THE MICROWAVE SOLAR RADAR EXPERIMENT. I. OBSERVATIONS

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ABSTRACT

This is a report on the first solar radar experiment in microwaves. It was carried out with the 300 m dish in Arecibo using a 250 kW transmitter. Receiving at a displaced frequency from the transmitted radar frequency allowed us to probe the Langmuir (plasma) wave energy density of the corona in the 170-270 MHz range. We have not found any echo in various regions on the Sun: quiet regions, active regions, type I radio sources and even a possible type IV radio source. This contradicts some models of type I radio bursts and a proposed scattering mechanism of metric solar radar echos. An alternative experiment, in which we received at the transmitted frequency, did not produce any echo either. The reflectivity of the Sun in microwaves is more than four orders of magnitude below the reflectivity in meter waves. In the second paper of this series, upper limits on Langmuir wave densities will be calculated from these results for the various pointing positions.

Subject headings: radar astronomy — Sun: corona — Sun: radio radiation

I. INTRODUCTION

The motivation for the solar radar experiment in microwaves stems from the possibility of reflection on high frequency electrostatic (Langmuir) waves and thereby of measuring the energy of these waves. The theory of coupling between radar and plasma waves is presented in Benz, Lantos, and Nelson (1981), henceforth referred to as Paper II. The unique feature of the observations described here is that the frequency at reception was displaced from the transmission frequency to take into account the considerable Langmuir wave frequency. The results of an attempt to receive at the transmission frequency will also be presented.

Here we concentrate on the data concerning possible reflection from sites of type I bursts. The observations were taken in 1977 and 1978 with the 1000 foot (305 m) dish in Arecibo. Preliminary results of the 1977 set have been published by Benz and Fitze (1979). Comparison of our results with other (passive) observations of the same targets will be carried out and their interpretation given in Paper II of this series. The instrumental setup was similar for the two years' observations; this is explained in § II. Section III illustrates the data analysis procedures applied. The results are presented in § IV with emphasis on the 1978 data; these demonstrate the lack of detectable echoes. The upper limit is determined by fluctuations in the background, the origin of which is discussed in § V. A summary appears in § VI.

II. INSTRUMENTATION

A transmission frequency of 2380 MHz has been chosen. It is based on the idea of probing type I radio sources in the corona, which have been interpreted as places of enhanced level of Langmuir waves (Takakura 1963; Sy 1973; and others). Their emission frequency of 50 to 300 MHz requires a radar frequency in the microwaves (Benz and Fitze 1979, eq. 5). The klystron at Arecibo developed a power of 250 kW, which was modulated to yield on-off pulses of 1.5 s and 0.5 s duration for 1977 and 1978, respectively. This coded transmission lasted for about 15 minutes for each run. The energy was focused into a 2.2 beamwidth, thus covering about $10^3$ km on the Sun. The beam position was corrected for the motions of the Earth throughout each run (but not for the rotation of the Sun).

Receiving was at 2600 MHz with a bandwidth of 100 MHz. This displacement from the transmission frequency allows the investigation of interactions with Langmuir waves in the range 170–270 MHz. A different feed had to be used for reception. The changeover and positioning of the 2600 MHz feed to view the illuminated region took roughly one minute. With the 2600 MHz feed, the telescope yielded a beamwidth of 3.1', large enough to guarantee complete coverage of the illuminated area. Receiving was started about one round trip travel time after the start of transmission and lasted for about 20 minutes. The reception duration was chosen to be longer than the expected echo length in order to give a baseline of observations without echoes for comparison. We used a two-channel total power receiver with a system temperature of 1060 K. After preamplification, the signal was mixed down to an intermediate frequency of 260 MHz with a bandwidth of 100 MHz. This band was split into two well separated channels, each of 40 MHz bandwidth, which were detected sep-
arately. (In 1977 we used only one channel of 100 MHz bandwidth.) A low pass filter was then applied to suppress fluctuations above 10 Hz. The signals were integrated for 1/16 of a pulse period (1/32 in 1977), sampled, digitized, and recorded. Simultaneously, we recorded the measured deviation of the actual from the desired feed position in azimuth and elevation.

