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RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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Abstract: During three nights and two mornings at the end of December 1964, two lunar radars were used to perform the first measurements of the total integrated electron density between the earth and the moon. The measurements were accomplished by determining the difference in time delay between 25 and 50 Mc/s moon-reflected signals to an accuracy of 10 μsec. The experiment was made possible by the use of FM radar transmissions with time-bandwidth products of 10^5. Subtraction of ionospheric electron contents from the totals determined from the differential group delay measurements, suggests that there are two distinct regions beyond the ionosphere. Within the solar wind wake of the earth, in the quadrant opposite the sun, the average cislunar electron density beyond the ionosphere is approximately (300 ± 50) cm^{-3}. In the general direction of the sun, where most of the radar path is beyond the shock wave boundary, the average density is much lower, $(100 {}^{+70}_{-150})$ cm^{-3}. Ionospheric and magnetospheric contents and experimental uncertainty are discussed. While only a few measurements have been made, the initial results clearly show a marked effect which is interpreted here as an average electron density inside the shock front, in a magnetospheric wake extending at least as far as the lunar orbit, which exceeds the solar wind density by about 200 cm^{-3}.

Author

General Discussion: During the years following the attainment of the first lunar radar echoes in 1946 [De Witt and Stodola, 1949], the major scientific effort in the field was centered around determining the characteristics of the moon as a reflector. By 1951, it had been shown that the complicated fading patterns exhibited by lunar reflected signals could be separated into two components, one ionospheric and one due to lunar libration [Kerr and Shain, 1951]. Then, in 1953, experimenters using decameter wavelengths noted that the ionospheric fading could be explained in part by rotation of the plane of polarization as the signal traversed the earth's ionosphere [Murray and Hargreaves, 1954], and could thus provide a measure of the electron content of the ionosphere [Browne et al, 1956]. A Faraday rotation method for determining total ionospheric electron content by the use of two frequencies was employed at the Jodrell Bank lunar radar [Taylor, 1963], and has been more recently applied at Stanford as part of a routine lunar radar program. The technique has become steadily more refined due primarily to the efforts of satellite experimenters [Garriott, 1960; Little and Lawrence, 1960] and now, through a recent greater understanding of the second order effects [Ross, 1965], it is likely that total ionospheric electron content below 1000 km can be determined to a few percent.

A dispersive Doppler technique, widely used by satellite experimenters during the past few years, has been one of the most rewarding methods of studying the rate of change of electron content through the ionosphere and, by the use of radar, over the earth-moon path. Several communications in the past [Howard et al, 1964 a, b] have discussed the combination of Doppler and Faraday measurements to yield information not only about the ionosphere, but about the medium beyond several earth radii. A recently completed study of five months of lunar radar returns, using automatic data reduction techniques, has produced evidence which strongly suggests the vertical transport of photoelectrons in the ionosphere above 1000 km, and in addition suggests a discontinuity in density in the cislunar medium at the earth's magnetohydrodynamic shock wave boundary [Yoh et al, 1965 a, b]. This last result in particular complements the new group-path measurements reported here.

Several techniques for measuring total electron content along the path have been devised [Eshleman, Gallagher and Barthle, 1960], and a number of these have been tried over the years with the Stanford transmitters. Basically, it is desired to measure the total round trip time for a lunar reflected signal and compare it with the figure for propagation in a vacuum.

The free space delay time can be expressed as:

$$T_o = S/c$$

where S is the total path length and c is the free space velocity of propagation.

The group velocity of a radio wave is related to the free space velocity by:

$$v_g = c(1 - f_o^2/f^2)^{\frac{1}{2}}$$

where f is the radio frequency and f_o is the plasma frequency, and it is assumed that $f \gg f_o$.

Finally, the plasma frequency is related to the electron density through:

$$f_o^2 = c^2 r_e N/\pi = 80.6\ N$$

where r_e is the classical electron radius (2.8178×10^{-15} meters) and N is the number of electrons per cubic meter.

Using these relations, it can be shown that the propagation time T of the radio frequency energy normalized by the free space delay is:

$$\frac{T}{T_o} = 1 + \frac{\overline{f_o^2}}{2f^2}$$

or expressed in a more useful way:

$$\frac{T - T_o}{T_o} = \frac{\overline{f_o^2}}{2f^2}$$

where $\overline{f_o^2}$ is the mean square plasma frequency along the propagation path, and $f \gg f_o$ at all points.

