Bi-Static Correlation Radar for Velocity Sensing in Spacecraft

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Field-strength correlation can provide a means for velocity sensing which is particularly well suited to lunar landing missions. An earth-based transmitter directed toward the moon can set up an irregular field-strength distribution which is the sum of the direct wave and of many waves reflected from the lunar surface. This irregular pattern can be sensed by simple receivers with appropriately spaced antennas on a spacecraft. Because the field-strength pattern will be essentially stationary with respect to the lunar surface, the speed that is measured by cross correlating the features of the pattern will be that of the vehicle with respect to the moon itself. Since this technique is based on tracking the peak of the correlation function, the nature of this function has been investigated both analytically and experimentally by simulation. In general, the results indicate that the correlation functions which would be obtained in the vicinity of the moon are suitable for tracking. A spaceborne velocity sensor employing this principle should be operable anywhere within a region defined by radial extension of the visible half of the moon out to an altitude of about 1000 miles.

Introduction

ESSENTIAL to any lunar landing mission is an accurate measure of the magnitude and direction of the spacecraft velocity with respect to the moon's surface. These measurements can be performed aboard the vehicle by conventional radar techniques, but weight restrictions limit the effective power of a self-contained radar, confining its operation to relatively low altitudes. However, bi-static or semiactive correlation radar is particularly well suited to this application and can accomplish velocity sensing at much higher altitudes.

In a bi-static radar sensor, the transmitter and receiver are at separate locations, as opposed to the conventional self-contained radar where the transmitter and receiver are together. By using a powerful transmitter on earth, an "artificial atmosphere" of microwave energy is set up adjacent to the visible side of the moon and used as a medium for velocity sensing by receivers on board the spacecraft. This electromagnetic "atmosphere" is actually an irregular distribution of field strength that results from the constructive and destructive interference between the direct wave from the earth-based transmitter and the reflected waves that are scattered from the moon's surface. Since this irregular field-strength pattern is very nearly stationary with respect to the moon, the velocity of the vehicle as measured by sensing the pattern is, in effect, the velocity with respect to the moon itself.

Deriving velocity information by sensing the field-strength pattern involves cross correlating the signals received by separate antennas on the spacecraft. If two antennas are placed on the vehicle so that one follows directly in the path of the other, then both antennas will sense the same irregular field-strength fluctuations. However, the signals from the two antennas will be separated by a time delay that is equal to the distance between the antennas divided by the speed of the vehicle. Cross correlation provides a means of measuring this time delay, and since the antenna spacing is known, the speed can be computed. By using a suitable array of antennas instead of only two, the direction of the velocity vector with respect to the spacecraft also can be sensed.

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Velocity Measurement by Field-Strength Correlation

If a plane wave is incident on a plane reflecting surface, the reflection is also a plane wave. Constructive and destructive interference between the incident energy and the reflected energy gives rise to a regular standing-wave pattern, where contours of constant field strength are planes parallel to the reflecting surface. At any point in the space near the reflecting surface, the field consists of two components: a direct ray from the source, and a reflected ray that comes from only one point on the surface. A receiver moving through this space along a line that is not parallel to the reflecting surface will detect a regular, periodic variation in field-strength. If the reflected signal is weak compared to the direct signal, or if the receiver employs synchronous detection, then its output will vary sinusoidally.

A reflecting surface that is irregular will scatter the incident energy rather than reflect it as a plane wave. The result is an irregular field-strength distribution, in which the variations depend on the nature and characteristics of the scattering surface. In general, the features of the pattern are of the order of a wavelength in size. The field at a point in the space now consists of a direct component and many reflected components, each of which is scattered from a different point on the surface (Fig. 1). A receiver moving in any direction through this space will detect an irregular variation in field strength which resembles band-limited noise. If the source transmits only a single frequency, and if its location is fixed with respect to the scattering surface, then the "fine structure" in the pat-

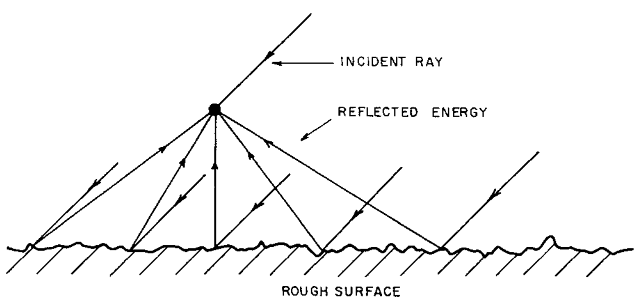

Fig. 1 Scattering from rough surface produces irregular field-strength pattern.

