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Radar Echoes from the Sun

Man's first direct contact with the sun opens new approaches for the study of solar events.

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On a number of mornings in September 1958, April 1959, and September 1959, attempts were made at Stanford University to obtain radar echoes from the sun. The data obtained on three days in April have been intensively analyzed with the aid of a digital electronic computer. It appears that solar echoes were obtained on each of these days. This experiment was possible only because of the availability of facilities built up at Stanford for several different research programs (*1*).

In 1952 Kerr (*2*) discussed the scientific information that might be gained from radar studies of the sun and planets, if sufficiently sensitive radar systems could be built. Others (*3*) have also discussed the importance of radar studies of the solar system and the magnitude of the required installations. But continuing advances in large antennas, high-powered transmitters, low-noise receivers, and data-processing techniques will soon make it possible to conduct important radar investigations out to distances which include essentially all of the solar system. The dramatic beginning of radar probing beyond the moon was announced last year when scientists at the Lincoln Laboratory of the Massachusetts Institute of Technology described the first radar detection of Venus (*4*).

The equipment and techniques for radar detection of the sun differ in several ways from those required for detection of the nearer planets. As Kerr has pointed out (*2*) a relatively low radar frequency is needed to avoid extensive absorption in the solar corona above the reflecting points. He estimates that the optimum frequency is near 30 megacycles per second. Much higher frequencies can be used to detect planets, so higher antenna gain can be obtained for a given antenna size. The new low-noise receiving devices, which are so important for radar sensitivity at the higher frequencies, are of no value at the lower frequencies where cosmic and solar noise limit the detectability of weak signals. In addition, the characteristics of solar noise differ from the better understood features of random receiver and cosmic noise, so care must be exercised in determining whether a solar echo has been obtained. These special features were expected to make radar detection of the sun very difficult, even though, because of the sun's size and despite its distance, a solar echo would be 100 times more intense than an echo from Venus.

Equipment and Test Procedure

For the April 1959 sun-echo tests a transmitter (Collins FRT-22) having about 40 kilowatts' average output power was operated at about 25.6 megacycles per second. The transmitter was pulsed on and off alternately throughout a time interval of 15 minutes, each on and each off period lasting 30 seconds.

The antenna system used for both transmission and reception consisted of four rhombic antennas in a broadside array, covering a rectangular area of 800 by 725 feet. The antenna gain is estimated to be 25 decibels relative to that of an omnidirectional antenna. The principal antenna beam is directed approximately east at an elevation of 10 degrees. The sun is in the antenna beam only for about 30 minutes soon after sunrise on a few days near each equinoctial period.

The travel time of a radar pulse to the sun (approximately 93 million miles away) and back to the earth is about 1000 seconds. At the end of the transmitting period of 900 seconds, the antenna was connected directly to the receiving system, and the transmitter and pulsing circuits were turned off. The receiver and its preamplifier are of conventional design. An intermediate frequency bandwidth of 2000 cycles per second was used, and this band was translated with the receiver beat-frequency oscillator so that its lower end was at zero frequency. The receiver was tuned to the transmitted frequency since the computed Doppler shift was less than 25 cycles per second. The output was recorded on magnetic tape for later detection and analysis.

Trials were scheduled for each morning from 5 to 13 April, inclusive. Because of various difficulties (for example, equipment failures, timing ambiguity, and radio interference), recordings suitable for intensive analysis were obtained only on 7, 10, and 12 April.

The test procedure for September 1958 differed in several respects from that described above. The recorded data have not yet been analyzed in detail. In September 1959, changes were made in the coding of the transmitted waves and in the antenna. The antenna modification was made for the need of the program for which the antenna was first constructed and was designed for short-pulse work only. A risk was taken in operating the modified antenna with