For the moon T_o is about 2.6 seconds and the extra delay $(T - T_o)$ at a radar frequency f of 25 Mc and for $\bar{N} = 10^8$ m^{-3} (100 cm^{-3}) is 16.8 microseconds. Thus, to make a meaningful comparison possible, T_o must be known to better than about 1 part in 10^6.

In the absence of precise knowledge of the free space delay, $\overline{f_o^2}$ may be determined by measuring the group delay simultaneously at two frequencies. The difference in delays will then be:

$$T_1 - T_2 = T_o \frac{\overline{f_o^2}}{2} \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right)$$

where f_1 and f_2 are the two radar frequencies and T_1 and T_2 are the propagation times on the two corresponding frequencies. For the Stanford radars on 25 and 50 Mc, and assuming $\bar{N} = 10^8$ m^{-3}, the differential delay will be 12.63 microseconds. A plot of calculated differential delay vs $\bar{N}$ (in number cm^{-3}) is shown in Fig. 1.

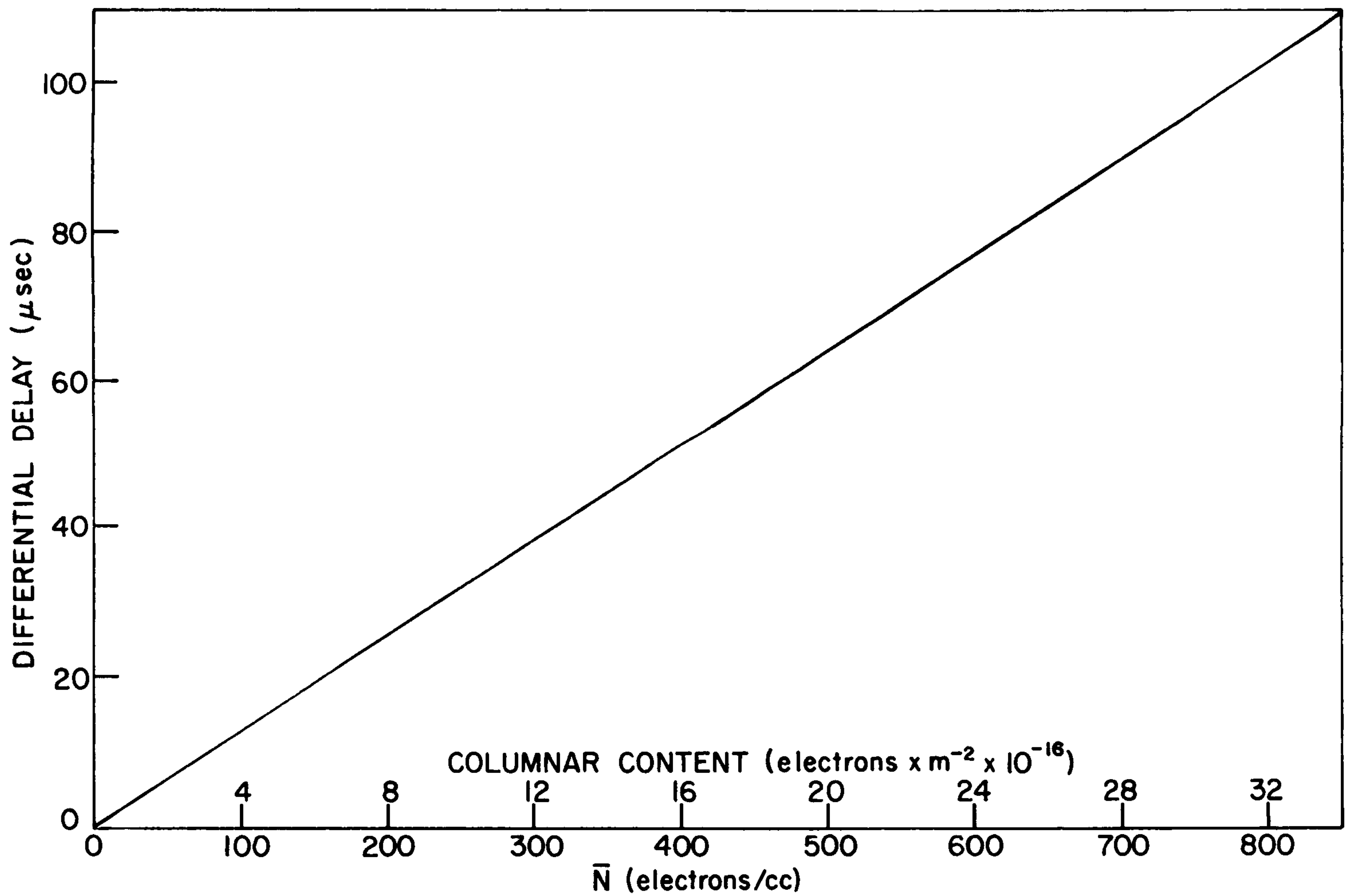


Fig. 1: CALCULATED DIFFERENTIAL GROUP DELAY FOR TWO RADARS OPERATING ON 25 AND 50 MCS VS. COLUMNAR ELECTRON CONTENT AND AVERAGE DENSITY BASED ON LUNAR RANGE OF 400,000 KM.

The differential group delay expected from the ionospheric portion of the earth-moon path can be obtained by using electron densities from several sources, such as satellites S66 and Syncom [Garriott and Smith, 1965], and the Stanford vertical incidence ionosonde. The ionospheric contents noted during December 1964, ranged from a nighttime low of about 2×10^{16} electrons per square meter to a midday high of about 20×10^{16} m^{-2}. If this columnar content were to be spread evenly along the earth-moon path (60 earth radii or approximately 400,000 km), it would mean an $\overline{N}$ of from 50 to 500 cm^{-3}. When translated to differential group delay terms using, for example, the upper abscissa scale of Fig. 1, it can be seen that the variation in group delay caused by the ionosphere alone can range between about 7 and 65 microseconds. The magnetospheric content is probably less than 3×10^{16} m^{-2} [Helliwell, 1965], or, in differential delay terms, less than 10 microseconds.

A measurement of lunar-echo group delay to an accuracy of a few microseconds is thus required in order to establish a useful measurement of the cislunar columnar electron content. Experiments toward this goal have been conducted at Stanford for several years.

The available transmitters are essentially CW types (with peak-power capability of twice their average power rating), and several pulse-compression techniques have been tried in an attempt to achieve adequate range resolution and signal-to-noise ratio. A single measurement has been obtained, employing a pseudo-random pulse-code transmission and cross correlation detection. The result agrees with those to be discussed; however, the data-reduction problems encountered using this method have led to the use of the alternate frequency-modulated system described in the following paragraphs.

