A Proposal to Establish a Solar Radar at Arecibo – July 16, 2001

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Summary:

It is possible to probe the solar corona with radar at frequencies between 18 MHz and 50 MHz. The transmitted wave will be coherently reflected between 1.1 and 2.5 R_S. In addition to providing the ability to probe a very important region, radar provides one of the few methods of observing coronal mass ejection's (CME's) directed Earthward.

Solar echoes were first detected at 26 MHz at Stanford in 1959, and an extensive series of 38 MHz measurements were made at El Campo in 1961-1969 [James, 1970]. These have never been adequately explained: the echoes were much weaker than expected and highly variable; the doppler broadening was much larger than expected and also quite variable; anomalous ranges (≈ 0.4 R_S); and anomalous doppler shifts (≈ 200 km/s) were observed.

We have since learned a great deal about the corona and the solar wind, and the radar observations could undoubtedly be explained if we had complementary observations from Yohkoh, Soho, and Trace. It is likely that the echoes were weak because coronal holes reflect weakly, and the anomalous observations were probably due to CME's.

It would be very valuable to repeat the experiments with modern radar technology, and complementary optical, UV, and X-ray observations of the corona. A dual-polarization, tunable radar would provide estimates of the density and magnetic field, and their radial gradients in this very interesting region. Unfortunately no existing radar can do this work.

The purpose of this presentation is to outline an opportunity to establish a solar radar in conjunction with a proposed ionospheric heater at the Arecibo Observatory.

1. Introduction

One of the enduring mysteries of solar physics has been the solar radar observations made between 1961 and 1969 by an MIT group at El Campo in Texas [James, 1970]. These observations were unexpected in almost every sense. The strength of the echo was weaker than expected and highly variable. The mean doppler shift was larger than expected. The doppler broadening was much stronger than expected and also variable. There were significant anomalous events, and their properties were also quite variable. Unfortunately the observations were terminated after 1969, and no existing instrument is capable of repeating them. The observations attracted the attention of well-known solar physicists [e.g. Owocki, Newkirk and Sime, 1982] but they were unable to explain even the gross features of the observations. These authors concluded, "... the present dataset does not support the hypothesis that radar observations of the Sun will be useful in determining the properties of large-scale coronal features." A trickle of interest continues [e.g. Chashei and Shishov, 1994] but it is now on the fringe of solar physics.

In fact the James group was "ahead of its time." The radar observations ended just at the start of an explosion of coronal work, which transformed the field. This explosion started with "Skylab" and the first coronal features identified were "coronal holes". Unfortunately it appears very likely that coronal holes are also radar holes. The second important coronal features identified were "coronal mass ejections", and they really were understood only after the Solar Maximum Mission. Consequently workers such as [Owocki et al., 1982] tried to identify enhanced radar echoes with coronal holes rather than CME's. In retrospect it is obvious that CME's are the source of enhanced echo strength, indeed they are probably responsible for all the anomalous observations.

The case for repeating the solar radar experiments requires a balance of the cost with the potential increase in our knowledge of the Sun. The El Campo radar was a very powerful instrument and it was used daily for 8 years – it would be prohibitively expensive to duplicate the observations. One must ask, "how can we expect to solve the problem and make a real contribution to solar physics in a shorter time?"

We believe that this is possible for three reasons. First, we can create an improved solar radar at a feasible cost. The El Campo radar was constrained in two important ways, by the use of an array antenna. Array antennas are inherently narrow in bandwidth, and providing dual polarization doubles the cost. These constraints can be removed using the very large Arecibo primary reflector. Second, we now have complementary solar instruments such as Yohkoh, Soho and Trace, which give us an excellent view of the coronal structure at the radar reflection point. Third, we have a much better understanding of the corona and the solar wind, and their evolution during the solar activity cycle.

2. The El Campo Observations:

To judge what we might learn from a new solar radar we need at least a general understanding of the earlier observations. The basis for that is our improved understanding of the corona. We now know that there are three fundamental "phases" of the solar wind. The quasi-static wind is bimodal - fast or slow. The transient wind is dominated by coronal mass ejections (CME's). The fast wind originates in open magnetic structures, it is more homogeneous, cooler, and less dense than the slow wind. The slow wind is observed over complex close magnetic structures and contains at least one embedded current sheet. Significant inflows are observed as high as 5 R_S near the current sheets. The origin of the slow wind is unknown. CME's arise from closed field regions, often near the boundary with open regions. They carry loops of magnetic field and enhanced density. They may be faster or slower than the ambient solar wind. CME's are more frequent during the maximum of solar activity, but they occur at all phases of the activity cycle. During solar minimum the corona is dominated by fast polar coronal holes, with a narrow belt of slow wind around the equator. At solar maximum the slow wind belt expands and covers the whole surface.

