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RADAR STUDIES OF THE SUN AT 38 MC/S

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ABSTRACT

About 1000 daily radar experiments have been made of the Sun at El Campo, Texas, since April, 1961. This paper presents some of the results of these experiments. The average intensity, mean range, and range depth of the solar echo have been found to vary with sunspot number, but correlations of these parameters on a daily basis are low. The radar signal is reflected from coronal irregularities that are moving at velocities up to 200 km/s. At times there is an increase in the echo intensity, and when this happens there are often high-corona irregularities moving at about 20 km/s. Some possible reasons for these effects are discussed.

INTRODUCTION

Radar studies of the solar corona have been made near El Campo, Texas, on a routine basis since 1961. These experiments represent a new way of studying the solar corona and, when fully exploited, should provide a valuable supplement to studies of the Sun by other means.

The equipment and procedures are described elsewhere (James 1964). Briefly, one radar experiment is performed by transmitting a coded signal toward the Sun for 16 min., the round-trip time, and then receiving the echo for the following 16 min. The average transmitted power is 500 kw, and the antenna gain is 33 to 36 db relative to isotropic.

Normally, one radar experiment per day is made as the Sun passes through the antenna beam. A large volume of data has been collected and studied, but complete interpretations have not been made partly because of the complexity of the echo. Certain long-term patterns are beginning to emerge. For example, it appears that the average echo intensity is directly related to the sunspot cycle. The purpose of this paper is to present some of the data taken during the last 5 years and to discuss interpretations of the results.

THEORY OF REFLECTIONS

The solar corona consists of an ionized gas whose mean density decreases with distance from the Sun's center. Radar waves will propagate through regions of such a medium where the electron density is less than a certain critical value. As a radar wave approaches the Sun from Earth, it will penetrate the corona to a certain depth and be reflected from the "surface" where the refractive index becomes zero. The refractive index, n, in a plasma having a negligible magnetic field is given by

$$n^2 = 1 - \frac{X}{1+Z^2},$$

where

$$X = \frac{N e^2}{m \epsilon_0 \omega^2} \quad \text{and} \quad Z = \frac{\nu}{\omega},$$

and where N is the ionization density in electrons per cubic meter, e and m the charge and mass of the electron, ϵ_0 the permittivity of free space ($e^2/\epsilon_0 m$ = 3182 MKSA units), $\omega(=2\pi f)$ the angular radio frequency, and ν the electron collision frequency.

The solar corona has many irregularities of electron density so that the surface of reflection is rough and irregular. These surfaces of reflection are continuously in motion, producing a large Doppler spreading of the radar echo.

A small amount of radio energy is scattered back by individual electrons (Thompson scattering), but this type of scattering is at least 10 orders of magnitude too weak to explain the observed echo.

Some energy may be scattered by irregularities whose ionization density is slightly less than critical, and this scattered energy has been shown by Gallet (1955) to be proportional to $\langle(\Delta N/N)^2\rangle\ [X/(1-X)]^2$, where $\langle(\Delta N/N)^2\rangle$ is the mean square fractional variation of electron density. In order for this type of scattering to be appreciable, a large number of scatterers are required.

For a smooth, spherically symmetric corona the paths of radio waves can be computed. Figure 1 shows an example of such ray paths. The dotted line of Figure 1 represents the critical density sphere where complete reflection occurs for any rays penetrating to that

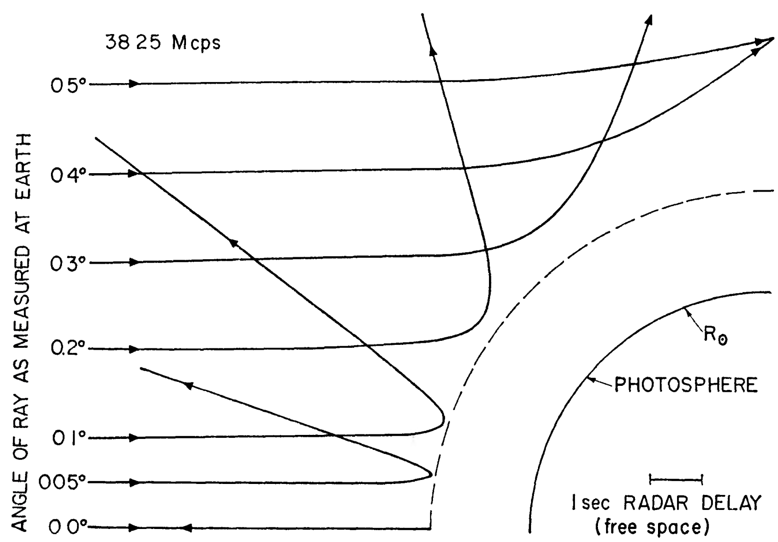

FIG. 1.—Computed ray paths at 38.25 Mc/s in a spherically symmetric corona with Baumbach-Allen density (Allen 1947). The dotted line represents the sphere where the refractive index is zero.