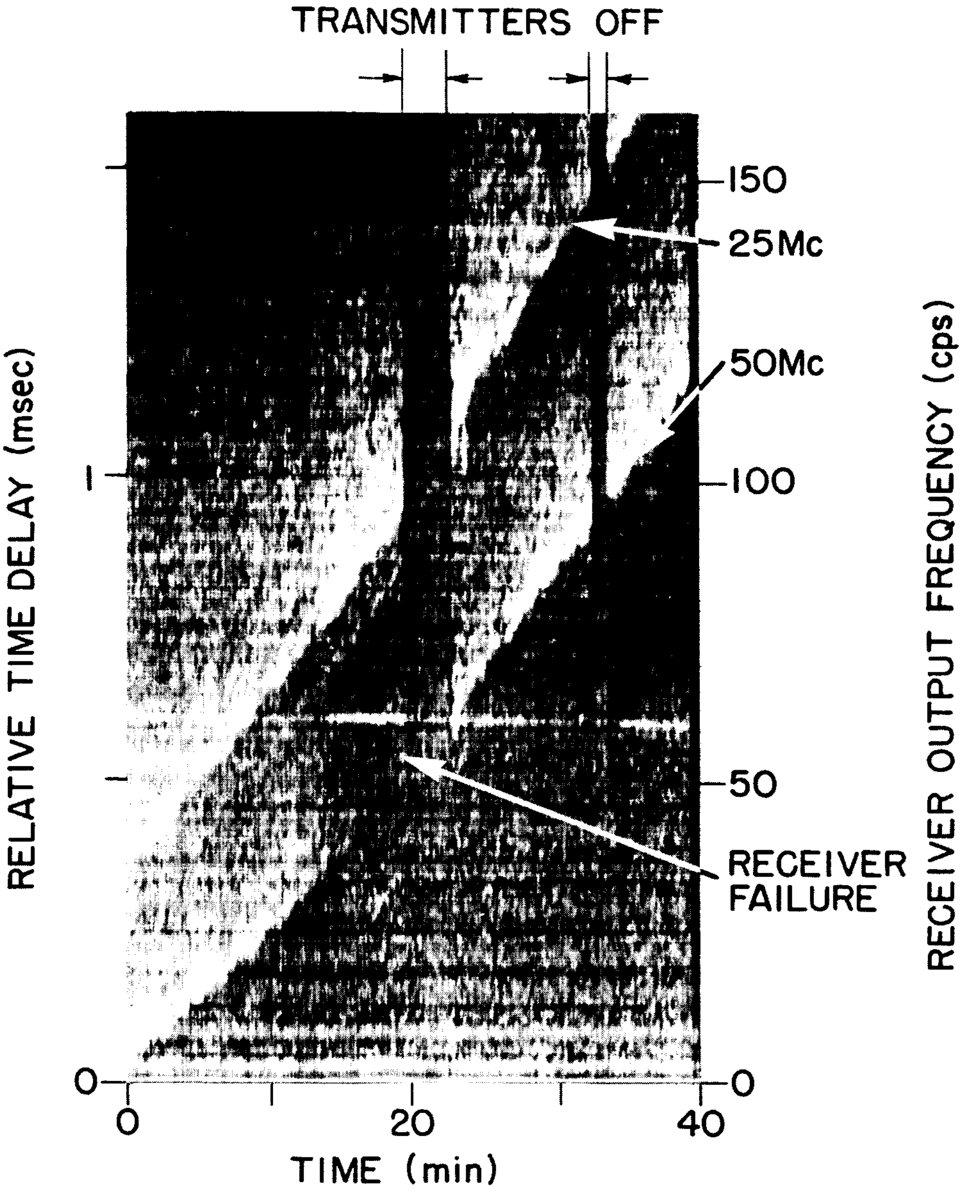
The use of an FM or "chirp" radar is a well-known technique for obtaining high-average power together with good range resolution. Inaccuracies involved in sweep generation and compression have, however, generally restricted use of FM transmissions to time-bandwidth products of 10^4 or less. A recent development at Stanford has been the digital synthesis of a frequency sweep, and this method allows the generation of an FM signal with frequency and timing accuracy equal to that of the controlling frequency standard.

A time-bandwidth product of 10^5 was employed for the lunar measurements. A linear sweep of 100 kc was executed once per second. The frequency sweeps were radiated simultaneously from two transmitters. One developed 300 kw of average power output between 24.9 and 25 Mc; the other produced 50 kw, sweeping the range from 49.8 to 49.9 Mc. The antennas used each had a gain of about 25 db. These were a 48-element log-periodic array on 24.9 Mc and a 150 foot dish on 49.8 Mc. All signals and timing in the system were synthesized from a crystal standard having a stability of 5 parts in 10^{10} per day. Hence, system stability was at least an order of magnitude better than the required measurement accuracy.

Frequency sweeps were simultaneously transmitted on each frequency (25 and 50 Mc) for a period of 2.6 seconds. Following this transmitting period, the receivers were connected to the antennas for the succeeding 2.6 seconds, after which the operation was repeated, resulting in a 50 percent duty cycle. A second synthesized frequency sweep, identical to that transmitted but delayed by the exact lunar round-trip time plus a few microseconds, was employed as a local oscillator signal in the receivers. The beat note between lunar echoes and this oscillator was recorded on magnetic tape. The tape was re-recorded to compress the data 64 or 128 times before processing on a Rayspan spectrum analyzer.