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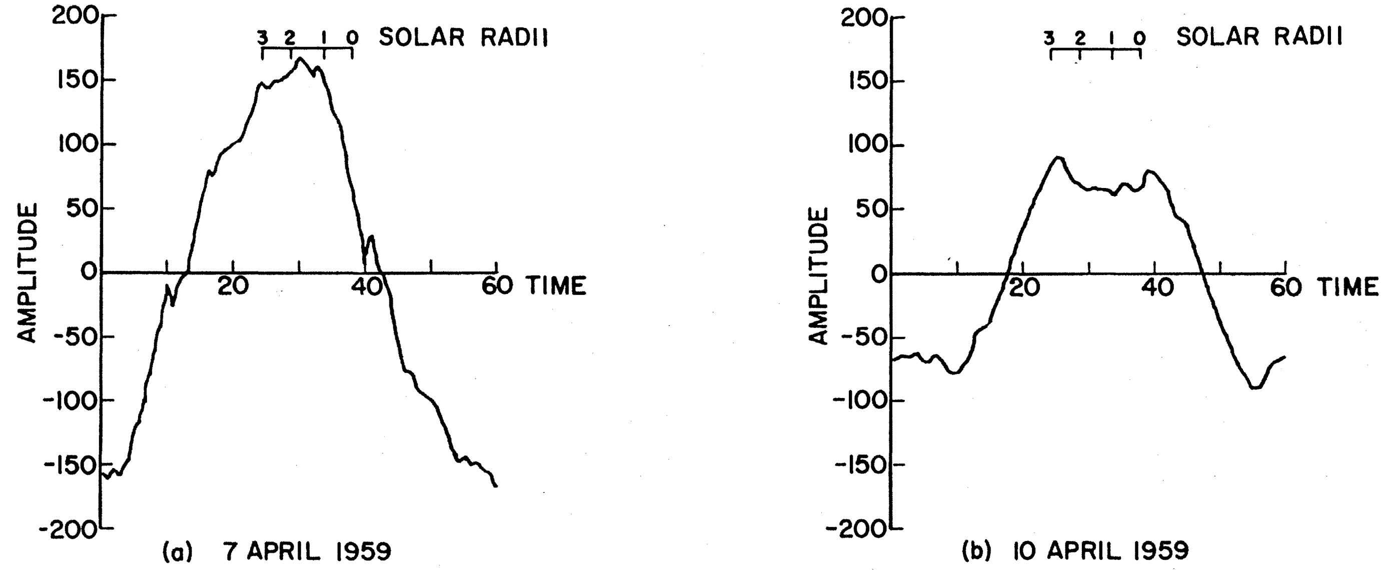
the long pulse needed for the solar experiment. Data analysis was proceeding when it was discovered that certain antenna components had failed during the testing so that antenna performance was seriously impaired. Therefore interest was diverted to the April 1959 test results, and only these are discussed further.

Data Analysis and Results

Data analysis was conducted with an IBM 797 computer and associated equipment. The recordings made on 7, 10, and 12 April at 0 to 2000 cycles per second were sampled electronically 4000 times each second, and thus the data were converted from analog to digital form. The absolute values of the samples were summed for periods of one second, and these one-second sums were stored for further analysis. (By taking absolute values, the receiver output was detected in an ideal linear detector.) The longest usable echo time common to the three days is 12 minutes, or 720 one-second sums.