Antenna calibration was done on standard celestial sources and yielded 6.3 ± 0.1 K Jy⁻¹ at 2380 MHz and 2.1 ± 0.1 K Jy⁻¹ at 2600 MHz (in 1977 the latter was 2.7 ± 0.1 K Jy⁻¹). The antenna gain at Arecibo starts to decrease at zenith angles larger than about 11° for the 2380 MHz feed and at about 20° for the 2600 MHz feed. Only the former value influenced some measurements. For the receiver calibration, done for every run, an 880 K noise source was added before preamplification via a directional coupler. The accuracy of echo flux measurements is limited by the antenna calibration.

The pointing accuracy was determined by comparison with celestial sources with declinations similar to that of the Sun. The systematic error was found to be less than 5° for the 2380 MHz feed and less than 7° for the 2600 MHz feed. For the jitter of the guiding system, we found a peak-to-peak fluctuation of 6°. In addition, a resonance in the guiding control system produced azimuth oscillations with an amplitude up to 25° at a frequency of about one-fourth Hz. This is still small compared to the beam size and therefore irrelevant for aiming at the desired sources. However, it produced considerable oscillations of the received flux when the antenna was pointed to a region with a spatially variable background. Since the radar pulse frequency was chosen to be well separated from this feed resonance (particularly in 1978), these oscillations usually did not disturb the measurements.

III. DATA REDUCTION

The goal of the data reduction was to find the echo strength or its upper limit. For the observations to be described here, the Fourier transform was applied, which gave information not only on the amplitude of the signal at the pulse frequency but also on other oscillations. The outputs of the 2600 MHz receiver of the 305 m dish were two data strings covering roughly 20 minutes of observations. In the reduction, these data were divided into n segments of equal number m of data points. Segments which were received during a time of a possible echo were treated separately from segments without a possibility of an echo.

The next step was to take the sum and difference between the two channels (after subtracting the mean value in each channel). Since the background fluctuated roughly in phase in the two channels, the subtraction increased the sensitivity considerably. Subtraction is effective only if the echo strength in the two channels is different by about an order of magnitude as suggested in Paper II. For the other case of nearly equal strength echoes, they would appear in the sum of the two channels, but with less sensitivity.

Raw data on possible type I radio sources are shown in Figures 1 and 2. Figure 1 represents measurements of a region on the (photospheric) disk. The difference of the two channels reduces the amplitude of the long period fluctuations by a factor of about 6. Figure 2 demonstrates data taken of a region above the limb. The fact that taking the difference increases the noise indicates that the noise in the two channels is independent. In this case, the sum is to be preferred (top curve).

To reduce the effects of sharp boundaries in the Fourier transformation, we first used nonrectangular windows (Kaiser-Bessel, third order) over the segments and made them overlap slightly (cf. Harris 1978). The improvement was little, however, since single peaks in the spectrum (both instrumental and solar) never exceeded 10 dB above background, and the Kaiser-Bessel windows have been deleted later in favor of a simple rectangular window.

Each segment i was Fourier transformed

$$s_i(f) = \sum_{j=1}^{m} w(j \tau) D_i(j \tau) \exp(-2\pi if j \tau), \quad (1)$$

where w is the window function, $D_i$ the data (difference or sum of both channels), and $\tau$ the sampling time. The power spectrum is then $s_i s_i^*$. After proper calibration, each spectrum was plotted and checked. We found that the amplitude of the background oscillations near the frequency of interest was surprisingly variable. No correlation with type I radio emission or any other activity is discernible. The background oscillations do not seem to be related to Langmuir waves; in any case, the height of an echo peak should be independent of the background. For average spectra we have thus selected the segments with "good seeing," i.e., low background.

a) Accuracy and Thresholds

In order to estimate the significance of spectral peaks and to give statistics upper limits to nondetected, peaks we use the variability theory (e.g., Blackman and Tukey 1958). The problem is to estimate the true power spectrum from the average of n spectra derived from finite segments of m data points representing equally spaced measurements with a sampling time $\tau$. If the individual spectral densities at a given frequency $f s_1, s_2, \ldots , s_n$ are independent and have a Gaussian distribution, then the sum of the squares

$$P \equiv \sum_{i=1}^{n} s_i^2 = \sum_{i=1}^{n} P_i$$

has a $\chi^2$ distribution shifted by $n \bar{s}^2$ and multiplied by

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σ², the variance of sᵢ. The effective number of degrees of freedom, \( n_{\text{eff}} \), is given by

\[ n_{\text{eff}} = \frac{w_e}{\Delta f} \]  