A typical Rayspan readout is shown in Fig. 2. It can be seen that the difference between leading edge positions can be determined to an accuracy of about 10 microseconds. The echo frequency is a function of both range (time delay affects frequency), and range rate (range rate Doppler). The presentation is different from what might be expected, since the 24.9 Mc transmitter is swept upwards in frequency, while the 49.8 Mc transmitter is swept downward, due to technical considerations. The 24.9 Mc curve thus represents range plus range rate Doppler, while the 49.8 Mc curve displays range minus range rate Doppler (twice the 24.9 Mc range rate Doppler). The difference between the curves is thus 3/2 x 50 Mc range rate Doppler plus differential group delay. Range rate Doppler is measured before and after each data run and the results plotted. The difference between the two Rayspan curves is scaled and plotted on the same graph. The difference between these two curves is then differential group delay. A typical plot of scaled results is shown in Fig. 3.

Since the "chirp" generation equipment was heavily committed to other programs, only very limited time has been devoted to lunar work. Of the eight days' runs, five days produced usable data. Measurements made on these five days have been scaled and plotted using the method described above.



TWO-FREQUENCY LUNAR ECHOES ON FM RADAR, STANFORD, CALIFORNIA, 24.9-25.0Mc AND 49.8-49.9Mc, 22 DEC 1964

Fig. 2: TWO-FREQUENCY LUNAR ECHOES ON FM RADAR, STANFORD, CALIFORNIA, 24.9 - 25.0 MC AND 49.8 - 49.9 MC, 22 DECEMBER, 1964.