depth. For each ray the point nearest the Sun's center is called the turning point. The actual corona is not smooth so that the actual ray paths will only approximately follow the paths as shown. The reader can imagine some random bending of the rays caused by refractions by irregularities, with the most severe bending occurring near the critical density sphere. Most of the irregularities responsible for the solar radar echo are believed to be within one-fifth solar radius of the critical sphere. If this is true, the observed echo should exhibit two characteristics; namely, (1) the range depth should be about 2 sec or less, and (2) the distribution of echo energy with range should rise more sharply than it decreases, as range is increased. These two effects have been observed, especially near sunspot minimum.

Attenuation and group delay can also be computed for a spherically symmetric model. Some results of computations are shown in Figures 2 and 3. The attenuation plotted in Figure 2 is the two-way loss of energy for a signal reflected at the turning points, and the time delays plotted in Figure 3 are the additional two-way group delays to the turning points. Note that both the attenuation and the group delay are greater for the central ray. The attenuation is less for higher temperatures because the particle collision cross-section decreases as temperature increases.

The round-trip time delay is measured accurately by the radar system. This time delay can be used to locate levels in the corona only when the true additional group delay is known. Because there is at present no accurate means of measuring the additional group delay, computed group delays must be used. Additional group delays as a function of the multiplying factor for the ionization density are shown plotted in Figure 4. The coronal density given by Pottasch (1960) is used. Note that when the estimate of the ionization density is in error by a factor of 5, the error in the range scale is less than 0.3 $R_\odot$.

The motion of scattering centers on the Sun is measured by means of the Doppler shift, which for a line-of-sight velocity, v, is given by

$$\Delta f = -\frac{2vn}{c} f ,$$

where f is the transmitted frequency, c the velocity of light, n the refractive index of the medium in which the reflecting center is moving, and where $vn \ll c$. Proper account

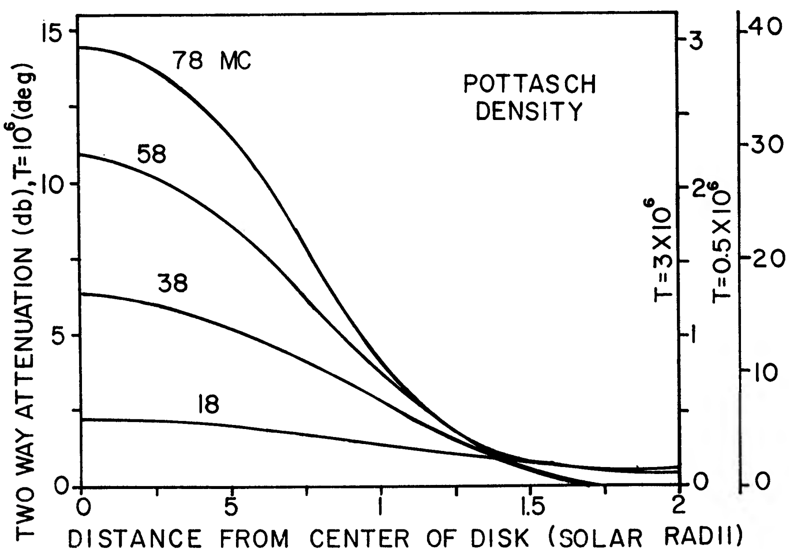

FIG. 2.—Computed two-way signal attenuation for the Pottasch density (Pottasch 1960) and for rays reflected at the turning points.

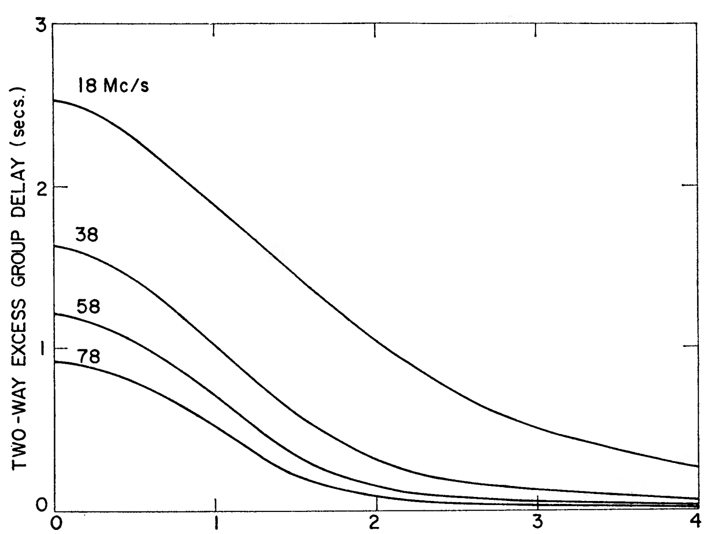

FIG. 3.—Computed excess group delays for the Pottasch density and for rays reflected at the turning points.