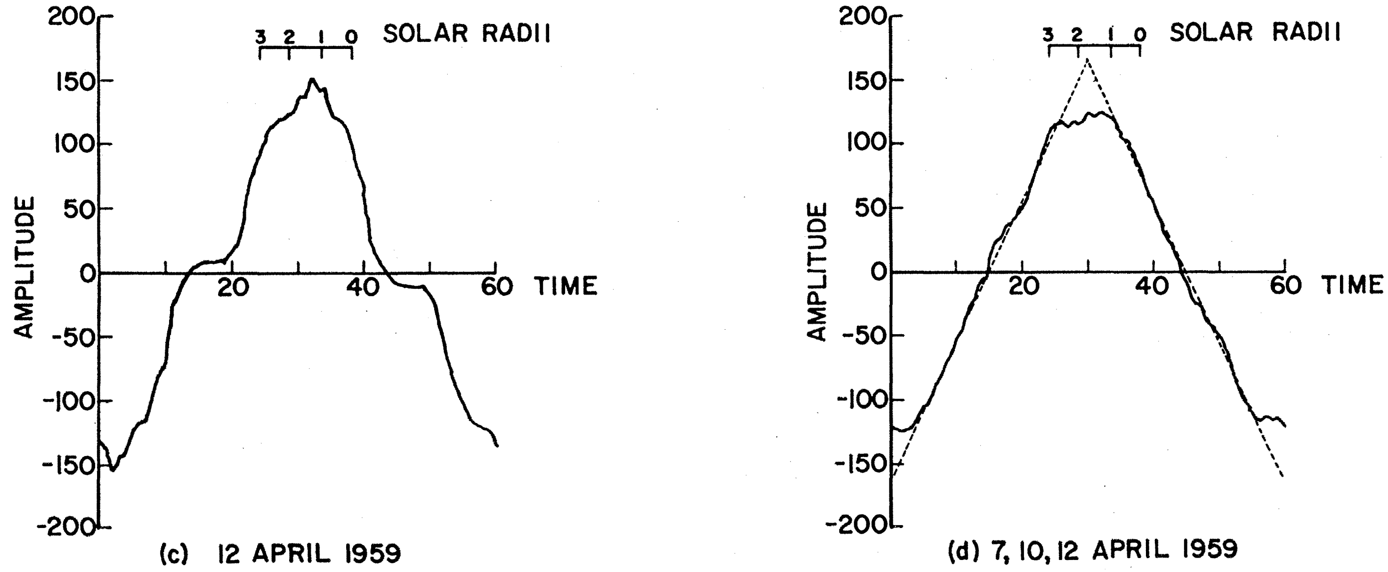
A square wave of period 1 minute, representing the transmitted wave, was cross-correlated with the 720 one-second sums for each day. That is, the sums 1 through 30 were added, 31 through 60 were subtracted, 61 through 90 were added . . . , and 691 through 720 were subtracted, to obtain one point of the cross-correlation curve. The next point was obtained by adding the sums 2 through 31, subtracting those from 32 through 61, and so on, the first one-second sum being included with the subtraction of the sums 692 through 720. After 60 cross-correlation points were obtained in this way, the values would start to repeat, so only 60 points (seconds) were computed. The cross-correlation curves that result are shown in Fig. 1.

Curves *a, b,* and *c* in Fig. 1 show the cross-correlation curves for 7, 10, and 12 April, respectively, and curve *d* is a composite curve for the three days.



(a) 7 APRIL 1959

(b) 10 APRIL 1959



(c) 12 APRIL 1959

(d) 7, 10, 12 APRIL 1959

Fig. 1. Processed data (cross-correlation of 12 minutes of transmitted code with 12 minutes of received signal), showing evidence of radar echoes from the sun. (*a*) Results for 7 April; (*b*) results for 10 April; (*c*) results for 12 April; (*d*) combination of all data compared with an ideal echo curve. The ordinate is relative amplitude in arbitrary units, and the abscissa is relative time in seconds.

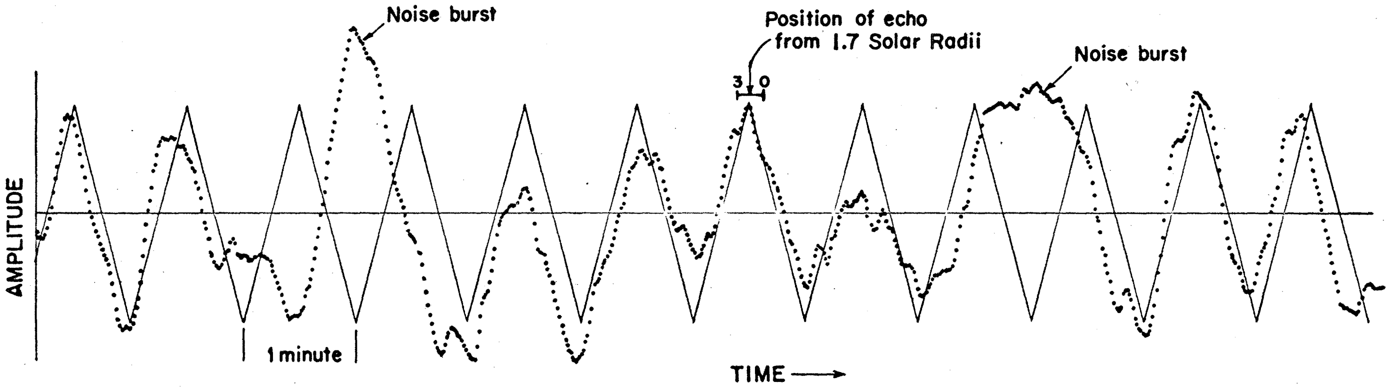


Fig. 2. Processed data (cross-correlation of 1 minute of transmitted code with 12 minutes of received signal), showing individual echo returns and disturbing noise bursts compared with ideal echo curve for 7 April 1959. Curve *a* in Fig. 1 is derived from these data. The ordinate is relative amplitude in arbitrary units, and the abscissa is relative time in seconds.