The El Campo observations began during the declining phase of solar activity and continued through the minimum until the activity began to increase, but were not taken during solar maximum. The observations were made at a single frequency in linear polarization. One cycle of 16 min transmission followed by 16 min reception was made each day.

2.1 The radar cross section

The echo strength (radar cross section) was lower than was expected because the calculation was based on a spherically symmetric model. In fact the Sun was dominated by the polar holes which had only half the density with which the calculations were done. The reflection height in the polar holes is 1.2 Rs instead of 1.4 Rs. Furthermore the temperature in a polar hole is lower than the value used in the calculation by a factor of 1.6. The net effect will be to increase the attenuation and thus reduce the reflected power by approximately a factor of two.

The polar holes are not well modeled as a spherical reflector. They are filled with cool, thin, dense flux-tubes (polar plumes) embedded in a more homogeneous inter-plume region. The observed plumes have a typical diameter of 2 deg, but a spectrum of thinner structures may exist, as they would not have sufficient contrast to be observable by white-light coronagraphs. These dense flux-tubes will forward scatter the incident wave, and it will undergo multiple reflections as it becomes trapped deep in the low density regions between the plumes.

Thus coronal holes are "radar holes", which explains why [Owocki et al., 1982] found no correlation between coronal holes and enhanced scattering. It is clear that we cannot expect to use solar radar to study the fast wind.

The average cross section over 1961 to 1969 shows the solar cycle well. The echo is minimum when the polar holes cover most of the disc, and maximum when most of the disc is covered by closed field loops.

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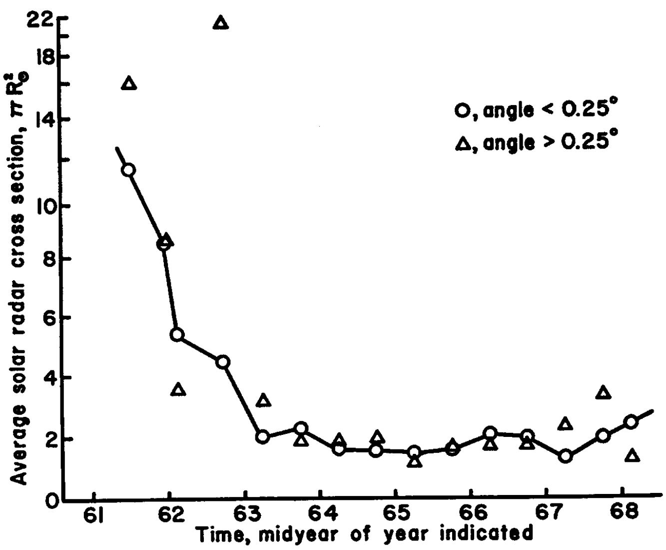


Fig. 4. Average values of cross-section measured at 38.2 MHz at El Campo. The connected points represent values measured when the absolute value of the misalignment of antenna beam and sun was less than ¼°. The other points are for greater misalignments.

2.2 Anomalous cross section increases

The daily cross section measurements shown below in 1963 and 1964, show a great deal of variability and occasional much larger values.