(cf. Blackman and Tukey 1958), \( w_e \) being the equivalent width of the spectral window used in equation (1) and \( \Delta f = (2\pi/nm)^{-1} \), the elementary frequency band. For a rectangular window \( w_e = (m\pi)^{-1} \), one finds \( n_{\text{eff}} = 2n \). This, however, only holds for strictly Gaussian distributions. To allow for certain deviations from the Gaussian distribution we will reduce \( n_{\text{eff}} \) by 30% to

\[ n_{\text{eff}} \approx \frac{2}{3} n. \]  

as recommended by Blackman and Tukey (1958). Given the degree of freedom, we can determine the confidence limits of estimates for the \( \chi^2 \) distributions. Since we will have only few such estimates to do, a 90% confidence limit will be sufficient.

**IV. RESULTS**

Metric radio noise storms consist of a broad-band continuum and a very large number of narrow-band, short bursts (for a review cf. Elgarøy 1977). Storms are a long-lived (hours to days) manifestation of solar activity and are a possible site of Langmuir waves. Although there are often several centers of noise storm activity simultaneously present, a specific source is relatively stable in position. However, the source size is probably smaller (at least for type I bursts) than the beam, and its position is considerably uncertain due to limited accuracy of measurements, refraction in the corona and Earth’s ionosphere, and source motion. We can therefore only give a probability for having hit the desired target. This probability will be estimated in paper II of this series.

\[ a) \text{ Raw Data} \]

Figures 1 and 2 show typical raw data of the 1978 experiment for different target sites, on the disk and above the limb, respectively. The former set has typical
background fluctuations (cf. § V) and, since large brightness gradients are present, the feed oscillations (here at 3.6 s period) are clearly visible. The data of Figure 2 are very different: the background is mainly system noise. Solar fluctuations are expected to be weak if due to coronal changes and enter mainly by antenna side lobes. It is of interest to compare the cross-correlation, $C(t)$, between the two channels for each site (Fig. 3). $C(t)$ is calculated from data reduced to zero average,

$$C(t) = \frac{1}{m} \sum_{j=1}^{m} \left[ D_1(j\tau) - \bar{D} \right] \left[ D_2(j\tau - t) - \bar{D} \right],$$  

where 1 and 2 denote the channels, $m$ is the total number of data points in the considered interval, and $\bar{D}$ and $\bar{D}$ are their respective average values. Figure 3 confirms the high correlation between the two channels and the instrumental oscillations for the disk observations, and the low correlation and absence of instrumental oscillations for an off-disk target. The large peak near zero lag in curve A (and less pronounced also in B) includes both solar and instrumental peaks. Negative values at large lags $t$ are due to different slopes in the two data sets. It is obvious from Figure 3 that taking the difference between channels only yields a lower background level of fluctuations on the disk.

**b) Echo Analysis**

After adding or subtracting the channels the data was Fourier transformed according to equation (1), plotted for checking, and finally averaged over the different segments. A typical averaged Fourier spectrum is shown in Figure 4. It refers to a position on the disk and to the difference of the channels. For comparison, the spectra of elevation and azimuth errors are shown. The flux spectrum differs remarkably in slope from the instrumental ones above about 1 Hz, our main region of interest. We will discuss the origin of the background fluctuations in § V.