If there were no noise but if there were echoes from a discrete target, the cross-correlation curve would be one cycle of a perfect triangular wave with crests at a position determined by the target range. The dashed Λ-shaped curve shown in Fig. 1*d* represents this ideal condition. If the target were large and echoes were returning from several ranges, the peaks of the Λ curve would be less sharp, but the sides would still be straight. If there were random noise and no echoes present in the samples, the cross-correlation curve would fluctuate over a small range near the zero ordinate. In fact a noise sample of the same rectified average as the solar-echo samples has been subjected to the same receiver, recorder, and computer processing as was used for the radar returns, and the maximum deviation from zero was 16.5 decibels below the peak of the ideal Λ curve.

While it is evident that random (Gaussian) noise could not produce amplitudes comparable with those observed in the cross-correlation curves, strong impulse and burst noise from the sun can produce wide fluctuations in curves of this type. Thus special care must be exercised in interpreting Fig. 1.

In a later paragraph is discussed a different treatment of the April data which leads to numerical probabilities very nearly equal to unity that solar echoes were obtained. Immediately below are five strong arguments to indicate that the curves of Fig. 1 represent the successful radar detection of the sun.

1) *Position of the peaks.* Solar noise is equally likely to produce a peak in the cross-correlation curve at any point along the time base. The ideal Λ curve of Fig. 1*d* is drawn at a position corresponding to an assumed reflection at 1.7 solar radii. A scale corresponding to reflection points from 0 to 3 solar radii is shown over the positive crest of each curve. It can be seen that the position of *each* cross-correlation peak corresponds to reflection near the positions that would be expected from computations such as those of Kerr (*2*).

2) *Symmetry.* While the cross-correlation curves must have an inverted repetition at 30 seconds, solar noise would not in general produce a mirror symmetry about any time coordinate. If echoes are present there should be such mirror symmetry about the peak time, and this shape is evident in the curves of Fig. 1.

3) *Linearity of the sides.* Again, solar noise would not in general produce linear sides, while echoes would.

4) *Improvement in composite curve.* If the curves for the individual days contain both signal and noise, the composite curve for the three days should be a closer approximation of the ideal signal (Λ) shape. This is very strikingly evident in the figure.

5) *Signal-to-noise ratio.* In comparison with the hypothetical system described by Kerr (*2*), the present system should obtain sun echoes at a signal-to-noise power ratio of about –22 decibels in the intermediate frequency amplifier, or –44 decibels immediately after the detector. This rough computation was made just a few hours before the sums of the 7 April run were available. These sums indicate a ratio of mean signal-to-noise voltage before post detection integration of 1/155, or, if mean power is approximately the square of mean voltage, a power of –43.8 decibels. The closeness of these two figures cannot be considered anything but fortuitous, but the fact that they are within even 10 decibels of each other is significant. The signal-to-noise power ratios before integration for 10 and 12 April are –48.8 and –44.8 decibels, respectively. The computer program has been checked with test signals for signal-to-noise ratios near these values.

A clearer understanding of the effects of impulse and burst noise from the sun can perhaps be obtained from attempts to detect each individual solar echo instead of the integrated effect of many echoes. Figure 2 shows the cross-correlation of a single cycle of a square wave with 12 minutes of the one-second sums of April 7. The ideal triangular curve, placed at a position corresponding to reflection at 1.7 solar radii, is shown for comparison. (There is a range ambiguity of about 13 solar radii based on the 60-second periodicity of the transmitted wave, but it is not believed that the reflection could be this far from the sun.) There are serious disruptions from the ideal curve near the third and ninth cycles, but the cross-correlation curve always returns approximately to the ideal position and shape. Such disruptions could be caused by outbursts of solar noise.

In an attempt to express numerically the probability that solar echoes were obtained, curves like those shown in Fig. 2 were also made for 10 and 12 April, and for several periods in April and September 1959 when only noise was present. That is, a limited amount of data has been obtained on solar noise alone to compare with the periods when signals may be present. It is felt that the positions of the peaks in the cross-correlation curves are more significant than their amplitudes for differentiating between signal and impulsive noise. From the limited data on noise it appears that the positions of the peaks, referred to the same one-minute period, have Poisson distributions, as would be expected. If a Poisson distribution of the noise peaks is assumed, the positions of the measured peaks on 7, 10, and 12 April, expressed in solar radii between 0 and 13, are bunched to such a degree that the probabilities are on the order of 10^{-4} that they could be caused by solar noise alone. Since the position of the bunched peaks for each day corresponds to the expected range of the reflecting regions, the probabilities that solar echoes were obtained on each day are very nearly unity, being about 1 to 10^{-5}. This result is for each day considered independently. Since similar results were obtained on all three days, the total probability of success is even much nearer unity.

