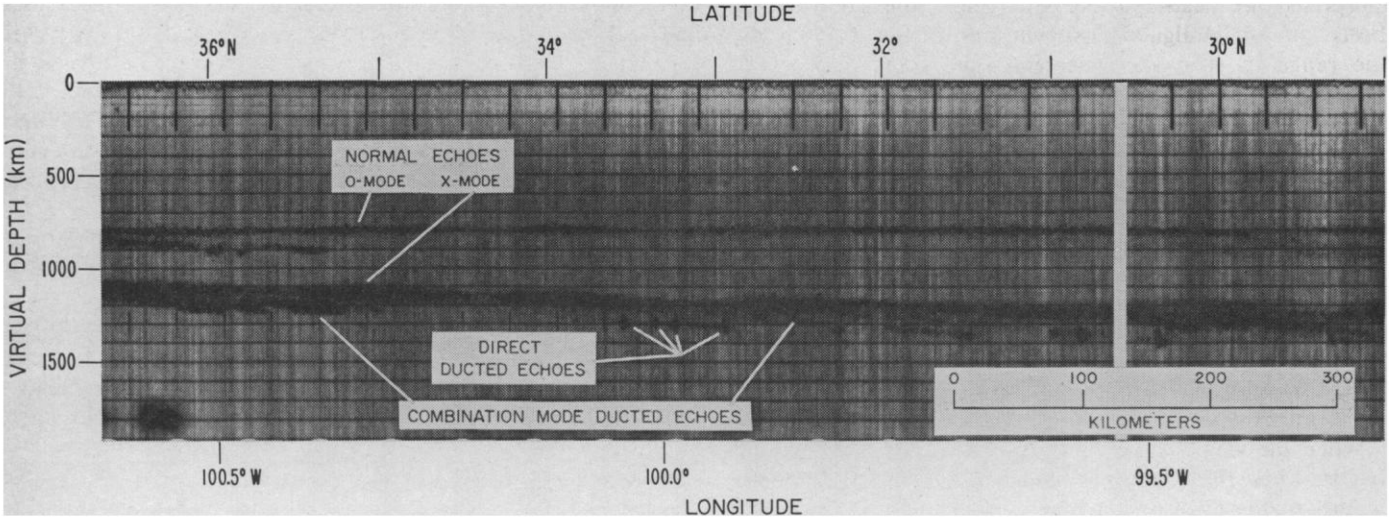

Fig. 5. Ducted spread-F echoes. The magnetic dip decreases from 66° to 58° across this record. 2.00 Mcy/sec, 4 September 1964, 1105 UT (0425 LMT).