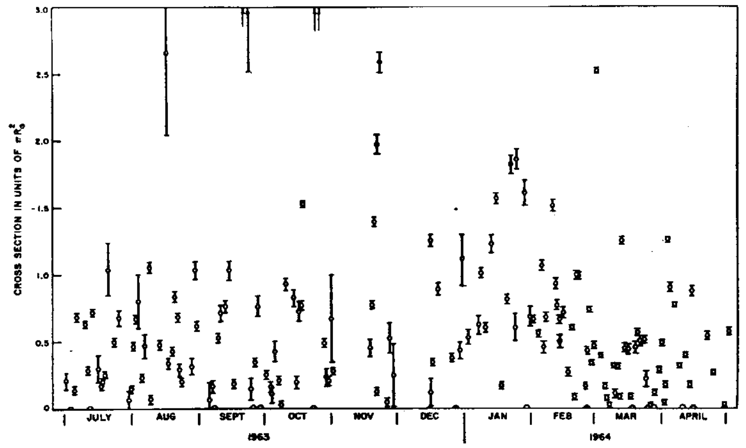


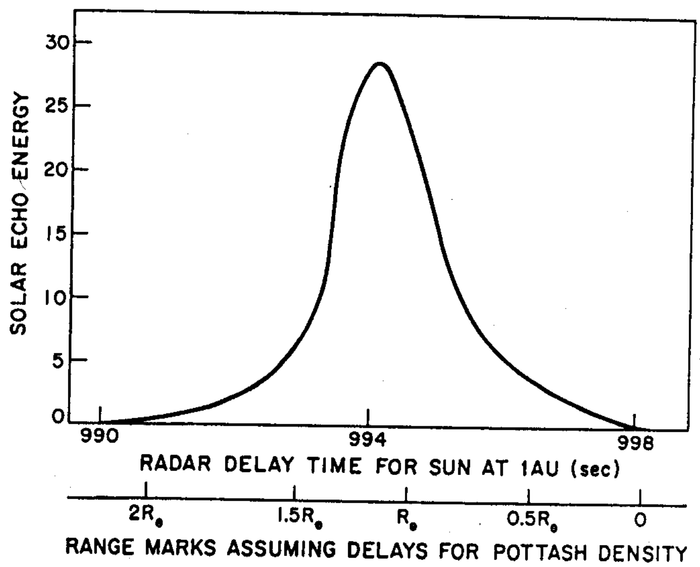
Fig. 7-28, Daily values of solar radar cross section at 38.25 Mc/s measured at El Campo, Texas. The limits about each point represent ±1 standard deviation for the signal integration process. These cross sections were adjusted to apply for echo energy falling within a broad band.

RADAR ASTRONOMY

We know that dense closed field loops will caused enhanced scattering so it is very likely that these anomalous increases in cross section are in fact CME's. Large CME's are not uncommon during the declining and minimum phases of solar activity. Their frequency is consistent with the El Campo observations of greatly increased cross section.

2.3 The observed range of peak reflection

The average echo energy vs range during 1963 and 1964 is shown in Figure 3.



One can see a rapid increase at about 1.4 R_S. This corresponds to the density profile of an equatorial coronal streamer. These large-scale closed-field structures extend up to a maximum of about 2.5 R_S, so the observed echoes probably come from the top of loops which just reached 1.4 R_S. The longer delays are probably not due to deeper penetration into the corona, but to echoes from the solar limbs.

There are also earlier echoes, evidently from distances as large as 2 R_S. These are probably a combination of large CME's on disc and very dense helmet streamers. A significant number of high cross section events also exhibited anomalous delays, about 2 sec longer than expected. This delay corresponds to about 0.4 R_S. These long-delayed echoes probably come from CME's rising above the solar limbs.

2.4 Some Range-gated Doppler Spectra

These range-doppler plots were selected [James, 1968] to illustrate the variety of phenomena observed. Three of the four plots below show unusually strong echoes, as indicated by the scale marked on the abscissa. These are probably due to Earth-ward directed CME's beginning to lift off the disc. One can see apparent acceleration of these features as a positive doppler shift with increasing height. However some of this must be due to reflections from the sides of the CME where the flow is not exactly Earthward.

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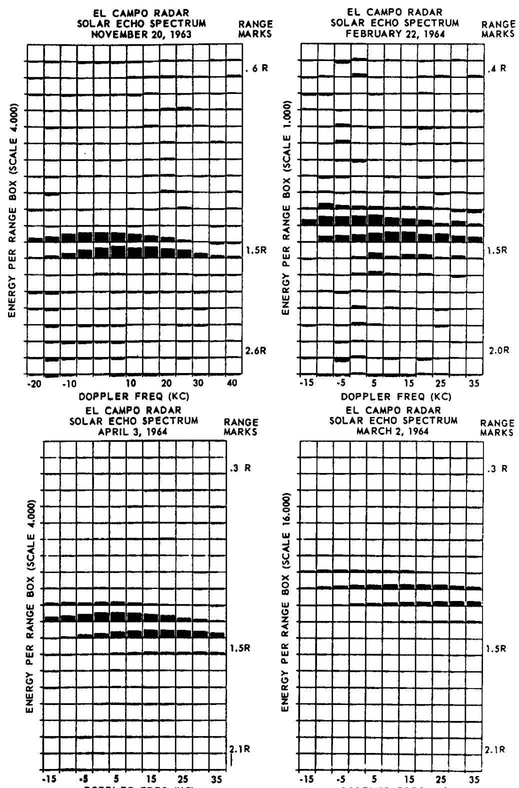