i) **Noise Storms**

We have analyzed a total of 12 observing sequences (each of about 15 minutes duration) of possible noise storm source regions with the above observing procedures. Four of them refer to 1977 data of very low type I activity. Furthermore, we have analyzed 15 sequences which we considered, however, to have a small probability to have hit a noise storm source. Only one of all these sequences, recorded on 1977 September 10, shows a clear peak at the radar pulse frequency. The statistical significance determined by the method described in § IIIa exceeds 99.99% probability for the reality of the peak. The peak is strongest between 17:04:06 and 17:04:54 UT. It is present from 17:03 UT and absent after 17:05 UT. There is a gap in observing from 17:01 until 17:03 UT. Solar activity, however, as recorded by Dwingeloo (courtesy of C. Slottje) did not correlate with the strength of this peak: weak type I and type III activity occurred between 17:00:06 and 17:02:35 UT, and a weak chain of type I bursts from 17:06:30 until 17:07:18 UT. On the other hand, the amplitude of the feed oscillations does correlate with this peak. In this period, these instrumental oscillations had a frequency of 0.22 Hz, which is within 2% of one-third of the radar pulse frequency. Hence, we believe that the peak is a third harmonic of a feed oscillation and thus instrumental.

In Table 1 the results concerning the observations relevant for noise storm regions are summarized. Date and start of reception is given for data identification. The observing time is the total interval which was selected (for "good seeing") to form the spectra. The observed power at the radar pulse frequency, $f_p$, has
Fig. 4—A typical power spectrum of an observing sequence of 1978 Sep 5 at a position on the disk. The data represent the average of 4
spectra, each of an observing interval of 64 s. Top: spectrum of the difference of the two data channels with an absolute calibration. Center
and bottom: spectrum of elevation and azimuth errors in arbitrary units (log scale is indicated). Dashed line: the position of the radar pulse
frequency (2 Hz).

TABLE 1
RESULTS OF RADAR OBSERVATIONS OF POSSIBLE NOISE STORM CHANNELS

<table>
<thead>
<tr>
<th>Date</th>
<th>Start of Observation (UT)</th>
<th>Obs. Time (s)</th>
<th>Degrees of Freedom (n_eff)</th>
<th>Elem. Freq. Band (f) (mHz)</th>
<th>Observed Power at f_c (Jy^2 Hz^{-1})</th>
<th>Mean Power at f_c (Jy^2 Hz^{-1})</th>
<th>90% Limit at f_c (Jy^2 Hz^{-1})</th>
<th>Upper Limit of Echo at 90% (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977 Aug 5</td>
<td>16:19:20</td>
<td>384</td>
<td>2.67</td>
<td>9.4</td>
<td>4026</td>
<td>5915</td>
<td>12760</td>
<td>22.7</td>
</tr>
<tr>
<td>1977 Aug 6</td>
<td>17:37:30</td>
<td>768</td>
<td>5.33</td>
<td>9.4</td>
<td>7315</td>
<td>3082</td>
<td>5618</td>
<td>14.6</td>
</tr>
<tr>
<td>1977 Aug 7</td>
<td>16:16:10</td>
<td>768</td>
<td>2.67</td>
<td>4.7</td>
<td>35.70</td>
<td>58.06</td>
<td>136.0</td>
<td>1.66</td>
</tr>
<tr>
<td>1977 Aug 7</td>
<td>17:42:00</td>
<td>768</td>
<td>2.67</td>
<td>4.7</td>
<td>162.27</td>
<td>80.94</td>
<td>174.6</td>
<td>1.88</td>
</tr>
<tr>
<td>1978 Sep 2</td>
<td>16:14:30</td>
<td>640</td>
<td>6.67</td>
<td>7.8</td>
<td>2520</td>
<td>.2078</td>
<td>3607</td>
<td>9.77</td>
</tr>
<tr>
<td>1978 Sep 2</td>
<td>16:53:40</td>
<td>640</td>
<td>6.67</td>
<td>7.8</td>
<td>1266</td>
<td>2569</td>
<td>4460</td>
<td>10.86</td>
</tr>
<tr>
<td>1978 Sep 3</td>
<td>16:34:00</td>
<td>768</td>
<td>8.00</td>
<td>7.8</td>
<td>2950</td>
<td>3480</td>
<td>5810</td>
<td>12.06</td>
</tr>
<tr>
<td>1978 Sep 4</td>
<td>15:53:00</td>
<td>512</td>
<td>5.33</td>
<td>7.8</td>
<td>56.55</td>
<td>99.25</td>
<td>180.93</td>
<td>2.26</td>
</tr>
<tr>
<td>1978 Sep 5</td>
<td>16:39:20</td>
<td>384</td>
<td>4.00</td>
<td>7.8</td>
<td>533.9</td>
<td>848.7</td>
<td>1650.7</td>
<td>7.07</td>
</tr>
<tr>
<td>1978 Sep 5</td>
<td>17:15:00</td>
<td>512</td>
<td>5.33</td>
<td>7.8</td>
<td>14.64</td>
<td>30.00</td>
<td>54.69</td>
<td>1.24</td>
</tr>
<tr>
<td>1978 Sep 5</td>
<td>16:05:40</td>
<td>896</td>
<td>9.33</td>
<td>7.8</td>
<td>0.112</td>
<td>0.100</td>
<td>0.163</td>
<td>0.0628</td>
</tr>
<tr>
<td>1978 Sep 11</td>
<td>16:47:40</td>
<td>896</td>
<td>9.33</td>
<td>7.8</td>
<td>0.081</td>
<td>0.150</td>
<td>0.244</td>
<td>0.0768</td>
</tr>
</tbody>
</table>

