Microwave Acoustic Simulation of Airborne Radar Ground Echoes

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Abstract—A method is described for generating simulated microwave frequency radar terrain echoes. This method makes it possible for the first time to realistically duplicate in the laboratory the principal characteristics of echoes due to radar motion and terrain roughness. These characteristics include variation of echo delay, Doppler shift, random fine structure, and their time variation. The simulation is based on modeling of the radar beam propagation and diffuse reflection processes by use of microwave acoustic energy in a solid medium. Scaling relations between radar and acoustic model parameters are derived. An experimental program was carried out whose purpose was to develop a practical solution to the problem of varying the distance between a microwave acoustic transducer and a reflecting surface, and to determine the overall feasibility of the simulation method. Results indicating its practicability are presented and directions for further work are suggested.

INTRODUCTION

ACOUSTIC modeling of the phenomena of electromagnetic wave scattering from complex radar targets such as terrain has long been used for the construction of radar operator training devices [1], [2]. In that application, a scale model of the object or terrain area of interest is immersed in a water tank and is illuminated by an ultrasonic pulse that is radiated from a transducer whose directional characteristics and motion in the water tank are appropriately scaled. The ultrasonic echoes received at the transducer are converted to electrical signals and then displayed or otherwise utilized in a manner analogous to that in the actual radar.

Moore [3] and Edison [4] have shown that this ultrasonic modeling or simulation technique can be used as a quantitative engineering tool in design and performance prediction for radars that make use of terrain echoes, such as altimeter radars, or for radars whose performance may be strongly influenced by terrain. An example of a radar design problem that involves the structure of terrain echoes in a fundamental way is that of choosing a radar waveform that will permit adequate discrimination between echoes from the closest ground point and other points within the angular spread of the radar beam. Inadequate discrimination will lead to erroneous altitude indication. A different but related problem arises in the case of a terrain avoidance radar where a compromise must be made in the choice of the time constant for smoothing the altitude indication. This smoothing time must be short enough to insure response to significant
changes in the height of the terrain being traversed, but long enough to adequately suppress signal fluctuations associated with the random structure of the electromagnetic field scattered from a rough surface when illuminated by a monochromatic wave.

The work of Moore [3] and Edison [4] shows that in addition to its use in training devices and as a system design tool, ultrasonic simulation can also be used either to predict radar performance over a wide range of operating conditions, or to verify analytical predictions for selected conditions. But in all such applications of the water tank simulator, it is found necessary to scale the frequency and time scale of operation relative to the radar case by factors of 100 or more. An upper frequency limit of about 10 MHz is set by the strong frequency dependence of acoustic attenuation in water; and in order to maintain a reasonable number of carrier cycles within the acoustic pulse at the reduced carrier frequency, a stretched time scale is required.

The necessity for a large change of frequency and time scale from that of the radar is of little concern when the simulator is to be used as a specialized analog computer. But it is evident that the echo signals produced in the simulator cannot be used as test signals for laboratory investigation of actual radar equipment. It is the purpose of this paper to describe a method of overcoming this limitation by modifying the simulation technique so that echo signals are produced that accurately emulate those received by the radar under its intended operating environment. Clearly, such a capability would significantly extend the usefulness of simulation as a design and evaluation tool. In addition to its application as a training aid and for system design and performance investigations of the kind permitted by the water tank simulator, a "real-time" simulator can be used to investigate experimentally the adequacy of proposed equipment design approaches and to make comparative laboratory evaluations of alternate approaches. Similarly, as equipment design proceeds, the effects of proposed design modifications can be evaluated at an early stage in the design process. At a later state in the development of a radar that is to become part of an integrated avionics system, the ability to produce realistic radar test signals will permit a more thorough investigation of the interaction of the radar with other elements of the system than would be possible using only standard laboratory test signal sources. Also, because flight testing of radar equipment is extremely expensive, preliminary testing with the help of a simulator can establish the ranges of operating conditions over which flight testing should be concentrated. Finally, microwave acoustic real-time simulation may permit equipment evaluation under operating conditions not accessible during flight testing because of safety considerations or performance limitations of available test aircraft.