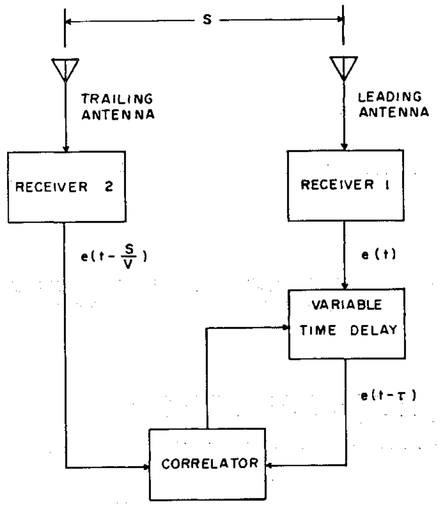

Fig. 2 Simplified block diagram of correlation velocity sensor.

tern will be fixed in position with respect to the surface. Therefore, a sensor which measures speed with respect to the field-strength pattern also will measure speed with respect to the scattering surface.

Consider now two receivers whose antennas are separated by a fixed distance s. Assume that each antenna accepts energy equally from all directions. If these two antennas move through the space such that a line through their centers is parallel to the direction of motion, then both will move along the same path. Both receivers will detect the same field-strength fluctuations, but the noiselike output from the trailing receiver will be delayed by a time equal to s/v, where v is the vehicle's velocity.

Cross correlation provides a means of measuring the time delay between the two signals independently of their waveform. Figure 2 shows a simplified block diagram of the signal processing equipment. The signal from the leading receiver is passed through a circuit that inserts a known, adjustable time delay τ. This delayed signal is then multiplied with the signal from the trailing receiver, and the output of the multiplier is time averaged. The averaged output is proportional to the degree of match or correlation between the signals. If the delay element is adjusted to duplicate exactly the delay because of the antenna separation (i.e., $\tau = s/v$), then the two signals will arrive at the multiplier simultaneously, and the maximum correlation will be indicated. By incorporating a feedback loop from the correlator to the variable delay element, the system can be made to adjust τ automatically for changes in v; in other words, it can be arranged to track the peak of correlation.

The correlation function always has a major peak, or maximum, at $\tau = s/v$. Other minor peaks may be spaced symmetrically about this correlation peak. For any speed, the location of the correlation peak on the delay axis is proportional to the antenna spacing, but the shape of the curve is independent of the spacing (upper part of Fig. 3). Now if the degree of correlation is plotted as a function of the ratio of time delay to antenna spacing, the location of the major peak will depend only on the speed, but the width of the correlation peak will be inversely proportional to the antenna spacing (lower part of Fig. 3). The effect of using more closely spaced antennas is, therefore, to stretch the correlation function along the delay axis, making the major peak more prominent and easier to acquire.

Until now we have considered two antennas aligned with the vehicle's velocity vector. Consider now an arrangement where there are two trailing antennas and one leading antenna. The separation between the two trailing antennas is relatively small and perpendicular to the direction of motion. The time-delay element can be adjusted to maximize the degree of correlation between the leading signal and either of the trailing signals, and the difference between the two values of correlation with the two trailing antennas can be used as an error signal for aligning the vehicle to its velocity vector. By using a similar antenna arrangement in the perpendicular plane, the velocity can be tracked in all three dimensions.

