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Soil-Penetrating Synthetic Aperture Radar

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Soil-Penetrating Synthetic Aperture Radar

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Abstract

This report summarizes the results for the first year of a two year Laboratory Directed Research and Development (LDRD) effort. This effort included a system study, preliminary data acquisition, and preliminary algorithm development. The system study determined the optimum frequency and bandwidth, surveyed soil parameters and targets, and defined radar cross section in lossy media. The data acquisition imaged buried objects with a rail-SAR. Algorithm development included a radar echo model, three-dimensional processing, sidelobe optimization, phase history data interpolation, and clutter estimation/cancellation.

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Summary

Synthetic aperture radar (SAR) was proposed as a means for overcoming some of the problems involved in detecting underground targets with radar. SAR has several distinct advantages in such an application. First, to achieve significant resolutions at low frequencies, very long apertures are required. These yield very large processing gains, which help overcome the high soil propagation attenuation. Second, the resulting resolution helps overcome surface clutter, since a buried target need compete only with clutter in the same resolution cell. Finally, SAR provides a means for surveying large apertures rapidly. Mapping rates as high as one square mile per minute have been demonstrated with high frequency SARs.

SAR detection of buried targets still has a number of problems. The greatest problem is overcoming surface clutter. A second problem is RF interference. Maintaining coherence across the aperture and focusing the image are also problems. Finally, the large soil propagation attenuation is still a problem, especially for deep targets, even with the large SAR processing gain.

Surface clutter can be suppressed in a number of ways. First, high resolution helps because the target need compete only with clutter in its resolution cell. However, the practical limit on resolution in both dimensions is thought to be on the order of the wavelength. Second, using a 2D aperture to produce 3D images allows all surface clutter to be excluded from the target's resolution cell. The extent to which this can discriminate against clutter is limited by the sidelobe level of the 3D impulse response. Third, clutter discrimination can be improved to some extent by shaping the sidelobes such that they decrease with increasing distance from the main lobe. Finally, additional bandwidth can be used to estimate the surface clutter, and thereby suppress it. Doing this results in a significant increase in receiver noise, and amounts to trading signal-to-noise (S/N) ratio for signal-to-clutter (S/C) ratio.

RF interference is a significant constraint on performance. The desired frequency range includes a number of powerful commercial sources, as well as several exclusion bands. Interfering sources can be removed by notch filters, but the phase distortion introduced by the filters produces unacceptable degradation of the impulse response. Clutter cancellation loops can also suppress interfering sources, but are not applicable for exclusion bands. Exclusion bands are frequencies dedicated to various emergency uses, and any transmission in them is prohibited. The transmitter can be gated off (assuming a chirp waveform is transmitted) at those frequencies, but the resulting "hole" in the phase history data degrades the impulse response. Techniques for interpolating these holes were investigated, but no satisfactory solution has yet been found. Techniques investigated included orthogonal series (such as the Fourier series) and linear interpolation.

Maintaining coherence across the aperture and focusing the image are related problems. Coherence may be a problem with non-homogeneous soils, which can introduce extraneous phases on a pulse-to-pulse basis. Focusing will require compensating for dispersion in the antenna and in soil propagation. Antenna dispersion can be measured

and corrected. Although it could be corrected in the data processing, it may be easier to correct it with the frequency generator. Ground dispersion is another problem. Partial correction may be possible in the data processing if something is known about the soil properties. Auto focus may be able to correct residual dispersion. Auto focus is a one-dimensional correction. If the phase error varies only from pulse to pulse, then auto focus can take advantage of the redundancy in range to estimate and eliminate it. Auto focus then works best with a homogeneous soil, a smooth surface, and a relatively constant aspect angle over the map.

The general conclusion so far is that SAR helps a great deal, but for deep, underground facilities (10 to 50 m), SAR still has serious problems. It will be necessary to use every possible means to suppress surface clutter, and any possible collateral information should be exploited. The second year of the LDRD should then evaluate the net effect of using all known techniques, and should look for any possible "Achilles' heels" that might reveal the existence of deep structures. One possible Achilles' heel, called time domain reflectometry, was identified in the first year, and will be considered in the second.