The simulation approach to be described uses acoustic modeling of the radar signal propagation and scattering, as in the water tank simulator. However, the modeling is done in a solid medium to permit the use of microwave frequency signals and dimensions are adjusted to maintain a 1:1 time scale relative to the radar case. Moreover, the modeling is done in such a way that the simulator can accept radar transmitter power and deliver simulated ground echo signals to the radar receiver. As discussed further below, only the problem of simulating diffuse terrain scattering is considered in this paper, as specular scattering plays only a minor (usually negligible) role for most terrain types. However, it will be evident that the modeling technique can be extended to include some types of specular scattering surfaces if necessary.

Simulation of radar motion obviously is a formidable problem when the modeling medium is a solid. However, as will be seen, the dynamically changing geometry of the paths from radar to different points on the terrain surface is an all-important aspect of the simulation problem. Therefore, provision must be made to simulate radar motion relative to the scattering surface. Following a discussion of the relationship between radar signal parameters and radar/target geometry, an approach is described for realizing the desired signal characteristics. Next, the scaling relationships to be satisfied in the model to insure 1:1 time and frequency scaling are developed, and the results of an experimental feasibility investigation of the modeling technique are given.

**ECHO SIGNAL PARAMETERS IN RELATION TO TARGET GEOMETRY**

Fig. 1 illustrates the geometrical and terrain factors already mentioned in the introduction that strongly influence the temporal characteristics of ground return signals. The most important of these is the distance $h$ measured from the surface point $A$ vertically below the radar. The simulator must duplicate the propagation time $T_A = (2h/c)$ for microwave energy traveling the distance $2h$ from radar to surface and back. If the radar moves along a path inclined at an angle $\theta$ from the vertical, the rate of change of altitude is $\dot{h} = V \cos \theta$, and the corresponding rate of change of echo time delay is

$$T_A = \frac{2h}{c} = -\frac{2V}{c} \cos \theta. \quad (1)$$

In the case of a short pulse radar, transmission will occur at discrete points along the flight path, as indicated by the numbered points in Fig. 1. Because of the changing propagation delay expressed by (1), successive echoes will be received with different time delays relative to the transmitted pulse. Denoting the pulse-to-pulse change of time delay by $\Delta T_A$ and the radar interpulse period by $T_r$, we have approximately

$$\Delta T_A \cong T_A T_r = -\frac{2VT_r}{c} \cos \theta. \quad (2)$$

Any error in this approximation is negligible provided the change in $\theta$ between pulses remains small compared to one radian, a condition that is almost always satisfied in practice.

It is useful to express this pulse-to-pulse delay change in units of transmitted microwave signal RF period given by $1/f_r$, where $f_r$ is the microwave frequency. In these units, the delay increment has the significance of an incremental
phase change measured in cycles. Calling this $\Delta \phi_A$ we have from (2),
\[ \Delta \phi_A = \frac{\Delta T_A}{(1/f_r)} = \frac{2V}{\lambda_r} T_r \cos \theta_r \text{ (cycles)} \] (3)

where $\lambda_r = c/f_r$ is the radar wavelength.

An expression for the Doppler shift of the received signal in the case of a continuous-wave radar is easily derived from (3) by regarding $T_r$ as an arbitrary observation interval during which phase change of the echo relative to the transmitter is measured. Dividing both sides by this quantity we have for the Doppler shift of the echo from point $A$,
\[ f_d = \frac{\Delta \phi_A}{T_r} = \frac{2V}{\lambda_r} \cos \theta_r. \] (4)

In the preceding discussion, only the signal from a localized echoing object, $A$, immediately below the radar has been considered. In Fig. 2, this signal is represented by the upper waveform trace labeled $A$. But many other points on the ground and within the radar antenna beam can produce echoes that overlap that from point $A$. Signals from typical points $B$ and $C$ also are shown in the figure, slightly displaced in time to correspond to the different distances of these points from the radar. When such overlapping RF pulse waveforms are added, the intensity (power) of the resultant or composite waveform depends strongly on the relative RF phases of the component signals. Since the phases of the component signals are random for the return from ordinary terrain, the intensity of the composite signal is also a random variable. This randomness manifests itself in two ways: 1) in fine structure within a single pulse echo, and 2) in gross fluctuations in pulse shape as the radar moves relative to the terrain.