Note.—The values of 1978 Sep. 2–5 refer to results obtained by subtracting the two channels.
then to be compared with the relative height of adjacent bins. This was done by comparing it to the value of a second order polynomial fitted through the 15 adjacent values on each side. This value is considered an estimate to be compared with the relative height of adjacent values. The mean value of a second order polynomial fitted through the 15 adjacent values on each side is used to calculate the confidence limits according to the \( \chi^2 \) distribution. If the upper confidence limit of the mean value without echo is exceeded by the observed spectral power, the possibility of an echo contribution has to be considered. If this is not the case, the upper confidence limit yields an upper limit of the echo flux density \( S_e \):

\[
S_e = 2(\Delta f/2\Delta P)^{1/2},
\]

where \( \Delta P \) is the difference of upper confidence limit and mean spectral power at \( f_e \). The first factor 2 comes from the fact that an on-off signal is twice the amplitude of its Fourier transform; the second factor 2 (in the square root) is due to the loss in sensitivity by receiving only one linear polarization. The values of 1978 September 2–5 given in Table 1 refer to results obtained by subtracting the two channels.

The observed power at \( f_e \) exceeds the 90% confidence limit only in one case, 1977 August 6. This case is to be taken more seriously than the 1977 September 10 experiment, because (1) the enhanced level at \( f_e \) persists throughout most of the observing time, (2) a weak type I storm was present, (3) the signal vanishes when no echo is possible, and (4) the probability that we were pointing at the source of the type I emission is high (60%; see Paper II). However, the expected \( f_e \) is displaced from the observed feature by one bin (9.4 \( \times 10^{-3} \) Hz), and there is an even higher peak three bins further. This latter peak seems to be a third harmonic of the same instrument oscillation as 1977 September 10. Thus, we do not consider this a likely detection of an echo.

ii) Type IV Burst Source

On 1977 September 9, 1625–1638 UT we may have observed by chance the source of a type IV radio burst. The Zurich spectrograph registered an event extending from about 200 MHz into the microwaves. At 238 MHz Trieste measured a peak flux of \( 120 \times 10^{-19} \) ergs cm\(^{-2} \) Hz\(^{-1} \) s\(^{-1} \). The associated H\( \alpha \) flare of importance SN occurred at the position N07/E85. The Arecibo telescope was pointing at a position which was displaced radially outward by only 3'42", or 160,000 km. This is exactly at the 220 MHz plasma level radially above the H\( \alpha \) flare site in the 10×Baumbach-Allen density model. We estimate the probability of having hit at least partially the source region of the 170–270 MHz part of the type IV burst to be 60%. The position was above the limb, but the radar experiment was not very sensitive since the relatively broad side lobes picked up considerable flux of the flare at the receiving frequency of 2600 MHz. Although at that frequency the microwave burst was certainly not in the beam (but closer to the H\( \alpha \) flare), it saturated the receiver during maximum. In the 144 s of relatively good data during the rising phase we did not detect any echo. The observed power at the radar pulse frequency is below the mean power of 22,000 Jy\(^2\) Hz\(^{-1} \). The upper limit of the echo flux, calculated the same way as in Table 1, is 72.4 Jy.

iii) Receiving at Transmitter Frequency

So far we have reported on the experiment to detect an echo shifted by the plasma frequency (170–270 MHz). We have also searched for echoes at 2380 MHz, the transmitter frequency. Such an echo could be caused by specular reflection at the plasma level or interactions with low frequency waves. It is the corresponding experiment at microwaves to that of James (1970) in meter waves.