should be taken of the curvature of the ray paths when interpreting Doppler spectra. The Doppler shifts resulting from radially directed motions, for example, will be smaller than expected on the basis of the component of motion in the direction of Earth, except for the echoes near the center of the disk (see Fig. 1). The magnitude of the Doppler shifts at 38 Mc/s due to Earth's rotational and orbital motions is less than 100 c/s, and that due to the Sun's rotation is less than 1 kc/s. Echo components with Doppler shifts of up to 60 kc/s have been observed, and these motions have been attributed to some type of plasma wave motion or to mass motions.

The effectiveness of the Sun in reflecting radar energy is reported as the solar radar cross-section A_0. This parameter is defined by the radar equation.

$$P_r = P_t \frac{G_t}{4\pi R^2} A_0 \frac{A_r}{4\pi R^2} p ,$$

where P_r and P_t are the received and transmitted powers, G_t the transmitting antenna gain, A_r the receiving antenna effective aperture, R the range from radar to Sun, and p

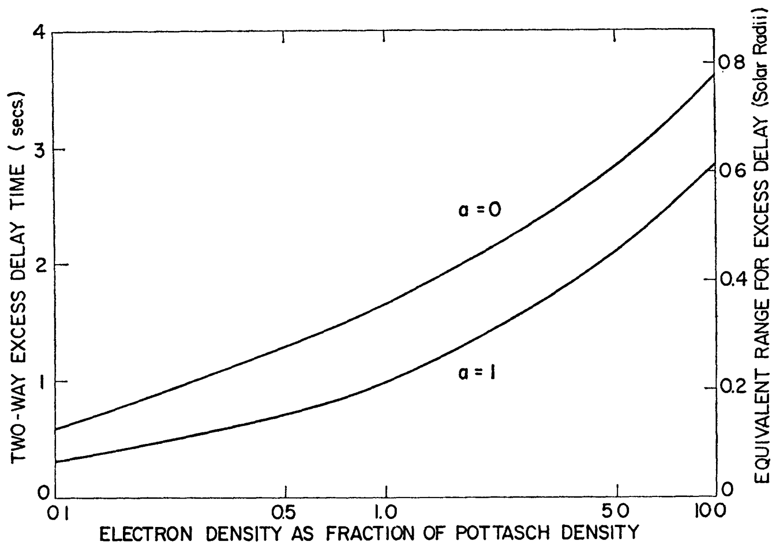

FIG. 4.—Computed excess group delays at 38 Mc/s for a ray directed at the center of the disk ($a = 0$), and for a ray directed at the limb ($a = 1\ R_\odot$). The electron density throughout the corona is assumed to be multiplied by the factor indicated.

the fraction of the returned power accepted by the antenna due to the effects of polarization misalignments. The factor p has been determined experimentally to be approximately $\frac{1}{2}$ for a linearly polarized antenna and, at least for echoes received during July and August, 1965, to be approximately one-half for a circularly polarized antenna (with linearly polarized transmission).

The cross-section of an ideal spherically symmetric sun is determined by two factors; (1) the effective radius of curvature of the reflecting plasma at the center of the disk, and (2) the attenuation of the radio wave in the corona above the reflecting level. The effective radius of curvature can be determined conveniently from computed ray paths.

The corona is not smooth and symmetrical but behaves as a rough reflector. Consequently, both the angular diameter and the cross-section of the actual Sun are larger than should be expected for a smooth corona. The increase in cross-section due to roughness depends upon the type of roughness. For a spherical surface, rough according to the Lambert cosine law of reflection, the increase in cross-section is by a factor of 2.7 (Grieg, Metzger, and Waer 1948). For a 10^6 ° K corona having the Pottasch density but roughened according to the Lambert law, the cross-section should be about $2\pi R_0^2$. For a similar corona having ten times this density, the computed cross-section is less ($0.8 \pi R_0^2$) because of the increased absorption for the assumed model. The results of similar computations for other densities and coronal temperatures are shown in Table 1. Note that temperature has a greater effect than the multiplier for the ionization density. As will be seen in the next section, the cross-section at times was more than $20\pi R_0^2$, which implies that at times the Sun is a much better reflector than the Lambert sphere.