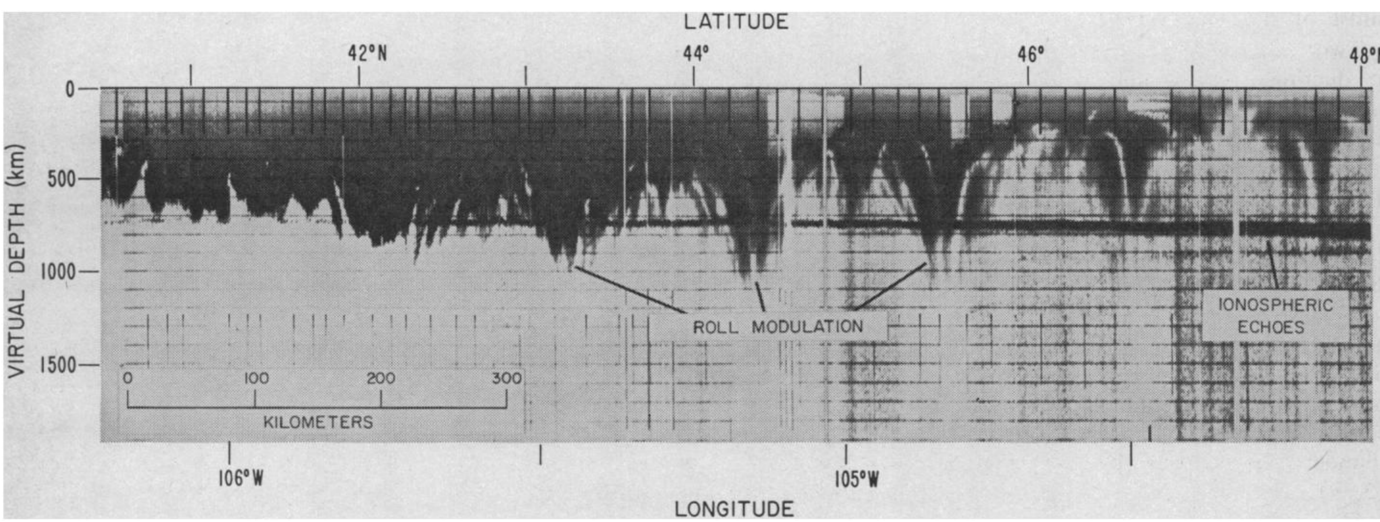

Fig. 6. Plasma resonance at $2f_H$ with roll modulation and interference pattern. 2.00 Mcy/sec, 27 August 1964, 0142 UT (1845 LMT) (the same period as Fig. 2).

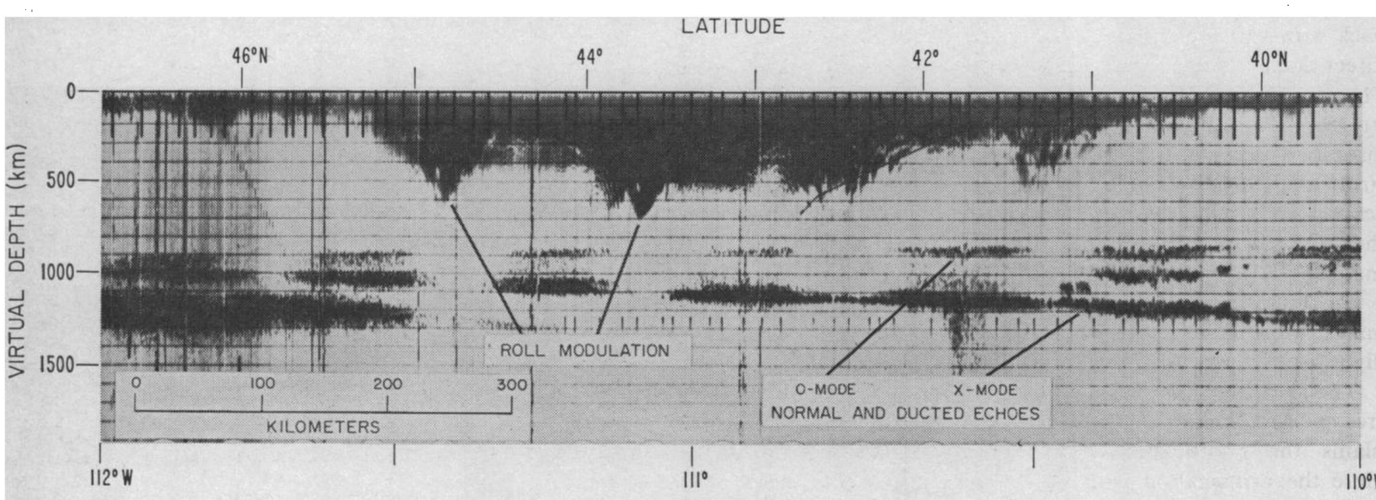

Fig. 7. Plasma resonance at $2f_H$ with fine interference pattern and out-of-phase roll modulation on the ionospheric echoes. 2.00 Mcy/sec, 1 September 1964, 1202 UT (0440 LMT).

interpreted as scattered echoes from sheets of field-aligned irregularities. The range to each sheet decreases as the satellite approaches and increases after the satellite has passed through. For comparison, a theoretical slope, corresponding to the velocity of the satellite, is superimposed on Fig. 4. Since in every case observed so far the range of the slanted traces has gone to zero, it appears that field-aligned irregularities are commonly arranged in sheets. The thickness of the slanted traces indicates that these sheets are at most tens of kilometers thick.

When the virtual range goes to zero, that is, when the sounder is embedded in the scattering irregularities, strong irregular echoes appear just below the scatter spread F on the normal traces. The range and intensity of these echoes suggest the presence of ducts in the midst of the scatterers.

Two echo configurations attributed to ducting (ducted spread F) along broad irregularities are shown in Fig. 5. The first, labeled "direct ducted echoes," consists of very intense, short-lived echoes at virtual depths a few percent greater than the normal echoes. The second, labeled "combination mode ducted echoes," consists of rather diffuse echoes which converge with the normal echoes. These two configurations can be explained by the same mechanisms proposed to explain similar echoes observed by the second topside sounder rocket and by Alouette I (*3, 9*).