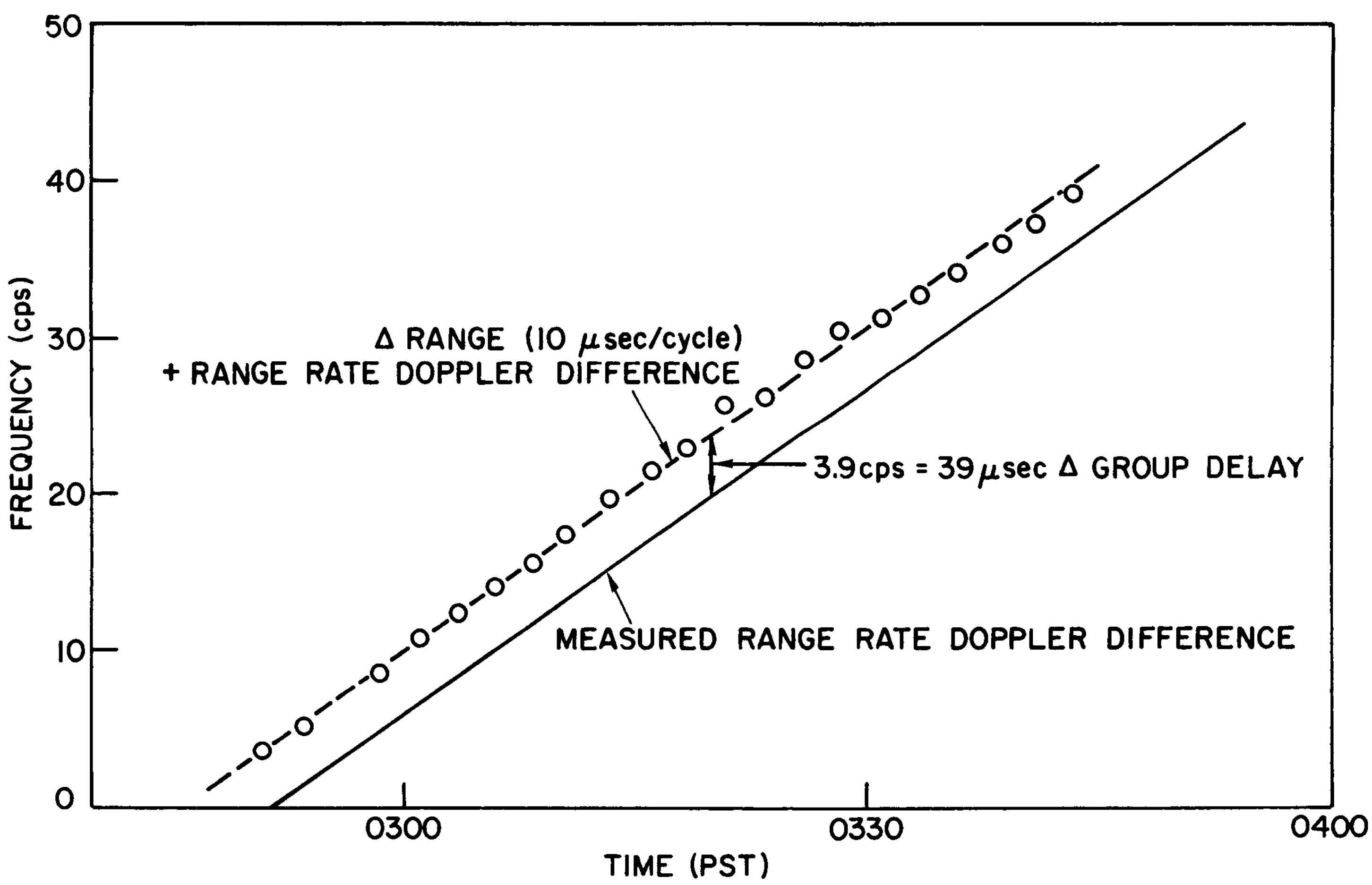


Fig. 3: PLOT OF RESULTS SCALED FROM 22 DECEMBER FM RADAR DATA.

Table 1 shows details of date, time of operation, lunar elevation angle at transit, the measured differential group delays, and the equivalent columnar electron content between the earth and the moon. Since the measurements were made near the lunar transit time, the nighttime results apply to directions away from the sun, while the mid-morning results are for directions at the edge of the quadrant toward the sun. The geometry is illustrated in Fig. 4.

Even before correcting specifically for the ionospheric contribution, it is evident from the total integrated densities that there must be a marked difference beyond the ionosphere for solar and anti-solar directions, since the total densities are comparable while ionospheric densities must be markedly different. In order to determine the ionospheric component, ionosonde and satellite measurements taken at the same time as the radar measurements were investigated. In the Table are listed ionospheric critical frequencies, integrated ionospheric electron densities determined from these frequencies, and ionospheric content determined by Faraday polarization measurements on Syncom [Garriott and Smith, 1965] and S66 [Bhonsle, 1965] satellites. The formula used for translating ionospheric critical frequencies to contents is based on a number of comparisons of ionosonde and Faraday measurements, and it is believed to be accurate to about ±20 percent.

After correction for the zenith angle, the ionospheric contents are subtracted from the totals to give the cislunar columnar content beyond an altitude of about 1000 km. These are listed in the next to last column in the Table. For December 17, 21, and 22, the ionosonde values were used, while for December 29 and 30, the Syncom measurements were