RESULTS

A total of 1000 daily solar-radar experiments were made at El Campo in the 5-year period following April, 1961.

An estimate of the average diameter of the radar sun could be made because the antenna beam width and radar-sun diameter were roughly the same. There were indications that the radar diameter changed from time to time; but the average diameter was found to be approximately 1°.

TABLE 1

RESULTS OF COMPUTATIONS OF SOLAR RADAR CROSS-SECTIONS FOR AN ASSUMED LAMBERT-LAW ROUGHNESS*

Pottasch Density Multiplier	Temperature of Corona (10^6 ° K)	Effective Radius of Reflecting Surface (Solar Radii)	Computed Mean Two-Way Attenuation (db)	Computed Cross-Section (πR_0^2)	
				No Attenuation	With Attenuation
0 1	0 5	0 98	4 0	2 6	1 0
0 1	1 0	0 98	1 6	2 6	1.8
0 1	3 0	0 98	0 3	2 6	2 4
1 0	0 5	1 2	12	6 5	0 41
1 0	1 0	1.2	5 0	6 5	2 0
1 0	3 0	1 2	1 0	6 5	5.1
10 0	0 5	1.7	22	7.8	0 049
10 0	1 0	1 7	10	7 8	0 78
10 0	3.0	1 7	1.9	7.8	5.0

* The Pottasch ionization density was used for computations of the effective radius of the reflecting surface and for computations of the signal attenuation to the turning points.

For each daily experiment an attempt was made to measure the total received echo energy and the distribution of energy in both range and Doppler frequency. Because of the sensitivity limitations of the radar system, there were times when some of these parameters could not be accurately measured. There were daily changes in all the parameters, but the change in the cross-section was usually the greatest. A change in apparent cross-section by 50 per cent per day was not unusual, but it is possible that some of this change was due to changes in the angular distribution which could not be detected with the 1° beam. The cross-sections reported in this paper have been adjusted to represent echo energy received in a very broad band.

Figure 5 shows a plot of average values of cross-section, mean range, range depth, and sunspot number. The sunspot curve is a running 3-month average of values published in *Quarterly Bulletin on Solar Activity* (International Astronomical Union), and in *Compilations of Solar-geophysical Data*, Part B (U.S. Department of Commerce). Each plotted value of cross-section represents a 2- to 3-month average of daily values. The unusually large values of cross-section, which were observed less than 5 per cent of the time, were omitted from these averages. A correction has been made in some cases for a small loss of echo energy due to the separation of transmitted frequencies (James 1964). Note that on a long-time basis the cross-section varies with sunspot number, but on a day-to-day basis the correlation is very low. Over short periods of time the cross-section is not correlated with sunspot number, calcium plage area, 2800 Mc/s radiated flux, geomagnetic index, or with cross-sections measured 27 days before or after.

The mean range values of Figure 5 were determined by first computing the centroid of the distribution of echo energy with delay time. The centroid was then related to the Sun's center assuming that the round-trip group delay in the corona was 1.6 sec, which is the computed value for the central ray for both the Pottasch and Baumbach-Allen density distributions. The additional group delay should be expected to increase with sunspot number and, if so, the variation of mean range would be larger than indicated in Figure 5.

The range depth plotted in Figure 5 is defined as twice the rms deviation from the centroid of the distribution of echo energy with range. Note that the average range depth tends to be correlated with average cross-section.

The average distribution of echo energy with range during September, October, and