Introduction

Burial is an effective and simple way to hide proliferation activities and equipment from either overhead or on-site observation. Current ability to detect buried objects is very limited, and there is a need for enhanced capabilities for subsurface object detection and location. A two-year laboratory directed R & D (LDRD) effort was funded to investigate application of synthetic aperture radar (SAR) to this problem. This report summarizes the first year's results and gives an overview tying them together. Recommendations for second year efforts are also given.

Ordinary ground penetrating radar (GPR) has typically produced marginal results, even under favorable conditions. Combining GPR with SAR provides a major increase in performance:

1. SAR can cover more (up to three orders of magnitude) area per unit time than a GPR because of higher aircraft velocity and wider swath width.
2. SAR provides a large processing gain (on the order of ten to the eighth to ten to the tenth) needed to overcome attenuation in the soil and to increase penetration depths (by ten to twelve skin depths).
3. SAR provides an important reduction in surface clutter by using an acute depression angle and by providing high ground resolution. The acute depression angle also makes it possible to form images from multiple azimuth angles.
4. SAR provides the two-dimensional resolution needed to do object identification and to make accurate measurements. It is also possible to do three-dimensional imaging with multiple passes.

The objective of this effort changed somewhat during the first year as a result of the findings of the Geophysical Underground Structure Team (GUST). GUST was a multi-laboratory team established by DOE NN-20 (then IS-20) to study DOE's role in the

detection of underground structures. They recommended that DOE efforts be directed toward objects at depths of 10 to 50 m. This was to avoid duplication of effort, since other agencies had efforts to detect objects at shallower depths. It was also thought that significant nonproliferation targets would probably be at these depths.

There were three first-year tasks. The first was a system study to determine targets, SAR parameters, and soil parameters. The second task was a preliminary data acquisition using a rail SAR. The third involved development of concepts and processing, including preliminary algorithm development. This included image-formation algorithms, target radar cross sections, and surface backscattering coefficients.

System Study

The system study considered overall system design and performed various parametric studies and optimizations. Soil parameters were tabulated and optimizations were performed for frequency and bandwidth.

Optimum Frequency

The appropriate criteria for selecting the SAR frequency is maximization of the signal-to-clutter ratio (S/C). Surface returns are not attenuated by soil propagation and tend to mask returns from buried objects. Large attenuation due to large depths also creates a signal-to-noise ratio (S/N) problem. However, preliminary calculations indicate that S/C is the more difficult problem, because processing gain only discriminates against receiver noise, not against surface returns. Thus it is easier to suppress receiver noise than to suppress surface returns, and S/C ultimately constrains performance.

The optimization started with a simple, "back-of-the-envelope" analysis to determine the qualitative frequency dependence of S/C [1]. This was followed by a more comprehensive and detailed model of soil properties, random-surface scattering, and canonical targets.

A simple, closed-form model was developed by noting that S/C is proportional to the ratio of the target radar cross section to the surface backscattering coefficient, multiplied by a two-way loss factor for propagation in the soil. The radar cross section was taken to be proportional to frequency to the "n" power, where n depends on the generic target type, or

- $n = 0$ for doubly-curved surfaces ($a > \lambda$)
- $n = 1$ for singly-curved surfaces ($a > \lambda$)
- $n = 2$ for flat surfaces ($a > \lambda$)
- $n = 4$ for Rayleigh objects ($a < \lambda$)

where a is a characteristic dimension of the object, and λ is the wavelength in the soil. The backscattering coefficient of the soil is proportional to frequency to the "m" power, where it is thought that m is between 0 and 2. The two-way loss factor (L) is

$$L = e^{-4\alpha fd}$$

where d is the one-way distance the signal travels in the ground and

$$\alpha = -Im \left\{ \frac{2\pi\sqrt{\epsilon_r}}{c} \right\}$$

and where ϵ_r is the soil's relative dielectric constant and c is the speed of light in a vacuum. Combining the above factors and taking a partial derivative with respect to frequency gives