From a preliminary analysis of the spectrum received it appears that the echo energy is spread over at least 2000 cycles per second. Solar rotation alone could account for much of this Doppler broadening, but gross motions in the solar corona would also be expected to produce a wide echo spectrum.

Conclusions

There is a growing interest in the potentialities of probing the solar system with man-made radio waves. An obvious name for this field of investigation is "radar astronomy." With the added versatility inherent in the control of the transmitted waves, it is expected that much will be learned which will complement and extend knowledge gained from passive visual and radio astronomy, and from rocket probe measurements.

The scientific information about the sun gained from the first radar experiments, described above, is very limited. However, it is now possible to plan with confidence the systems and test procedures needed for more meaningful radar studies of our dynamic sun. From the time variability of the echo strength, delay, polarization, and spectrum, much will surely be learned about the constantly changing solar phenomena which affect so vitally the earth and its surroundings. More sensitive installations that will be suitable for solar and other studies in radar astronomy are now under construction at several locations, including Stanford University.

References and Notes

1. The work reported here was supported principally by the Electronics Research Directorate of the Air Force Cambridge Research Center, under contract AF-19(604)2193. We wish to acknowledge in particular the assistance of Philip Newman and the late Joseph P. Casey, Jr., of that center. The solar experiments would not have been possible without the existence at Stanford of facilities built up for several other research programs. The antenna system was constructed for ionospheric research under the direction of O. G. Villard, Jr., with support from the Office of Naval Research under contract Nonr-225(33). T. V. Huang, W. A. Long, and others provided valuable assistance in the transmitting-receiving phase of the tests. The data processing facility was organized through the efforts of A. M. Peterson, with the assistance of R. D. Egan and D. S. Pratt. The IBM 797 unit was a gift from the International Business Machines Corp. to Stanford University for use in electrical engineering and mathematical research programs.
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Cosmic-Ray-Produced Silicon-32 in Nature

Silicon-32, discovered in marine sponges, shows promise as a means for dating oceanographic phenomena.

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The nuclear transmutations resulting from the interaction of cosmic rays with nuclear species in the atmosphere have produced a variety of radioactive products detectable on the surface of the earth. Such isotopes as C^{14}, H^{3}, Be^{10}, and P^{32} have been found, and their individual distributions and concentrations in the various geological domains have led to many significant concepts and contributions in geochemistry, geophysics, and geochronology (see, for example, *1*).

This article (*2*) concerns still another isotope produced by cosmic rays—Si^{32}, which we have detected in the marine environment. It is thought that this isotope is produced from the nuclear spallations of argon by cosmic rays. It has a half-life of roughly 710 years (*3*). Any Si^{32} that reaches the earth from the atmosphere will be rapidly diluted with stable silicon, and the resulting specific activity of Si^{32} will be very small. However, Si^{32} decays by negatron (β^{-}) emission to P^{32}, which is a negatron emitter with a half-life of 14.3 days. This makes it possible to detect Si^{32} by milking and by counting the P^{32} daughter from large amounts of silicon.

The principal exchange reservoir for Si^{32} is probably the marine hydrosphere which most likely receives Si^{32} via oceanic rains. The small amounts of silicon in surface marine waters should yield a relatively high specific activity of Si^{32}, whereas the fallout on land will be so diluted by exchange and other chemical interactions with the exposed crustal materials that the detection of this nuclide will be extremely difficult. We estimate the average concentration of Si^{32} to be 2.6×10^{-5} disintegrations per minute, per liter of sea water, or 8 disintegrations per minute, per kilogram of silicon, for a hypothetical thoroughly mixed ocean. The amount of sea water required to yield 1 disintegration per minute, an activity conveniently detectable, is 3.8×10^{4} liters. Since the handling of such an amount of water for the extraction of silicon presents many difficulties, Si^{32} was sought initially in siliceous (opaline) sponges, which derive

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