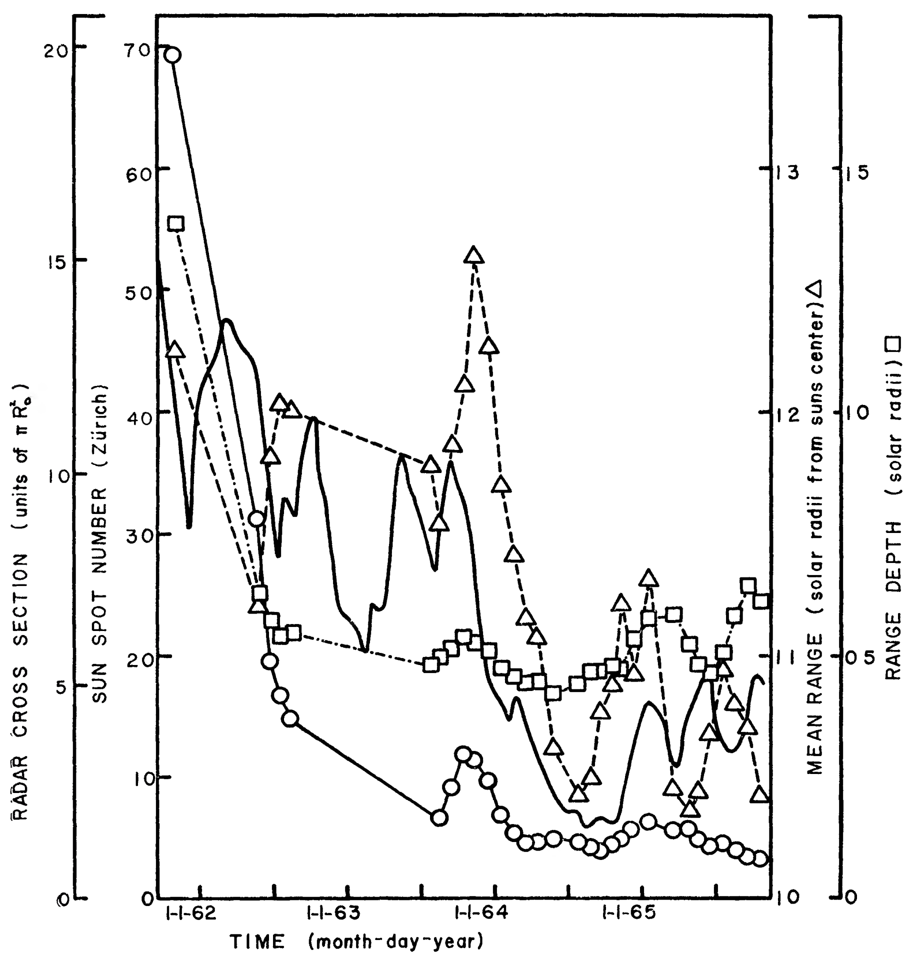

FIG. 5.—The variation of solar radar parameters, as measured at El Campo, and the average sunspot number with time. Each point represents an average of the radar measurements made over a 2- to 3-month period, and the sunspot number plot is a 3-month running average. The cross-section values were adjusted to apply for echo energy received over a wide band, and the mean range values were computed on the basis of an assumed 1.6-sec additional group delay in the corona.

November, 1965, is shown in Figure 6. The individual runs for these two plots were divided into two equal groups on the basis of cross-section. The average for the larger cross-section shows some energy components reflected from the high corona, but the low cross-section average shows no such echo components. These high-corona echoes imply irregularity densities as much as one hundred times the normal coronal density. The range marks were placed according to the following assumed schedule of excess group delays:

Range mark (R_0)	3	2	1	0	-1
Excess delay (secs.)	0	0 1	1 4	1	1

These delays are based on computed time delays to various points in the corona using the Baumbach-Allen density.

The average distribution of echo energy in Doppler frequency for 1963–1964 is shown in Figure 7. For a given daily experiment the spectrum may differ somewhat from this

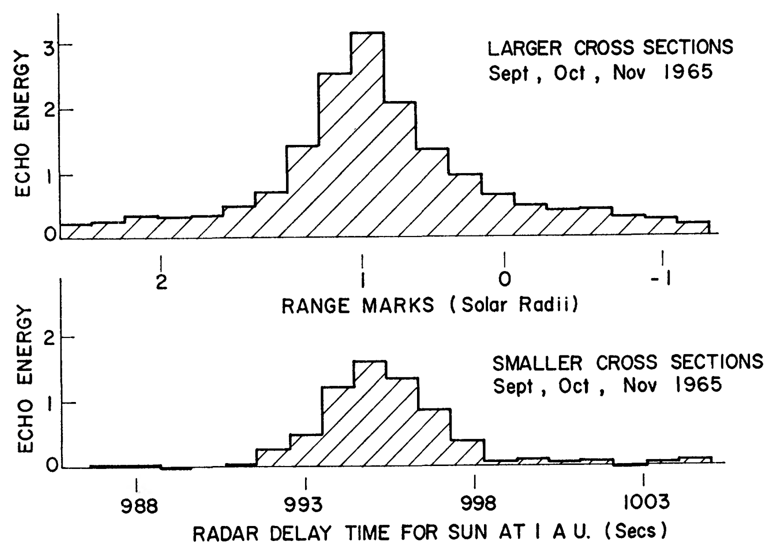

FIG. 6.—The average distributions of echo energy with range for the 3-month period September–November, 1965. The top plot is for days when the cross-section was large, and the lower plot is for days when the cross-section was small.