Application to Lunar Missions

A powerful transmitter on earth, probably of the type used for command communications to the spacecraft, could serve as the radiation source for lunar-mission use. The speed measured by the correlation velocity sensor actually will be that with respect to the surface of the moon. The same side of the moon always faces the earth, but because of the earth's rotation on its axis, a transmitter on earth is not perfectly stationary with respect to the moon's surface. The relative motion of the transmitter can be described by a range rate and a total libration rate. Of these two, the libration effect is the more significant. The effect of the libration is to cause slow changes in the field-strength distribution, but so long as the field pattern does not change appreciably during the time required for both antennas to pass a given point in the space, the velocity sensing can still be accomplished.

Figure 4 shows the minimum speed that can be sensed while maintaining at least 96% of the maximum possible correlation for the worst-case libration rate. The minimum allowable speed under this criterion depends on the altitude above the moon's surface. For example, with an antenna separation of six wavelengths, v_{min} is about 30 m/sec at an altitude of 100 km (62 miles). Since v_{min} decreases at lower altitudes this velocity limitation is not restrictive in a practical sense.

The maximum altitude above the lunar surface at which the correlation velocity sensor is operable depends on the varia-

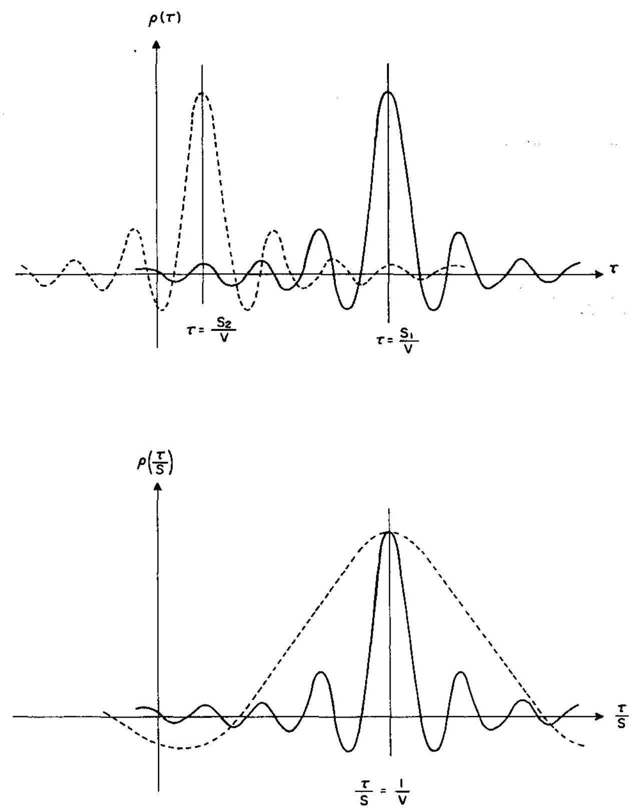

Fig. 3 Correlation function showing effect of antenna spacing.

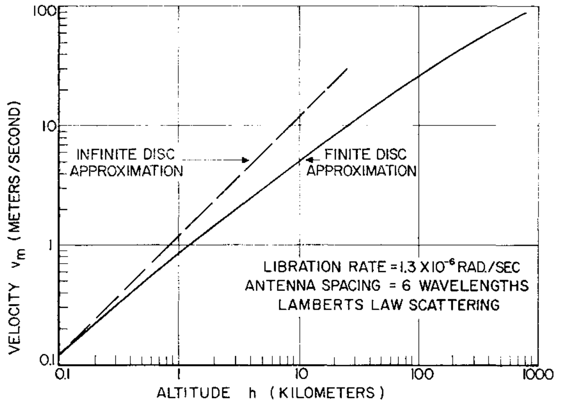

Fig. 4 Minimum velocity for 96% correlation under worst-case condition of libration rate.

tion of average signal strength with altitude. The strength of the reflected signal, rather than the direct signal, is of interest, since the magnitude of the spatial variations in field strength cannot exceed that of the reflected signal. The variation in signal level with altitude has been obtained analytically for the case of pure specular reflection, as would occur from a smooth sphere, and also for the case of Lambert's Law scattering, which takes place from certain types of rough surfaces. The actual scattering from the moon's surface may be considered a combination of these two effects.[1] Figure 5 shows the results of the analysis. The signal level undergoes only a slight reduction in the first 100 miles of altitude along the earth-moon centerline, and even at an altitude of 1000 miles the signal level is only about 10 db less than the value near the surface. (This is in contrast to the case of a self-contained radar, where the received signal power, even at low altitudes, is reduced by at least 6 db each time the altitude is doubled.) These results indicate that, using a transmitter of the type already in use (e.g., at the NASA Goldstone tracking station), the correlation velocity sensor can be operated at altitudes of up to at least 1000 miles above the moon, assuming a very nominal receiver noise figure and sufficient bandwidth to accommodate the highest expected velocity.