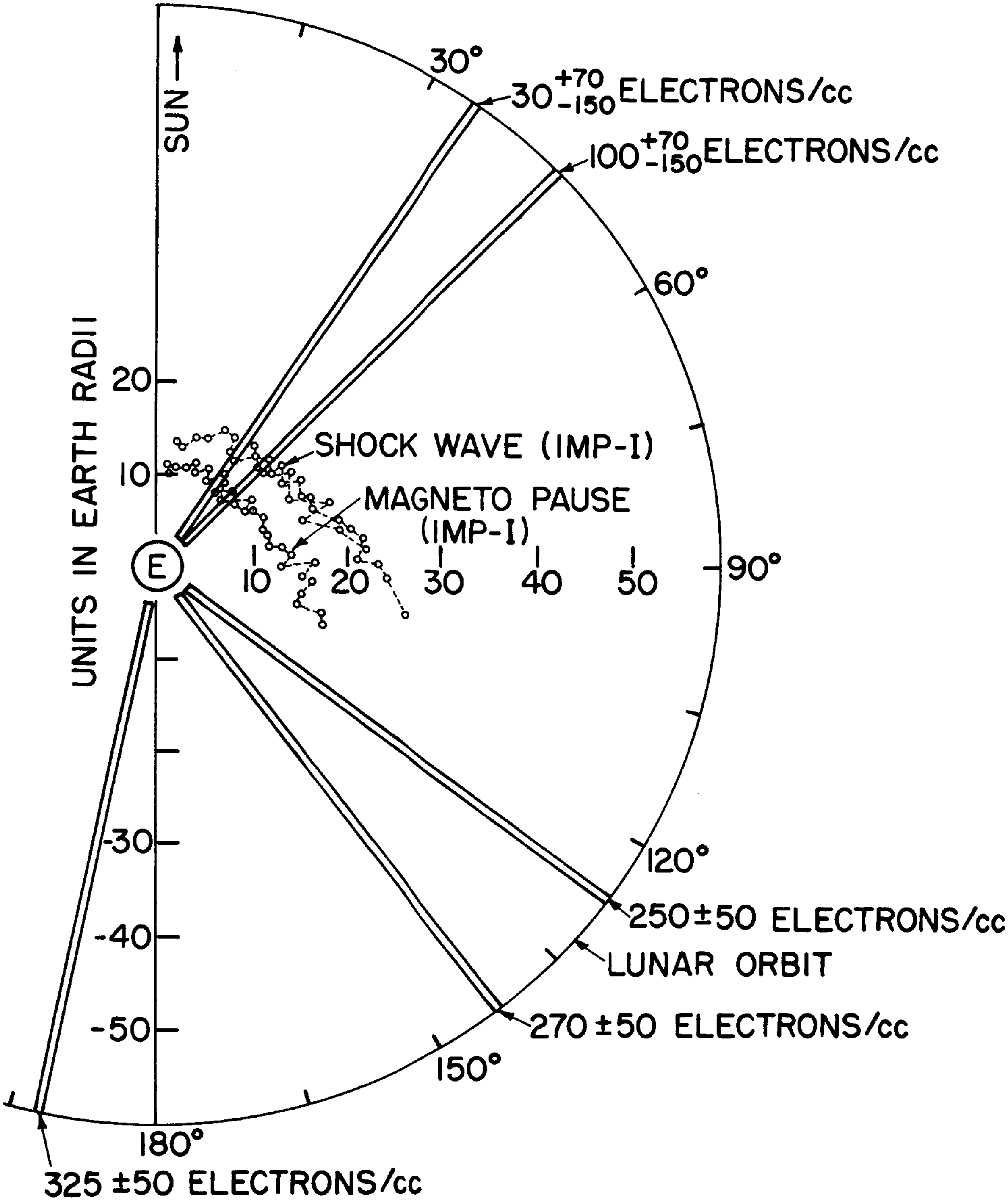


Fig. 4: PLOT OF TABLE 1 RESULTS IN GEOCENTRIC COORDINATES SHOWING MEASUREMENT DIRECTION RELATIVE TO THE EARTH-SUN LINE.

DATE	DATA TIME	MOON TRANSIT TIME	MOON ELEV ANGLE	ΔG µsec	N_T	foF2	N_I $1.9\frac{fo^2}{81}$	N_I SYNCOM FARADAY	N_I S66 FARADAY	Sec χ	N_I Sec χ	N_T- N_ISec χ-	$\bar{N}$ > 1K km
DEC 64	PST	PST	DEG	µsec	$x10^{-16}$ el/m^2	Mc	$x10^{-16}$ el/m^2	$x10^{-16}$ el/m^2	$x10^{-16}$ el/m^2	350 Km	$x10^{-16}$ el/m^2	$x10^{-16}$ el/m^2	el/cc
17	2330 ↓ 2340	2315	74.1	50 ↓ 50	15.5	3.2 ↓ 3.1	2.5 ↓ 2.3	NO DATA	2.1	1.04	2.6 ↓ 2.4	12.9 ↓ 13.1	325
21	0240 ↓ 0310	0230	75.0	42 ↓ 42	12.9	2.9 ↓ 3.0	2.0 ↓ 2.1	NO DATA	NO DATA	1.04	2.1 ↓ 2.2	10.8 ↓ 10.7	270
22	0300 ↓ 0400	0331	72.0	39 ↓ 39	12.3	3.2 ↓ 2.8	2.5 ↓ 1.8	NO DATA	NO DATA	1.05	2.6 ↓ 1.9	9.7 ↓ 10.4	240 ↓ 260
29	0830 ↓ 0900 ↓ 0930	0900	36.0	35 ↓ 35 ↓ 54	10.8 10.8 16.6	NO DATA	NO DATA	4.9 5.6 5.8	NO DATA	1.62	8.0 ↓ 9.1 ↓ 9.4	2.8 ↓ 1.7 ↓ 7.2	70 ↓ 45 ↓ 180
30	0930 ↓ 1000	0945	32.0	35 ↓ 35	10.8 10.8	4.6 ↓ 4.9	5.0 ↓ 5.6	5.3 5.5	NO DATA	1.79	9.5 ↓ 9.9	1.3 ↓ 0.9	35 ↓ 25

TABLE 1

used. In the last column are listed the corresponding values of average volume densities for the cislunar medium beyond the ionosphere.