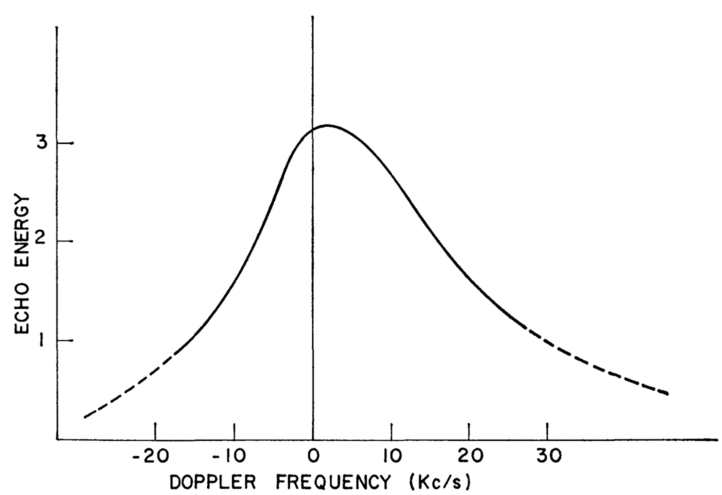

FIG. 7.—Distribution of echo energy with Doppler frequency for the period 1963–1964

average. The spread between the half-power points is usually between 25 and 40 kc/s, but values as low as 20 kc/s and as high as 70 kc/s have been observed. On a few occasions the energy at 5 kc/s and lower is considerably less than the energy at 0 kc/s and above. A line-of-sight target motion of 3.92 km/s produces a Doppler shift of 1 kc/s.

The distribution of echo energy in range and Doppler frequency for 21 days in September, October, and November, 1965, is shown in Figure 8. These days were typical, and the average cross-section for the days selected was the same as for the 3-month period. A similar distribution for 48 days in 1963–1964 is shown in Figure 9. For this compilation an attempt was made to select data that had high-corona echoes. Note that the high-corona energy in front of the Sun is Doppler-shifted 5–10 kc/s and has a narrow Doppler spread, whereas the energy near the limbs of the Sun shows a negative Doppler shift. The range marks for Figures 8 and 9 were placed as for Figure 6.

DISCUSSION OF RESULTS

The solar echo is reflected from some type of irregularity that is in apparent motion. The range-Doppler spectra (Figs. 8 and 9) suggest that this motion is predominantly

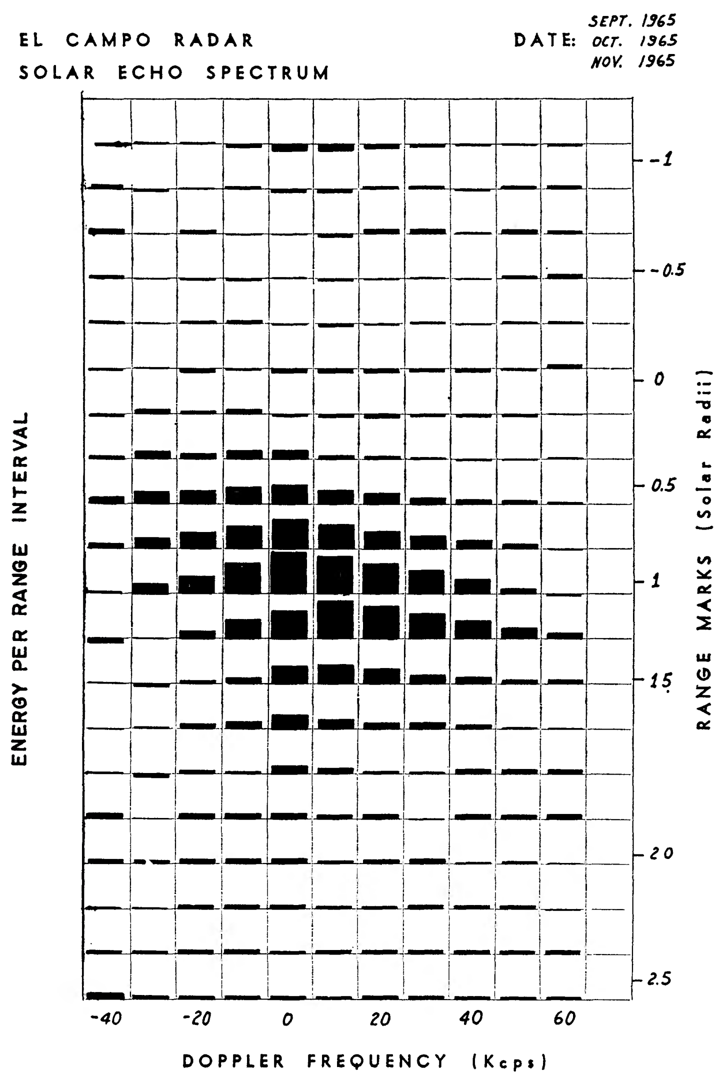

FIG. 8.—The distribution of solar echo energy in range and Doppler received at El Campo, Texas, for the 3-month period September–November, 1965.