The tracking of the correlation peak will be subject to random errors. The magnitude of these errors can be estimated using formulas derived by Green[2] for the accuracy of correlation measurements. Part of the random error results from noise and part results from the inherently random nature of the field-strength pattern. The fact that independent noise is additive to each of the two signals being cross correlated results in a threshold effect. The correlation falls off rapidly as the signal-to-noise ratio becomes less than about unity. However, for signal-to-noise ratios greater than unity, the effect of the additive noise becomes small so that the error is due primarily to the random nature of the field-strength pattern. The fluctuation error which remains at large signal-to-noise ratios depends strongly on the shape of the correlation function. For the type of correlation function which is believed to be representative of those which would be encountered in practice, the following equation provides an approximation to the average error in velocity v for large signal-to-noise ratios:

$$\Delta v/v = (\lambda/2s)(\lambda/2v\tau_{av})^{1/2}$$

where Δv = rms deviation in measured velocity, λ = wavelength, and τ_{av} = averaging time. The parameter $\lambda/2v\tau_{av}$ gives the ratio of correlator bandwidth to signal bandwidth and represents the effect of smoothing the random fluctuations over a finite time interval. The parameter $\lambda/2s$ arises from considering the change in correlation which results from a change in a velocity-related parameter, such as time delay or antenna separation. The equation applies to a selected component of velocity error, the selected component being either along the antenna axis or normal to it. The degree of accuracy which can be attained with a signal-to-noise ratio of at least several times unity is illustrated by assuming the following conditions: s = 75 cm, λ = 13 cm, v = 8000 fps, and τ_{av} = 1 sec. In this case the predicted rms value of random error is 0.05%.

Theoretical and Experimental Correlation Functions

Actually, the correlation function is a three-dimensional spatial autocorrelation function of field strength, but the action of the two spaced receivers reduces it to a cross-correlation function between the two time-separated signals, in one dimension that represents the direction of motion. If the two receiving channels have identical characteristics, then the cross-correlation function of the two signals is the same as the autocorrelation function of the field-strength pattern in one dimension, except for a shift along the delay axis which corresponds to the separation between the receiving antennas. The shape and side-lobe structure of the function are determined only by the field-strength distribution.

Calculations have been made of some theoretical autocorrelation functions, assuming Lambert's law scattering from a flat surface. The assumption of a flat surface is reasonable for the moon at altitudes that are small compared to the lunar radius. Several directions of motion, as well as incident radiation at various angles to the surface, were considered. An example is shown in Fig. 6. Such characteristics are suitable for tracking, provided that some means is included for avoiding acquisition of one of the minor peaks. The use of pairs of antennas with different spacings, as noted earlier, is one means of implementing proper acquisition.

Correlation functions also have been obtained experimentally for a field-strength distribution above a scattering surface. Figure 7 is a sketch of the experimental setup. The surface was a large floor area covered with several inches of sand, which was used because its surface texture could be

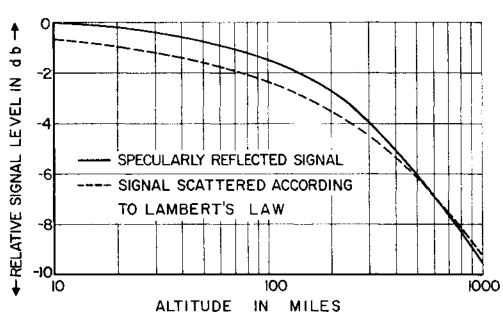

Fig. 5 Relative strength of signal from moon vs altitude along earth-moon centerline.