Both of these forms of randomness are clearly evident in the radar oscilloscope traces published by Edison et al. [5], showing echo signals for near vertical incidence. Echo intensity waveforms representative of their experimental results are shown in the lower part of Fig. 2 (traces 1 and 2). The differences between the traces illustrate the pulse-to-pulse echo waveform changes they observed. Thus, the fluctuation of echo signal intensity about the “average pulse” value, at a given point on the time axis, is a highly random process, and for most terrain types the rms variation is of the order of the mean value itself. This fact has been interpreted as evidence that terrain scattering of microwave signals is predominantly a diffuse scattering process (i.e., specular reflection is negligible) even at vertical incidence [6]. Such a conclusion is plausible because the physical condition for nonspecularity is that the surface irregularities be large compared to the radar wavelength. Most terrain types meet this condition with a few exceptions such as smooth water and very smooth drylake beds. The condition for nonspecularity can easily be satisfied in the acoustic model, as well be discussed more fully later.

In the above calculation of Doppler shift, we dealt only with the point $A$ vertically below the radar. We can easily generalize (4) for other points by noting that only the angle between the radar path and the line of sight to the point in question is important in determining Doppler shift since this angle determines the radar velocity component in the direction of the ground point. Thus, for the signal received from a scatterer at an angle $\theta$ measured from the radar velocity vector, we have for the Doppler shift,
\[ f_d = \frac{2V}{\lambda_r} \cos \theta. \] (5)

The spread of Doppler shifts for scatterers within an antenna beam pattern of angular width $\alpha$ measured in the plane containing the vertical and the radar velocity vector (Fig. 1) is obtained by evaluating (5) at the two edges of the beam and taking the difference of the two Doppler shift values. When the beam axis is vertical, the Doppler spread is
\[ \Delta f_d = \frac{4V}{\lambda_r} \sin \theta_r \left[ \sin \frac{\alpha}{2} \right]. \] (6)

When $\frac{\alpha}{2} \ll 1$ radian, we can write
\[ \Delta f_d \approx \frac{2V \alpha \sin \theta_r}{\lambda_r}. \] (7)

**Simulation Approach and Scaling Considerations**

Because the geometrical factors and relationships just discussed play such an important role in determining the amplitude history of the radar echoes in actual operation, it is essential that the simulation approach chosen should pre-
serve as many of these relationships as possible. Also, it is essential that the simulator duplicate the propagation time delay of the operational case if the device is to have maximum utility as a laboratory tool.

A number of techniques are available for producing variable propagation delay and Doppler shift; but only one of these appeared to lend itself to the simulation of the geometrical factors as well, namely, the use of acoustic waves in liquid or solid media. Further study showed that the choice of media should be limited to crystalline solids, as otherwise, the attenuation of microwave frequency acoustic waves would be excessive for the path length needed to obtain useful delays.

Fig. 3 illustrates the method of radar terrain echo simulation based on acoustic modeling to be considered in this paper. RF pulses from the radar under test are applied to a microwave-frequency piezoelectric transducer which generates an acoustic wave packet in the upper wedge-shaped block, this packet having the same frequency and because of lack of dispersion for acoustic waves, also the same wave shape as the transmitter RF output pulse. The transducer is designed so as to produce a diverging beam that is shaped to correspond to the transmitted beam of the radar. The bottom surface of the lower wedge is roughened to simulate roughness of the ground, and the acoustic wave packet or pulse is scattered from the roughened surface in a manner analogous to the scattering of the RF wave from the ground, as illustrated in Fig. 2 and discussed previously. After being scattered by the rough surface, a portion of the transmitted acoustic energy returns to the transducer where it is reconverted to RF energy and delivered to the radar as a simulated radar echo. In order to duplicate the effects on this signal of radar motion relative to the ground, one of the wedges is moved relative to the other along the diagonal mating surface. To insure good acoustic transmission between the blocks while allowing relative motion, their contacting surfaces are optically flat and bonded by means of a suitable lubricant.