radial. These moving irregularities may be motions of plasma (mass motions) or some type of wave motion, or some combination of the two. If the main echo is due to mass motions, the observed mass velocities agree with Parker's theory of the solar wind for coronal temperatures greater than 2×10^6 ° K (Parker 1963). Velocities as high as 150 km/s are always observed, and Parker predicts velocities of this order of magnitude at the 38 Mc/s reflecting level in the corona. The slowing down of the mass velocities at about 1.6 $R_{\odot}$ (Fig. 9) has not been predicted. This suggests that at least part of the echo may be reflected from wave-motion irregularities such as shock-wave fronts.

The irregularities responsible for the main solar echo may be some type of hydromagnetic shocks which are propagating in a predominately radial direction. If so, the shock-front velocities are from 100 to 200 km/s and are probably responsible for coronal heating. These shocks would vary in number and in intensity with time, but must always be present because all solar echoes show a large Doppler spreading. Such a variation in number and intensity of the shocks and the resulting changes in coronal temperature could be responsible for the observed changes in cross-section.

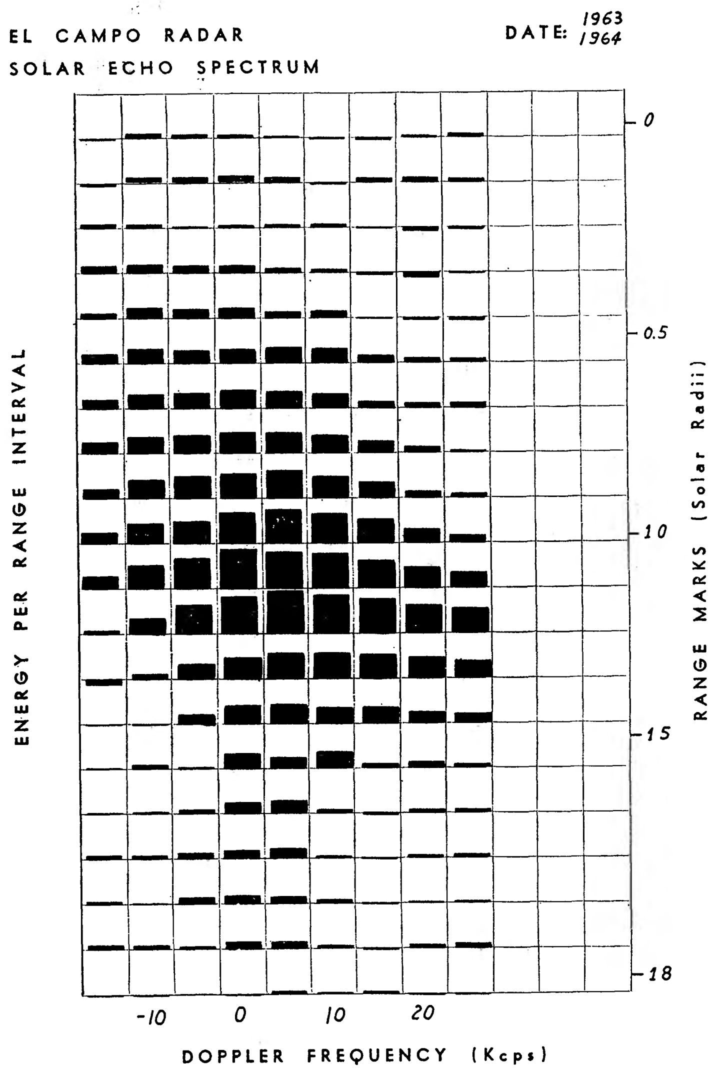

FIG. 9.—The distribution of echo energy in range and Doppler frequency for selected days in 1963–1964. Days that indicated high-corona echoes were selected for this average.

The high-corona echoes discussed in the previous section are present at many range intervals simultaneously; that is, they are not normally present at one range one day and at some other range another day. Furthermore, when they appear at earlier range intervals than the main echo, they also appear at later range intervals. These later range intervals undoubtedly represent reflections from the limbs and from coronal regions at greater distances than the center of the Sun. This suggests that the disturbances responsible for these echoes are present simultaneously all over the Sun and, if so, the disturbances are probably caused by wave motions. The velocity of these disturbances appears to be about 10–30 km/s, and they tend to be present on days when the main echo is larger than average.