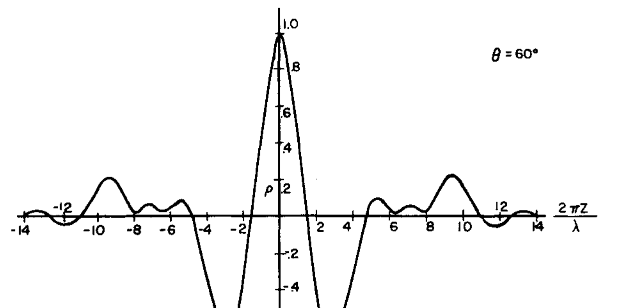

Fig. 6 Theoretical autocorrelation function of field strength for motion perpendicular to a plane surface that reflects according to Lambert's law. θ is angle between direction of incident radiation and surface normal. The z axis is displacement perpendicular to surface.

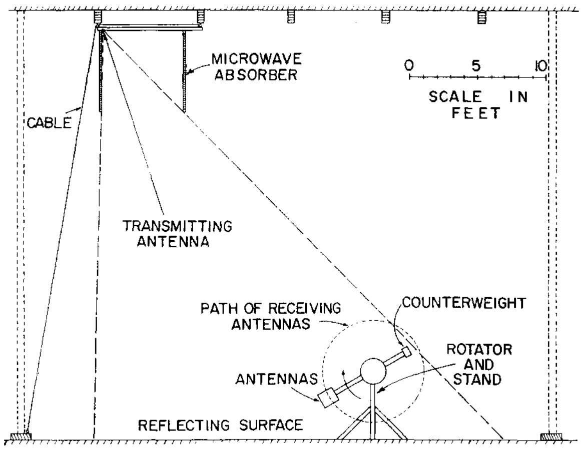

Fig. 7 Sketch of test apparatus for measuring correlation functions experimentally.

changed to obtain different scattering properties. The source of radiation was an unmodulated low-power klystron that was suspended from the ceiling of the building along with its antenna system, which directed the energy toward the scattering surface. A wavelength of 3.6 cm was used for convenience, but the technique is not restricted to any particular operating frequency. The field distribution was sensed by small antenna probes mounted at the end of a rotating arm. The antenna probes were placed so that one followed the other as they moved in their circular path. The two antennas were separated by a distance of about 2.5 wavelengths.

Figure 8 shows a simplified block diagram of the experimental signal processor. Instead of using two separate receivers, a switching technique with one receiver on a time-shared basis was employed. The signal waveforms were sampled and converted to binary form so that a shift register with a variable clock rate could be used as the variable delay element. A half-adder circuit was used as a polarity-coincidence detector. After averaging, its output is a voltage that

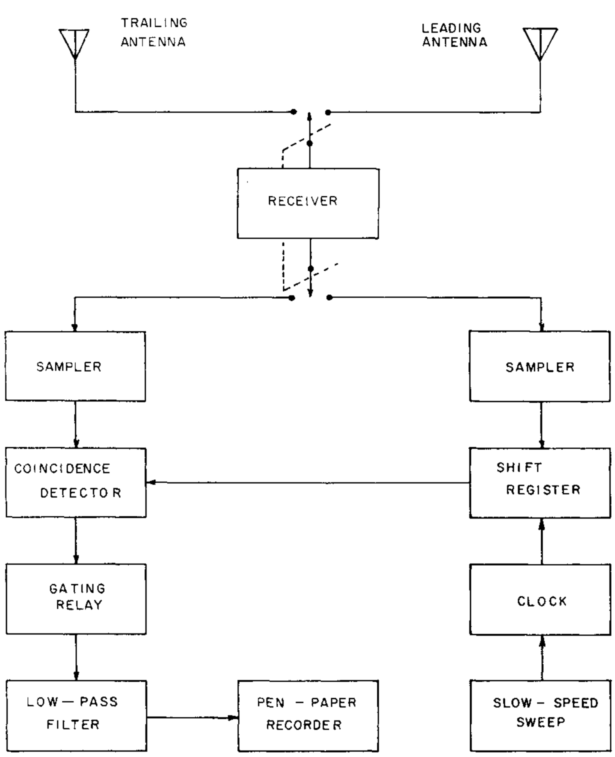

Fig. 8 Simplified block diagram of experimental equipment.

is proportional to the percentage of coincidences between the signals and hence is a measure of the degree of correlation. The correlation functions were recorded directly with a pen recorder while slowly varying the shift-register delay time. Instead of accepting data from the entire circular path, individual 60° arcs were gated out to approximate straight-line motion at various angles with the horizontal.