Direct-ducted echoes occur when the satellite actually passes through the ducting irregularity. Since the radio energy is then ducted all the way from the satellite to the reflection level and back with very small geometrical losses, direct-ducted echoes are very intense. The greater length along the inclined irregularity accounts for the greater virtual depth of the ducted echoes. From the duration of the direct-ducted echoes and the speed of the satellite, the thickness of the ducts can be estimated. The ducts of Fig. 5 were 2 to 4 km thick, in agreement with the estimates made from the second rocket flight (*9*).

The same mechanism, combined with free propagation in the ionosphere, explains the combination-mode echoes. Here the propagation path is refracted in the underlying ionosphere until it is aligned with a duct. The radio energy can then be trapped and ducted to the reflection level. The return echo follows the same route in the opposite direction. Combination-mode echoes can occur only when the satellite passes through the vertical plane containing a ducting irregularity. In Fig. 5, the combination-mode echoes form well-defined but discontinuous traces. This suggests that the ducting irregularities are also arranged in sheets.

Plasma resonances excited by the sounder transmitter were discovered in the previous topside sounder experiments (*12*). They have been attributed to oscillations of the electron gas in the neighborhood of the satellite (*13*). The restoring force is the longitudinal electrostatic field due to charge separation between the electrons and the stationary ions. According to this theory, oscillations can persist only at certain characteristic frequencies and in certain directions. At the plasma frequency, f_N, and at the electron gyrofrequency, f_H, resonant oscillations can persist only along the earth's magnetic field. At the harmonics of the gyrofrequency, nf_H ($n = 2, 3, \ldots$), and at the hybrid frequency, $f_T = (f_N^2 + f_H^2)^{\frac{1}{2}}$, they can persist only across the field.

The broad dark region along the top of Figs. 6 and 7 is the $2f_H$ resonance. It remains within the bandwidth of the sounding system for considerable distances because the gyrofrequency changes only slowly along the satellite orbit. At their strongest, the resonances can saturate the receiver system and persist for approximately 5 milliseconds (equivalent to virtual depth of 750 km).

The resonances and the ionospheric echoes are modulated by the spin or roll of the satellite about its axis. The intensity of the resonances depends on the angle between the sounding antennas and the direction of the earth's magnetic field, while the intensity of the ionospheric echoes depends on the angle to the vertical. Out-of-phase modulation of the resonance and the ionospheric echoes can be seen in Fig. 7. The frequency of the roll modulation is, of course, twice the spin rate, or about three per minute.

The pattern resembling interference fringes in the resonances (for example, the coarse fringes near 46° in Fig. 6, and the fine fringes near 44° in Fig. 7) is also modulated by roll. Since the spacing of the fringes varies both with time and with attitude of the antennas, it is unlikely that these patterns are caused by modulation at the ion gyrofrequency, as has been suggested (*14*). Instead, the spatial wavelengths present in the resonant oscillations apparently change with attitude and thus vary the standing-wave pattern around the satellite. The sounding receiver responds to this standing-wave pattern as the satellite proceeds through it and produces the complex fringes on the records. Study of the interference patterns on the resonances is likely to yield further insight into the physics of plasma resonance.

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References and Notes

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14. R. J. Fitzenreiter and L. J. Blumle, *ibid.* **69**, 407 (1964).
15. The satellite experiment has required the efforts of such a large number of people that they cannot all be listed here. Fred Zimmer and his crew at Airborne Instruments Laboratory, a division of Cutler-Hammer, Inc., performed the major contribution of design and construction of the satellite. They and the personnel at the Pacific Missile Range are to be complimented on the success of the launch. J. E. Jackson and E. D. Nelson of Goddard Space Flight Center, through their skillful management of the program, have played important roles. They, and the rest of the Topside Sounder Working Group have contributed years of effort to this experiment. Within the Central Radio Propagation Laboratory, the work of E. E. Ferguson (project engineer), R. G. Green (satellite controller), L. LaBaume (telemetry station supervisor), J. M. Watts, R. S. Lawrence, G. B. Goe, and many others has been essential. The program is supported by NASA.

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