We now determine the relationships that must exist between the parameters of the acoustic model and those of the original radar situation to reproduce the key characteristics of the radar signal treated in the previous section. For this purpose, in the following analysis we designate each parameter or dimension of the acoustic model by means of primed symbols that are otherwise identical to those used for the radar case. We then require identity of each of the corresponding parameters of the received signals.

For echo delay, the identity condition is $T_{d}' = T_d$, and the corresponding parameter requirement is $(h'/c') = (h/c)$, or

$$h' = h \left( \frac{c'}{c} \right).$$  \hspace{1cm} (8)

Since $c$ is determined once the ultrasonic modeling material is chosen, the “altitude” dimension $h'$ of the model is established when the radar altitude is specified.

Similarly, using (1) for rate of change of delay $T_{d}$ and (4) for echo Doppler shift $f_d$, we easily obtain the result $f' = f_d$, which is consistent with our initial implicit assumption that no frequency translation is to be introduced between the radar and the acoustic model.

From (7) for Doppler spread, we obtain

$$\frac{V' \alpha'}{\lambda'} \sin \theta' = \frac{V \alpha}{\lambda} \sin \theta_r.$$  \hspace{1cm} (9)

Combining (9) with (1) simplifies to the condition

$$\frac{\alpha'}{\sin \theta'} = \frac{\cot \theta'}{\cot \theta_r}.$$  \hspace{1cm} (10)

This result shows that the acoustic path angle $\theta'$ need not be made equal to the radar path angle $\theta_r$; provided $\alpha'$ is adjusted relative to $\alpha$ according to (10). However, if we impose the condition $\theta' = \theta_r$, then $\alpha' = \alpha$, and the geometry of the model becomes similar to the radar geometry. When the condition $\theta' = \theta_r$ is used in (1), we obtain as the requirement on acoustic path velocity

$$V' = V \left( \frac{c'}{c} \right).$$  \hspace{1cm} (11)

To indicate the magnitude of the dimensions and path velocities for the acoustic model we consider the case of a radar at $h=1$ km with $V=0.2$ km/s ($\sim 500$ mi/h), $\theta_r=45^\circ$, and a modeling medium with acoustic velocity $c' = 5 \times 10^9$ cm/s. Then according to (8) $h' = 1.67 \times 10^{-2}$ m $= 1.67$ cm, the acoustic delay is $T_{d} = 6.7 \mu$s, and from (11), $V' = 0.33$ cm/s. For $f'_d = 10^9$ Hz (L-band), the acoustic wavelength is $\lambda' = c'/f'_d = 5 \times 10^{-4}$ cm $= 5$ $\mu$m, and the Doppler shift, from (4), is $f'_d = 950$ Hz.

**Experimental Feasibility Investigation**

The purpose of our experimental program was primarily to determine the basic feasibility of microwave acoustic simulation along the lines set forth in the preceding sections. Therefore our investigation was limited to the problems that we anticipated would be the most critical. Foremost among these was the question of signals reproducibility and loss connected with the transmission through a moving bond. Referring to the configuration shown in Fig. 3 and assuming relative motion of the two blocks along the sloping surface, it is not obvious that an acoustic wave of a frequency of interest to us, $\sim 1$ GHz, could make the round trip with small enough degradation to make the scheme practicable.
In order to study this problem, the simplest of all cases, that of plane acoustic waves was chosen. In most of these experiments polished reflecting surfaces were used and 1 GHz pulsed longitudinal-mode acoustic waves (½ μs pulse duration) were generated by plane CdS transducers and propagated in sapphire blocks (at 500 MHz quartz was used). The transducer was placed at the end of a coaxial line and the associated stationary sapphire block was acoustically bonded by a ~1 micrometer thick film of a fairly high viscosity liquid to the other block which was moved back and forth with uniform velocity. The details of device construction and performance have been published elsewhere [7], so we summarize only pertinent results here. Under optimum conditions the round trip bond loss was 20 dB and the overall insertion loss was 53 dB for an instantaneous bandwidth of 7 MHz which was determined by an electrical matching section in the coaxial line. This bond loss was associated with operating conditions which yielded ½–1 dB signal amplitude reproducibility over several thousand cycles without reapplication of fluid. At some sacrifice of signal reproducibility even smaller bond losses were obtained. With a 1 GHz device, variable delays in the 3.7 to 7.2 μs range and Doppler shifts in the 770 to 2600 Hz range were obtained. Experimental Doppler shift values agree very well with those calculated on the basis of (5) for velocities in the range \(V=0.59\) to 2.12 cm/s. These values of delay times, Doppler shifts and velocities are close to those used in the example in the last section.