Data were recorded for both "rough" (Fig. 9) and "smooth" (Fig. 10) reflecting surfaces. The rough surface was such as would be found at a beach where people had been walking in the sand. The smooth surface was obtained by removing the major irregularities with a large scraper. The correlation functions for paths approximating horizontal motion have a relatively broad major peak and a low side-lobe level. If the delay axis is interpreted as being a spatial displacement instead of a time delay, it is seen that the width of the peak is about half of a wavelength. The functions for paths approximating vertical motion have a major peak that is about a quarter-wavelength in width, and they exhibit considerable periodicity. This periodic character is more pronounced with the smooth surface, since it is representative of specular reflection.

The velocity determined from the location of the correlation peak on the delay axis was in agreement with an independent velocity measurement to an accuracy of within a few percent in every case (nearly as good as the accuracy of lo-

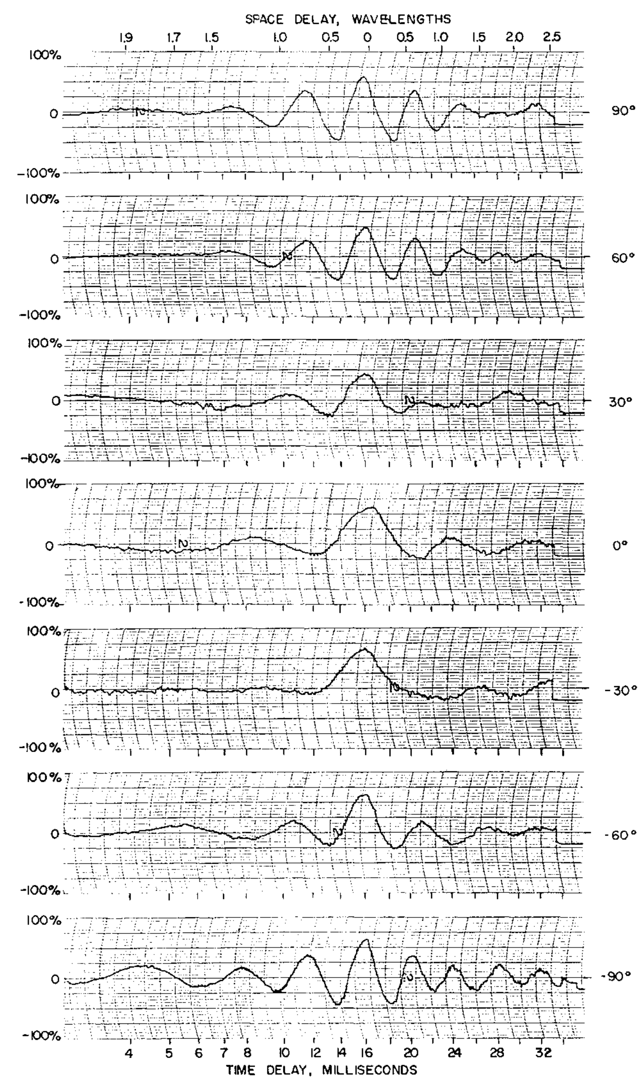

Fig. 9 Correlation functions of field strength for rough reflecting surface. Both delay scales apply to all seven graphs. Figures at right show angle between average direction of motion and horizontal.