The setup was similar to the other experiment, except that we used the same feed for transmission and for reception, an attenuated maser receiver with about 400 K system temperature and two receiving channels with 1 MHz and 10 MHz bandwidth, respectively. The pulse rate, scaled down from James's experiment to the conditions in the low corona and transition region, was chosen to be 50 MHz. The sampling rate was 400 Hz.

The beam was pointed to a variety of different regions. Real time information on the position of coronal holes was provided from He i observations at Kitt Peak (courtesy J. W. Harvey), on coronal dense structures by Mauna Loa (courtesy R. T. Hansen, HAO), and on active regions by the H\( \alpha \) patrol at Ramey Air Force Base (courtesy H. A. Adams). The active region was observed about one day before its maximum size. Subflares were reported from the region before, during and after the observations. The weak type I storm observed during the experiment by the Zurich spectrometers (then located at Dürnten) was within 1/5 of the center of the beam, according to Culgoora observations 9 hours later (personal communication from G. J. Nelson).

The data reduction was identical to the other experiment. Table 2 lists the results. The values shown refer to observations in the channel with 1 MHz bandwidth. Calibration is only accurate within a factor of 2. We have not found any significant peak at the radar pulse frequency. We calculated an upper limit to the echo flux the same way as in Table 1. The generally lower mean power as compared with Table 1 (i.e., lower background due to larger \( f_e \)) puts very stringent upper limits on the echo. The reflectivity \( \rho \) is defined as the ratio of the observed (upper limit) echo flux \( S_e \) to the flux expected from a loss-free, isotropic scatterer (e.g., metal sphere) at the Sun of the size of the radar beam:

\[
\rho = \frac{S_e \Delta f/4\pi R^2}{\Delta P},
\]

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### TABLE 2

RESULTS OF THE ALTERNATIVE RADAR EXPERIMENT RECEIVING AT 2380 MHz

<table>
<thead>
<tr>
<th>Object</th>
<th>Position</th>
<th>Date</th>
<th>Start of Reception (UT)</th>
<th>Observing Time (s)</th>
<th>Mean Power at f₀ (Jy Hz⁻¹)</th>
<th>90% Upper Limit (Jy Hz⁻¹)</th>
<th>Upper Limit Echo (mJy)</th>
<th>Upper Limit of ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal hole</td>
<td>N17/W36</td>
<td>1977 Aug 24</td>
<td>17h28m00s</td>
<td>1000</td>
<td>9.3 x 10⁻³</td>
<td>1.27 x 10⁻²</td>
<td>23.2</td>
<td>2.2 x 10⁻⁴</td>
</tr>
<tr>
<td>Coronal dense structure</td>
<td>p=3.15° R=1.1</td>
<td>1977 Aug 25</td>
<td>16 29 40</td>
<td>256</td>
<td>... a</td>
<td>... a</td>
<td>... a</td>
<td>... a</td>
</tr>
<tr>
<td>Active region</td>
<td>McMath 14915</td>
<td>1977 Aug 25</td>
<td>17 28 00</td>
<td>174</td>
<td>3.8 x 10⁻³</td>
<td>5.3 x 10⁻³</td>
<td>34.2</td>
<td>3.9 x 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>S25/E18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note.—The values shown refer to observations in the channel with 1 MHz bandwidth. Calibration is accurate only within a factor of 2.

Note the extremely low upper limit of the reflectivity ρ.

*a No calibration available.

where Δν is the receiver bandwidth, R, the Sun-Earth distance, and P the transmitter output power. The resulting upper limits on the reflectivity are about four orders of magnitude smaller than the observed radar reflectivity of the (global) Sun at metric waves (James 1970). These upper limits also demonstrate the high sensitivity of this experiment.