Fig. 7–29b. Observed distribution of solar echo energy with range and frequency. *R* range marks are located on the delay-time scale for an assumed excess group delay of two seconds.

The El Campo antenna had a fixed fan beam that was wide enough to illuminate the Sun for the round trip travel time of 16 min. As a result the reflections from structures on the solar limbs were very important. Even radially aligned structures on the solar limbs will backscatter strongly, so there is a strong “limb brightening” in the radar echo. This suggests an explanation for the observed doppler widths, but careful modeling would be required to confirm it.

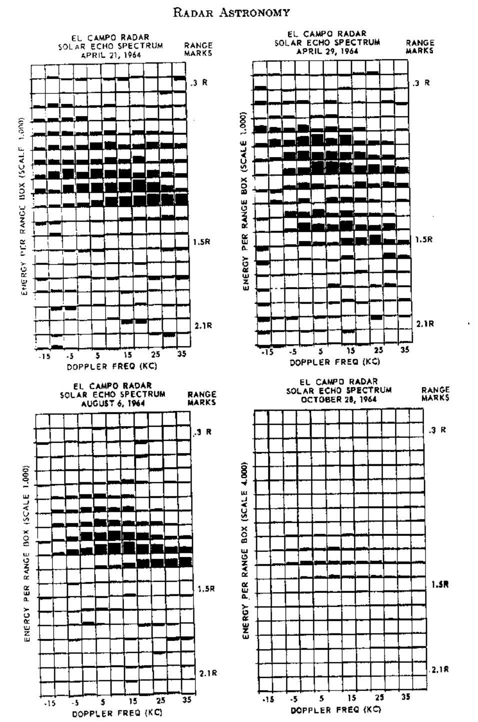

Fig. 7-29c. Observed distribution of solar echo energy with range and frequency. *R* range marks are located on the delay-time scale for an assumed excess group delay of two seconds.

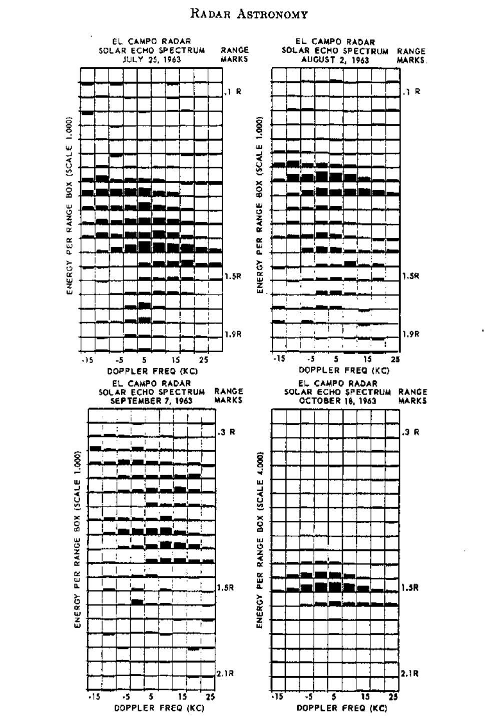

Fig. 7-29a. Observed distribution of solar echo energy with range and frequency. *R* range marks are located on the delay-time scale for an assumed excess group delay of two seconds.

3. Comparison of the Proposed Arecibo Radar with El Campo

(a) Transmitter: Arecibo has 600 Kw average, 2 Mw peak power from 3 MHz to 26 MHz. El Campo had 500 Kw continuous power at 38.2 MHz. The sensitivity at 26 MHz is thought to be about the same as at 38 MHz. There is more attenuation at 38 MHz, but the transmitting antenna gain is higher.