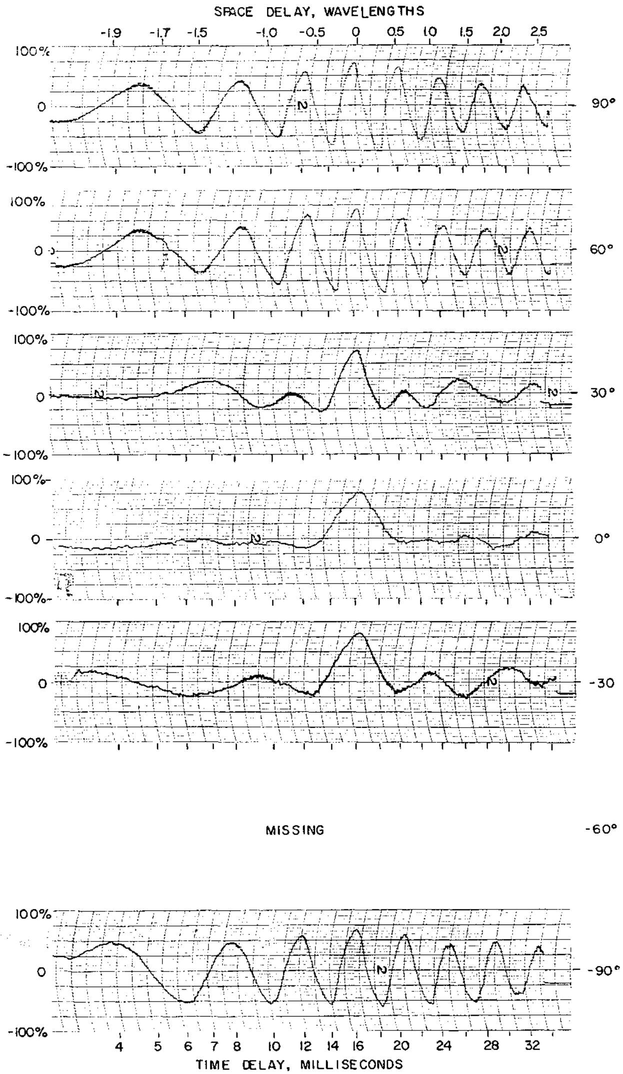

Fig. 10 Correlation functions of field strength for smooth reflecting surface.

cating the peak on the recording). No automatic tracking capability was included in the experiment. Ideally, the recorded correlation functions would be identical to the spatial correlation functions of the field-strength distribution and would show 100% correlation where the net delay between the two signals is zero. However, in the practical case the field patterns of the two antennas cannot be made identical. The theoretically calculated functions do not include the effects of specular reflection, which explains why they do not show the oscillatory character of the experimental functions in the case of vertical motion.

Altimeter Function

In addition to the velocity-sensing function, it is also possible to provide an altitude measuring capability using the bi-static radar technique. Basically, this would involve a measurement aboard the spacecraft of the time delay between the arrival of the direct signal from the transmitter and the earliest reflected signal from the moon's surface. Knowing the angle of arrival of the direct signal with respect to the local lunar vertical, the altitude of the spacecraft then can be computed. In this case it is necessary to modulate the earth-based transmitter with a waveform having a suitable autocorrelation function. Both the altimeter function and the velocity measuring function probably can be accomplished with the same spacecraft receiver and the same earth-based transmitter, e.g., by a time-sharing technique. It also appears to be possible to accomplish the two functions simultaneously by appropriate signal processing. Preliminary calculations show that, as far as signal strength is concerned, the altimeter function should be operable as far as 4000 miles from the moon.

Conclusion

The use of bi-static correlation radar affords a means for velocity sensing aboard spacecraft which is well suited to lunar missions. The method measures both direction and magnitude of the velocity relative to the moon's surface. The direction information is in the form of angular errors that can be used directly in aligning the retrothrust axis with the velocity vector for descent to the lunar surface. The technique can be made operable throughout a far greater range of altitudes than a self-contained radar system. The spaceborne equipment can be lightweight and low in primary power consumption, since no transmitter is included. Finally, it appears to be possible to incorporate an altitude-measuring function in addition to the velocity-measuring function in such a bi-static radar sensor.

References

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[2] Green, P. E., Jr., "The output signal-to-noise ratio of correlation detectors," Inst. Radio Engrs. Trans. Inform. Theory **IT-3,** 10–18 (March 1957).