V. ORIGIN OF BACKGROUND FLUCTUATIONS

The sensitivity of this experiment was generally limited by the level of background fluctuations at the radar pulse frequency. We now describe our effort to determine the origin of these fluctuations. As a first step the power spectra of various sources were compared. For active regions the average spectrum has approximately the shape of a power law, f⁻α, with an average value of α=3.6 ±0.1 at f=1 Hz. Typical values for the spectrum of the azimuth and zenith angle errors are α=2.5 and α=2.1, respectively (cf. Fig. 4). For a diode noise source of equal temperature α=0.81, and for 3C 76.1, a quasar, α=1.45. At positions slightly offset from the quasar, the level of fluctuations tended to increase, but α remained below 2. It is straightforward to conclude that the observed fluctuations on the Sun are not due to gain variations of the receiver, but are due to the Sun or to the antenna.

In a second step, a strong correlation was found between the power at 2 Hz in single spectra of the flux and of the azimuth and/or zenith angle pointing error (relative to the feed platform). This holds for each of the 10 cases we have analyzed and confirms that the fluctuations are at least partially caused by antenna pointing errors.

Figure 5, however, suggests that the average level of fluctuations at a given position may not be entirely instrumental. The observations were made at 2600 MHz in two channels with a setup identical to that of the (main) radar experiment. At each position the data of about 1 minute of observations were divided into 6–24 segments of 4 s of observations each. The segments were Fourier transformed. The mean power at 2 Hz in each spectrum was determined by a polynomial fit and averaged over the interval. Large values in the power spectrum at 2 Hz were eliminated since they are expected to be preferentially instrumental (wind gusts, tracking errors, and azimuth oscillations) leading to the above correlations. Indeed, they are generally found to coincide with mavericks in the 2 Hz amplitude of the power spectra of either azimuth or zenith angle pointing errors. We have first eliminated the highest 20% of the values for each position (curve A) and have been more restrictive (50%) for curve B. The ratio between curves A and B is a measure of the quality of the results: the larger this ratio, the larger the scatter of the values. Curve B is more likely to show noninstrumental fluctuations. We first note that the largest peak does not coincide with the largest gradient in flux but with the position of maximum flux (when compensated for the 24 hours difference between the time of the map and the time of the radar observations). The first (small) peak, however, coincides with the maximum gradient near the limb and is clearly instrumental. The nature of the third peak is unclear; it coincides with a filament channel and is possibly connected with the newly forming active region (McMath 15504).

We conclude this section by pointing out that most of the observed fluctuations are instrumental, but evidence...
for solar fluctuations exists. The amplitude of the solar fluctuations seems to be correlated with the microwave flux.

VI. CONCLUSIONS

The solar microwave radar experiment has failed to detect echoes from the Sun despite the use of an immense collecting area, a powerful transmitter, and careful data analysis. Various regions on the sun have been probed: type I radio sources, active regions, coronal holes, prominences, and streamers. Only two possible echo peaks at the radar pulse frequency have been found, both of which, however, were more likely instrumental. The experiment receiving at a frequency displaced from the transmitter was probing Langmuir waves in the 170–270 MHz range. From the absence of echoes, it will be possible in Paper II to infer an upper limit on Langmuir waves in different regions of the solar corona.

In a second experiment we attempted to detect echoes at the frequency of transmission. Again, no echo was found. Although it is well known from early calculations (Kerr 1952) that specular reflection at the plasma layer of microwaves is heavily damped, the scaling to micro-waves of the strong echo mechanisms at meter and decimeter wavelength would have suggested the possibility of such a scattering (probably on low frequency waves).

It will be shown in Paper II that the observed upper limits on echo strength leads leads to Langmuir wave energy densities far below the value required for the interpretation of the metric radar results by wave-wave scattering. On the other hand, specular reflections as suggested by James (1970) also seem unlikely in the light of the results of the alternative experiment (reception at transmitted frequency). Our observations show that the interpretation of the reflection process of meter waves and the physical conditions in the corona may be considerably more complex than previously anticipated. New radar observations at meter and decimeter wavelength with spatial resolution and with more than one experiment per day would be of greatest interest. Such observations could yield information on the levels of various low frequency plasma waves; such waves are signatures of coronal plasma processes and important parameters for the determining state of the plasma of the corona and the solar wind.
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REFERENCES


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