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Radar Echoes from Venus

Advances in several arts made possible this experiment in radio astronomy performed during the IGY.

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The possibility of obtaining radar echoes from celestial bodies outside the Earth-Moon neighborhood, and the scientific value of information obtainable from such echoes, has been discussed by Kerr (*1*) and others (*2*). The attainment of such objectives has been brought from the realm of theoretical interest to within the range of experimental accomplishment with the advent of (i) receiving amplifiers having low noise, such as the maser, (ii) high-power missile-tracking radar transmitters employing steerable antennas of large aperture, and (iii) flexible and stable digital data-processing techniques.

On 10 and 12 Feb. 1958, about 2 weeks after Venus' closest approach, signals from M.I.T. Lincoln Laboratory's Millstone Hill radar installation (*2a*) were directed toward Venus. That planet was then about 28 million statute miles from the Earth, and the time required for radar signals to reach Venus and return was about 5 minutes. The equipment was operated with the characteristics shown in Table 1. With these specifications, it should be possible to detect the planet near its time of closest approach to the Earth, provided that the planet is a good reflector at 440 megacycles per second and that the reflection is reasonably coherent over the pulse length. Under such conditions, a signal-to-noise ratio of − 10 decibels should be obtained at the output of a filter matched to a single received pulse when Venus is at a distance of 28 million miles. By repeated pulsing of the transmitter and proper integration of the received signal over several thousand pulses, a signal-to-noise ratio can be built up that is sufficient to establish the presence of the return unequivocally.

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Data Collection and Processing

Five separate runs were made, and data from four of these have been processed. In each run signals were transmitted for approximately 4.5 minutes; the transmitter was then turned off, and the receiver output was recorded on magnetic tape for the following 5 minutes.

Because of the uncertainty in the size of the solar system, which is several times the normal interpulse period employed (33.3 milliseconds), it was decided to code the transmission in such a way that range ambiguities could be resolved. For this purpose, the normal stream of transmitted pulses occurring 33.3 milliseconds apart was gated on and off by a binary maximal-length shift-register sequence (*3*). The transmitted waveform then had the appearance of a periodic train of 2-millisecond pulses, except that half of them were deleted in a pseudo-random fashion.

The transmitter used a high-power klystron, and the stability of the entire transmitter-receiver conversion chain held to within 1 cycle per second during the 10-minute period of each run. A three-level, solid-state maser (*4*) with a potassium (chromi) cobalticyanide crystal in a bath of liquid helium was employed with a directional coupler to provide the low-noise receiving front end.

In receiving, a spectral zone 3 kilocycles per second wide, centered roughly 20 kilocycles below the transmitted carrier in order to pass the Doppler-shifted radar return, was accurately converted down to an intermediate frequency lying in the audio region. After the amplitude of this signal was quantized into 64 levels by means of an analog-to-digital converter operating at a sampling rate of 12 kilocycles per second (crystal-controlled), the signal was recorded on magnetic tape in a format suitable for later processing by an IBM Type 704 electronic digital computer.

In processing, the recorded data are first passed through the digital equivalent of a matched filter whose impulse response is a sinusoidal pulse 2 milliseconds long. The frequency of the sinusoid is deduced from the expected Doppler due to Earth-Venus motion and Earth rotation, together with the known receiver conversion frequencies. The envelope of the filter output is then squared and cross-correlated against a replica of the transmitted envelope; proper compensation is made for the Doppler shift in the pulse repetition frequency caused by the receding motion of the planet. Cross-correlations were taken at 1-millisecond increments in the relative delay between the reference and the squared filter output, until a region of uncertainty of approximately 600 milliseconds had been completely explored.

Results

Of the four runs that have been processed, two show no evidence of radar returns. Each of the other two, however, exhibits in its cross-correlation function statistically significant evidence of a return, as is shown in Fig. 1. Figure 1 shows that portion of each of the final cross-correlation records lying in the neighborhood of the largest signal peaks. The records of the two days have been drawn with the central peaks aligned. The bottom curve shows the correlation function that would be expected for the type of modulation employed if noise were absent. The correlation curve consists of a periodic series of peaks of uniform height except for a single peak of double amplitude at the target range.

For clarity's sake, Fig. 1 shows a region of only ± 50 milliseconds about the center (that is, roughly ± 2 parts in 10^4 out of a round-trip travel time of 300 seconds). Our cross-correlation results actually extend over a much larger range of ± 1 part in 10^3, and the part not shown here looks much like a continuation of Fig. 1. That is, for the run of 10 February, throughout the larger region (except where the periodic half-height peaks are expected) all points are more than 1.3 standard deviations below the central peak of Fig. 1. For 12 February the figure is 1.9 standard deviations. At the points where half-height peaks are expected, the figures are 0.6 and 1.1 standard deviations for 10 and 12 February, respectively.