The dramatic rise in columnar content between 0900 and 0930 on December 29 is believed to be due primarily to an upward flow of photoelectrons from the upper ionosphere to the lower magnetosphere. Using combined phase path and Faraday polarization measurements on moon echoes, Yoh et al [1965 b] show, from the average of data taken over a period of several months (including December 1963), that there is a difference of content of about 5×10^{16} m^{-2} as registered by these two measurements in the morning (upward flow) and afternoon (downward flow). Nearly all of the morning change occurs between 0900 and 1000.

In Fig. 4, the geometry of the radar paths on the various days is shown with reference to the earth-sun line. The positions in the ecliptic of the solar-wind produced shock front and magnetopause, as measured by IMP-I [Ness et al, 1964], are also shown. With the radar paths are indicated average electron volume densities, and uncertainties in these values, for the cislunar medium beyond about 1000 km. The error limits are based on a ± 5 to 10 μsec combined uncertainty in measurement and in ionospheric content, plus an allowance in the daytime results of 5×10^{16} m^{-2} for electron transport between ionosphere and magnetosphere. Thus an allowance is made for a change in the magnetospheric content, but none is made of the remaining magnetospheric content.

Taking into account the various considerations discussed above, it appears that the daytime results are consistent with the extremely low (0 - 10 cm^{-3}) electron densities in the region beyond the shock front determined by several plasma probes. The uncertainties are such that these radar results cannot be used to help define this density.

A very different picture is obtained from the nighttime results, however. After an allowance of about 3×10^{16} m^{-2} integrated density is made for the higher volume density in the magnetosphere near the earth (out of perhaps five earth radii), it appears that a volume density of 150 to 250 cm^{-3} is required in the anti-solar quadrant, all of the way to the orbit of the moon.

The present results, based on individual group-path measurements, complement those reported by Yoh et al [1965 a], which are based on a five-month average of phase-path and Faraday polarization measurements. Together they suggest that:

a. the average cislunar electron density, in regions well away from the earth, is higher by several hundred electrons per cubic centimeter in the anti-solar quadrant than in directions toward the sun;

b. this change in density appears to occur with high gradients in the general region of the shock front; and

c. this high gradient region extends at least to the orbit of the moon.

It is not yet clear just how the present results compare with theory and other measurements. Theoretical expectations for volume density changes at a shock front in a collisionless plasma [e.g., Colgate, 1959] would give considerably lower densities inside the shock than suggested above, unless the solar wind density is much higher than the values which are now popular. However, these theories are rather idealized for application to the present problem, and they are still under development. Plasma measurements on IMP-I imply values inside the shock front of from about four to more than a hundred electrons per cubic centimeter [Wolfe, 1965; Olbert, 1965; Serbu, 1964]. The various instruments, however, work on different principles and are sensitive to somewhat different energy levels. It would appear that the retarding potential analyzer can best be used for comparison purposes, since it includes measurements of the more numerous electrons at thermal (0-5 ev) energies.

Preliminary results for the retarding potential analyzer on orbit number one of IMP-I, as reported by Serbu [1964], imply an electron density of about 200 cm^{-3} inside the shock front, with no measurable electrons in this energy range outside the shock. (For this orbit the shock front was at 16 earth radii.) There appear to be no changes in this energy range at the magnetopause (11 earth radii), while in the region from 2 to 4 earth radii, the density drops from several thousand to several hundred electrons per cubic centimeter. This single-orbit measurement of electron density change across the shock adds credence to the radar interpretation, although it pertains to a shock wave area near the earth, in the general direction of the sun. The radar experiments, on the other hand, suggest characteristics of the geometry, density, and change in density for more distant regions of the shock wave boundary and the cislunar medium.

The radar experiment described here needs to be refined, and considerably more data should be accumulated. A preliminary report is being made at this time because the initial results appear to be important with respect to the models of the solar wind and the wakes of the earth and moon which are developing very rapidly from a combination of theory and space probe and radar measurements.

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