(b) Antennas: The El Campo array had a fixed fan beam and an effective area of about 20,000m^2. It was linearly polarized and had a very narrow bandwidth. The Arecibo antenna has about the same area, but it has a steerable pencil beam with circular polarization and a broad bandwidth. Arecibo will be capable of four transmit-receive cycles per day during the summer.

(c) Modulation: The El Campo system used FSK and the frequency shift was comparable with the doppler spread, so the echo strength was reduced and the spectra were distorted. Arecibo will use pulse amplitude modulation (PAM).

(f) Performance: Arecibo will have about 10 times greater sensitivity and 4 times longer observation time, with dual polarization and multiple frequency coverage.

4. New Radar Observations:

The first order analysis presented above makes it pretty clear that a solar radar is a tool for observing the slow wind and CME's. Indeed it is one of the very few methods of observing an Earthward-directed CME from the Earth. We do not propose to construct a solar radar for the purpose of providing an early warning of such CME's, because that would require a dedicated instrument. However we will be able to quantify the sensitivity of such measurements in sufficient detail that it will be possible to design a dedicated radar with confidence. In particular we will be able to observe the acceleration of the CME at the lowest altitudes, below the altitude observable with the LASCO coronagraphs.

The new radar will be able to study the slow wind, which is undoubtedly the most complex and least-understood part of the corona. This would have seemed strange 30 years ago, because Parker's original theory successfully predicted the velocity of the slow wind, not the fast wind. However it is now realized that neither the fast, nor the slow wind can be driven by electron thermal conduction, and Parker's theory cannot be correct in detail, even though in concept it remains our guide. The problem with the slow wind is that we have no idea where it originates. It has been argued that the entire slow wind originates at the edge of open field regions, and none comes from the closed field regions. Others argue that much or even all of the slow wind leaks out from unresolved open field regions within complex closed field regions.

The most important features of the new radar will be:

(a) The combination of dual polarization and multiple frequency operation will permit measurements of both density and magnetic field, and their radial gradients between 1.6 and 1.8 R_S. It will also be possible to estimate the electron temperature because the signal attenuation is strongly temperature dependent.

(b) The sensitivity of the new radar will be used to improve resolution in range, doppler, and time; to sweep the frequency; and to sweep the antenna beam.

(c) The beam of the new radar will be narrow enough to separate reflections from the limbs of the corona. The spatial resolution can be further improved with interferometry. Low frequency receiving arrays are relatively inexpensive. The very high-resolution LOFAR array would be ideal for this purpose.

(d) The new radar will be able to track the Sun for more than 2 hrs during the summer. This will permit 4 transmit - receive cycles per day. This will greatly improve our ability to detect CME's during a relatively short campaign, i.e. one month, and it will also make it possible to track those CME's that we do observe.

The most important single advance is undoubtedly the magnetic field measurement. We already know the density reasonably well because it can be measured via Thomson scattering, using white light coronagraphs, but there are no direct measurements of the magnetic field in this region. The radar can measure B_R using an extension of the familiar Faraday rotation phenomenon. However, since the differential delay of the two circular polarizations is greater than the coherence time, the received echo will be unpolarized. Rather than measure the rotation of the plane of linear polarization, we measure the differential delay of the two circular components, which is also proportional to $N_E B_R$. The wave vector is parallel to the field, which is the optimal geometry for this observation. Furthermore the integral is dominated by the region near the turning point because the produce $N_E B_R$ decreases very rapidly with distance, so the spatial resolution is good.

5. The Opportunity:

The proposed ionospheric heater at Arecibo would replace one which was destroyed by a hurricane. The original heater, like other existing heaters, could not be modified for use as a solar radar for two reasons: the maximum frequency was too low; and the antenna gain was too low.

The proposed new heater eliminates both these problems. First, the transmitter would be a commercial unit which can be tuned far above the necessary heating frequency range to 26 MHz. Second, the proposed heater would use the very large primary dish at Arecibo.

The Arecibo Observatory has two further essential elements for a solar radar. First, it has modulation, coding, control, and receiver systems that will work at 26 MHz without modification. Second, it has the technical, operational, and scientific staff necessary to construct, maintain, and operate the radar, and to analyze the data.

The target for submission of the heater/solar radar proposal is December, 2001. The construction time will be at least one year after receipt of funding. Therefore it is not possible to make observations before the summer of 2003 and it could be delayed another year.

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