In addition to the evidence in each curve separately, there is the persuasive fact that the measured change in round-trip travel time between the two successful runs differs by only 2.2 milliseconds (about 200 miles), or about a pulse width, from the predicted value of 7.4755 seconds. Much of the slight discrepancy can be accounted for by round-off error in the astronomical tables (*5*), where daily Earth-Venus distances at close approach are tabulated to only six figures, or about 1 millisecond of accuracy. (Correction was made for effective center-to-surface distances (*6*) of the two planets.) It is also likely that noise has produced small displacements in the correlation peaks.

The round trip travel times deduced from the two peaks are 295.5065 ± .0005 seconds for 10 February and 302.9842 ± .0005 seconds for 12 February. Each of these travel times is that of the first transmitted pulse, which occurred at 14:21:05 E.S.T. on 10 February and 12:00:55 E.S.T. on 12 February. Preliminary calculations from the ephemeris (*5*) predict the delays shown by the heavy arrows in Fig. 1, and these values of delay were used as the starting points in searching for the signal peak. The calculation from the ephemeris used a velocity of light of 299,860 kilometers per second and, correspondingly, a distance scale of 498.580 seconds per astronomical unit (the mean radius of the earth's orbit.) If the velocity of light is assumed to be correct, then our result implies that the astronomical unit is about 0.0013 percent smaller than the value given in the ephemeris (*5*). On the other hand, the detailed optical analysis of the orbit of Eros performed by Rabe (*7*) indicates that the astronomical unit should be (0.018 ± .004) percent larger. Future radar observations, it is hoped, will resolve this disagreement.