On a monthly basis there is an increase of cross-section with sunspot number. The correlation on a day-to-day basis is not high, but occasionally the cross-section does increase with solar activity. An increased cross-section may be associated with an increased number of reflecting irregularities. These irregularities may be shock-wave fronts or mass motions. If the observed motions are associated with coronal heating, the increased temperature would result in a further increase in cross-section because of the decreased absorption, but a change in temperature cannot completely account for the changes in cross-section as illustrated by the examples of Table 1.

Over active regions in the corona there are often long, straight, coronal streamers that have ionization densities of the order of ten times the Baumbach-Allen density (Maxwell and Thompson 1962; Mustel 1962). These streamers are radially directed and associated with strong magnetic fields. The enhanced densities at great heights caused by these streamers would tend to cause an increase in cross-section because the absorption to the reflection points would be reduced. Furthermore, the pincushion geometry that the streamers would produce would further enhance the cross-section.

Other possible reasons for changes in cross-section are changes in the shape of the reflecting "surface," changes in electron density that cause a change in the size of the corona, and focusing effects of plasma between the Sun and Earth.

It is possible that the motions responsible for certain types of solar radio bursts are associated with the Doppler effects of the radar echo. At times noise bursts that are less than 1 sec in duration and that drift in frequency are observed at El Campo. Positive and negative drift rates of about ± 0.3 Mc/s/s have been observed. If these drift rates are due to motions in the corona that excite radiation at the plasma frequency and if the radar observes these motions, the radar Doppler frequency would be less than 500 kc/s. No attempt has been made to look for echoes at more than 100-kc/s Doppler shift; however, there is much more echo energy near zero than near 100 kc/s than would be expected on the basis of the noise-burst drift rates. Furthermore, the Doppler spreading is always observed, but the noise bursts are only occasionally observed. The drift rate of the Type II solar noise burst is about 0.1 Mc/s/s at 38 Mc/s (Maxwell and Thompson 1962) and is associated with a disturbance which moves outward from a flare at a velocity of the order of 10^3 km/s. A radar echo reflected from this disturbance would have a Doppler shift of 250 kc/s or less at 38 Mc/s.

FUTURE EXPERIMENTS

Solar studies at El Campo have demonstrated that radar can be used effectively to study the corona. Future systems should have more sensitivity and more angular resolution, and they should permit the corona to be studied at several frequencies and several times per day.

Antennas with beam widths that are small compared with the solar diameter are needed to reduce the uncertainties in the interpretation of the data and to study active regions.

A system having greater sensitivity than the present El Campo radar is needed for several reasons: (1) The echoes are at times too weak to be detected. (2) More details are needed in parts of the echo spectra that are inherently weak. (3) Noise bursts at times decrease the detection sensitivity. The cheapest way to obtain more sensitivity is to build a larger antenna until the size of the transmitting beam is no larger than the target area to be studied. After this point has been reached, the only way to increase sensitivity for an Earth-based radar is to increase transmitted power.

The antenna designed to receive the solar echo should not be frequency-sensitive, which is a characteristic of antenna arrays when the signal travel times from the various points of the wave front to the receiver are not the same. This situation causes different phase delays at different frequencies for the signal components from the various elements of the array, and hence causes the beam pointing to be a function of frequency. A solar radar antenna should not be more frequency-sensitive than to cause a gain difference, at two frequencies 100 kc/s apart, of more than 10 per cent for any pointing within the useful beam. This estimate is based on an average noise-burst rate of one 1-sec burst/10 sec, and assumes a receiver having a gain characteristic with a -1 slope (see James 1964).

There is a possibility that echoes can be detected in the 100–400-Mc/s frequency range. On the basis of the smooth coronal models, the attenuation would be very high here, but the Sun is not smooth. Any phenomenon that could cause a reflection higher in the corona than the reflection level for the smooth corona would cause a decrease in absorption. Two such phenomena are a strong magnetic field and a dense irregularity with a sharp boundary above the normal reflecting level. Both of these are present at times in the corona. Any system in this frequency range having an average power of 100 kW, an antenna beam width of 1° or less, and a receiving band width of about 1 Mc/s should be tried at various times on the Sun but especially near sunspot maximum.

It is possible that radar could be used to study the corona beyond the limbs of the Sun and thus monitor solar activity before and after it is apparent on the disk. This is suggested by the data in Figure 6. With narrow antenna beams, radar should be useful in studying the density and motions of irregularities, perhaps shocks, near active regions. The problem of coronal heating could also be studied by radar if the heating is due to shock waves or other plasma-density irregularities. There have been indications at El Campo of isolated plasma irregularities moving outward in the high corona. With a lower-frequency radar such irregularities might be tracked to a considerable distance from the Sun. These and other possibilities suggest an important role for radar in solar research.

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