As expected for longer travel paths and larger delays, the signal was more strongly attenuated, the average signal intensity being near \(-15\) dBm, which in our experiments corresponds to a signal-to-noise of 70 dB for reflections from the polished surface. When the sapphire surface was intentionally roughened by abrading it with diamond paste until it became opaque, the signal was degraded by about 30 dB. While the signal-to-noise ratio observed in our experiments is large, it is far from the ultimately obtainable limit. We have used only a few watts of driving power, whereas pulse power as high as 46 watts has been used [8] without damage to CdS film transducers. More recently, CdS transducers having conversion loss in the 10 to 15 dB range at these frequencies have been tested at pulse power as high as 100 watts without destructive effects which finally were observed at 125 watts [9]. Furthermore, our transducer was relatively inefficient, having as much as 13 dB conversion loss, and thus contributing 26 dB to the total loss. Although a number of authors have reported fabrication of transducers with conversion less than 10 dB at these frequencies, they have not dealt with the question of pulse power handling capability. However, it is reasonable to expect that a good CdS or ZnO transducer having, for example a conversion loss of only a few dB, should be able to withstand pulse powers substantially in excess of those used in our experiments. Thus, the decrease of signal-to-noise ratio which we have observed after roughening the reflecting surface can probably be compensated by employing higher driving power and a more efficient transducer.

Our experiments simulated the situation of a radar moving along a path such that \(\theta_0=45°\). By cutting the matching blocks appropriately, this angle can be changed to any reasonable value that needs to be simulated, without any detrimental effect on signal amplitude.

A quantitative estimate of the effects of beam shaping on signal amplitude, i.e., the effects of an operation involving cylindrical or spherical instead of plane acoustic waves, is made difficult because so much depends on a particular geometry. The treatment is further complicated by mode conversion for reflections at other than normal incidence. The transverse modes thus generated, however, will not interfere significantly with the longitudinal wave signal, since with liquid bonds at these frequencies, the transmission loss is much higher for transverse than for longitudinal waves. As an example of signal loss due to simple geometric beam spreading, and ignoring mode conversion effects, etc., let us consider a convex spherical-film transducer of radius of curvature 12 mm and 4 mm diameter. At the distance of 24 mm from the transducer (corresponding to ~5 μs delay for sapphire-like materials) an acoustic beam of 19° aperture will illuminate an area approximately the same as that of the transducer. Since approximately 10 percent of the reflected power will be intercepted by the transducer, it is clear that this loss will not be prohibitive. Phase randomization due to roughness will undoubtedly degrade the signal, but in a manner not significantly different from that for plane wave reflection by the rough plane surface as described above.

Because of elastic anisotropy, sapphire is not suited for beam shaping simulation experiments and they were not performed. For work of this nature, single crystals of yttrium aluminum garnet appear to be ideal since they are almost isotropic elastically, are available in large sizes, and exhibit low acoustic attenuation at high frequencies. With this material and in view of reasonably good signal reproducibility and signal-to-noise ratio obtained with the plane wave high-frequency acoustic radar simulator, it appears that the simulation of other aspects of radar ground return echoes as discussed above is feasible.

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References