A detailed statistical examination has

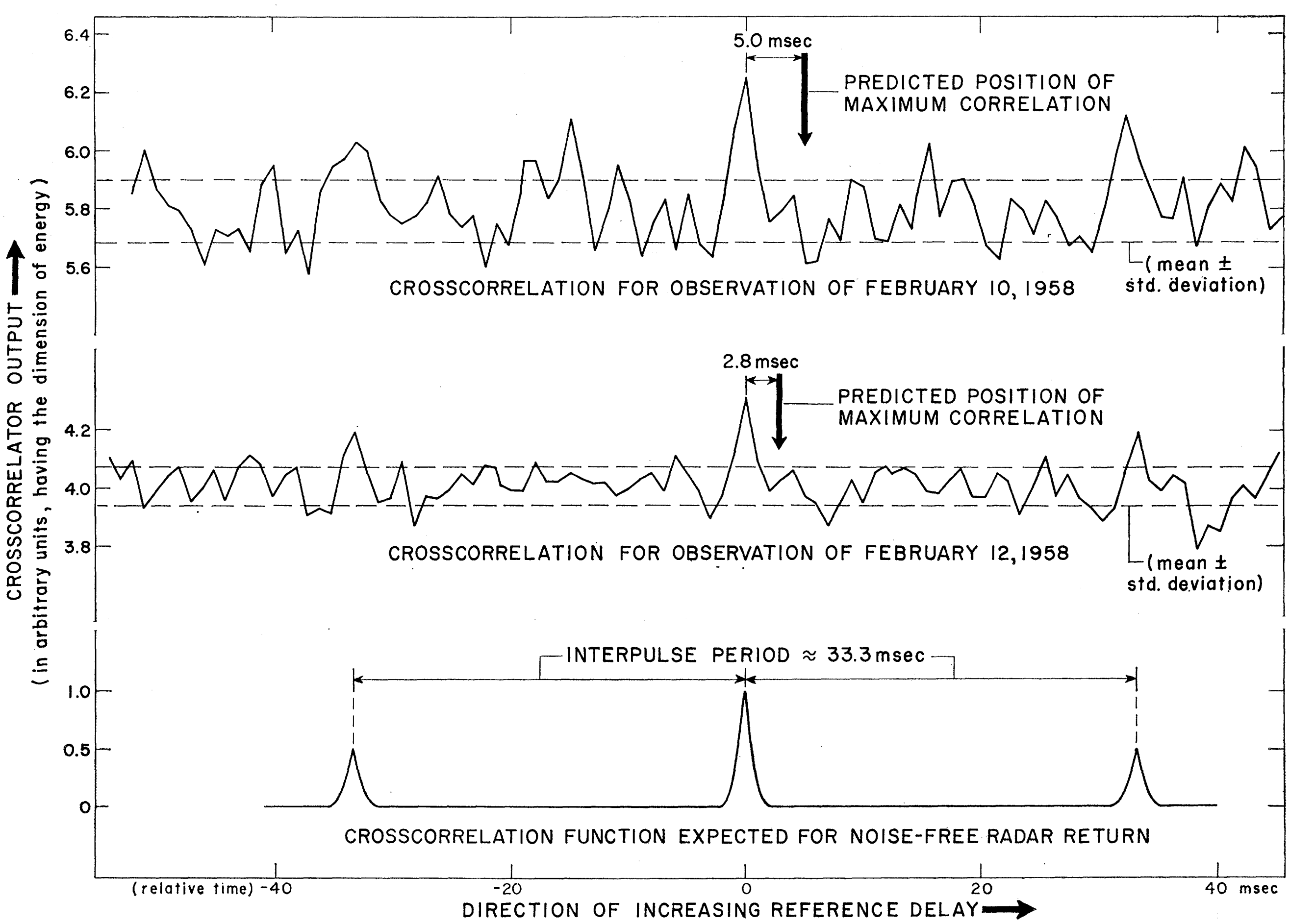

Fig. 1. Results of processing the signals received from the direction of Venus on 10 and 12 February 1958. On 10 February the predicted round-trip travel time for the first pulse was 295.5115 seconds, and the predicted signal-to-noise ratio after processing was 10.4 db. On 12 February the predicted travel time was 302.9870 seconds, and the predicted signal-to-noise ratio was 14.0 db. The predicted signal-to-noise ratios assume a perfectly reflecting target and an ideal, lossless system.

Table 1. Radar system characteristics.

Item	Characteristic
Transmitter	
Frequency	440 Mcy/sec
Pulse duration	2 msec
Peak power	265 kw
Transmitting-receiving antenna	
Form	84 ft steerable paraboloid
Gain	37.5 db
Polarization	
Transmitted	Circular
Received	Opposite circular
Equivalent noise input temperature of system	
Total	170°K
Antenna and feed	100°K
Maser and receiver	70°K

been made of the data for the two successful runs and has established that the fluctuation due to the background noise is in agreement with that expected theoretically. A theoretical analysis of the level of significance is thus justified. We have taken into account that the baseline fluctuations of Fig. 1 are not strictly normal, but actually high-order chi-square distributed (a conservative practice). The probability that background noise alone could have produced in these two runs, within the 600-millisecond range, cross-correlation peaks of amplitude equal to or greater than those observed, and having the relative alignment cited earlier, is less than 10^{-7}.

The strengths of the cross-correlation peaks on the successful runs imply that Venus is nearly a perfect reflector at 440 megacycles per second, if there are no scintillations. If there are amplitude fluctuations, however, the average reflectivity could have been considerably lower, since in the method of processing used here a signal contributes to the output in proportion to the square of its instantaneous strength. Of course this question cannot at present be resolved since it is impossible to observe individual returned pulses.

Among other checks that have been made on the planetary returns were analyses of their spectra which yield Doppler shifts in agreement with the astronomical predictions within the measurement uncertainties. Owing to the short pulses used, the accuracy of Doppler measurement is limited. There is no significant spectral broadening, so that presumably the returns are coherent over a 2-millisecond interval. On the other hand, no evidence of pulse-to-pulse coherence has been found. Examination of the raw data reveals no noise bursts, nor is there any indication of other than a statistically uniform buildup of the cross-correlation peaks with increasing integration time. All computer programs have been checked out on simulated signal-in-noise returns to check the correctness of the cross-correlation processing.

It is probable that the same techniques with minor improvements will be employed in the observations of Venus to be made at its next close approach, in September 1959. It appears possible, however, that a parametric amplifier may replace the maser.

Conclusion

It is evident that the success of the entire undertaking depended critically on the simultaneous application of significant advances in the state of several arts: (i) a maser operating in the 400-megacycle-per-second range; (ii) radar equipment combining high transmitter power and a large, precision antenna; (iii) digital recording and nonreal time digital processing of signals. It is felt that the advantages of such processing of received signals have been established for both passive and active radio and radar astronomy observations. The ability to "freeze" the data for later leisurely analysis appears to be important in an experiment in which a priori knowledge is lacking in several respects, and when there is only a relatively brief period in which observations can be made (*8*).

References and Notes

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8. This work was performed at Lincoln Laboratory, a research center operated by Massachusetts Institute of Technology with the joint support of the U.S. Army, Navy, and Air Force.