$$f_{opt} \approx \frac{n-m+2}{4\alpha d}$$

Thus an optimum frequency can be expected to exist which depends on soil attenuation, surface roughness, and target type. For example, a small (Rayleigh) target 5 m deep in dry sand ($\epsilon_r \approx 2.5 - i 0.03$) has an optimum frequency of about 1 GHz for $m = 2$. The optimum becomes 100 MHz if the depth is 50 m. In a more lossy, wet soil with $\epsilon_r = 5 - i 5$, the same object at 1 m has an optimum frequency of 47 MHz.

The details of the comprehensive model are in a published paper [1] and will only be summarized here.

Soil properties were modeled with a mathematical model based on the Debye equation, which incorporates the physics of the dipole/electric field interaction and contains parameters which can be adjusted to fit to measured data. Measured data for several soil types were included. Figure 1 shows the real and imaginary parts of the relative dielectric constant. The gray San Antonio clay loam is an ionic soil that becomes very lossy when wet. The sample with 20% water by weight is a worst case, and the 5% water sample is probably a more typical soil.

The backscattering coefficient was modeled as a function of the standard deviation and the correlation length of the surface-height (roughness), both measured in wavelengths. Three different models were used, depending on the roughness standard deviation. They were the Kirchoff scalar approximation, the Kirchoff stationary-phase approximation, and the small perturbation model.

Targets were modeled using spheres, cylinders, and flat plates. They were based on free-space radar cross sections, but with the wavelength scaled for the soil's dielectric constant. The cross section for a conducting sphere is given by the well-known Mie series. The cylinder model was based on the exact solution for the scattering width of an infinite-length cylinder, with the length used to compute total cross section. The flat plate model was based on low-frequency and high-frequency models with a mid-frequency curve fit to join the two models.

Figure 1. Dielectric constant as a function of frequency for representative soils.

The transmission loss from air to soil and back again at the air-soil interface, exclusive of other losses, is called the two-way transmission loss. It is a function of polarization, soil type, angle of incidence, and frequency. Vertical polarization offers some advantage for large incident angles because of the Brewster angle effect.

Calculations were made for several soil-target types. Figure 2 gives S/C for small conducting spheres in dry sand and the San Antonio clay loam. Although an optimum frequency is not seen in the frequency range plotted, good performance occurs above a few hundred MHz. Figure 3 gives S/C for two surface-roughness conditions for a 100 m long, 0.5 m diameter cylinder 3 m deep in San Antonio clay loam with 5% moisture content. The optimum frequency is about 200 MHz with the rougher surface and about 40 MHz for the smoother surface. Figure 4 gives S/C for a flat plate dihedral with a 30 m² area, buried 1 m deep, for different water contents. The polarization is vertical and the clutter model is for a gentle, random surface.

Figure 2. Signal-to-clutter ratio for two spheres

Figure 3. Signal-to-clutter ratio for a cylinder

Figure 4. Signal-to-clutter ratio for a flat plate

For most situations examined in this study, the optimum frequency lies in the VHF and UHF regions, although situations can be found where lower frequencies are better. For small incidence angles, the lower frequencies (HF and low VHF) are better, but because backscattering drops with incidence angle, larger angles ($> 40^\circ$) provide better performance at the upper VHF and UHF bands. As predicted by the simple model, the optimum frequency is higher for Rayleigh objects than for flat-plates, which in turn have a higher optimum frequency than cylinders. Also, as predicted, optimum frequency decreases as loss increases and as the object's depth increases.

Thus there is no single frequency that is optimal for all situations. A SAR with a selectable frequency would offer the potential to optimize its performance for a given mission.

Optimum Bandwidth

The strong frequency dependence of soil attenuation and dispersion restricts the amount of bandwidth that can be used. The soil, in effect, acts like a low pass filter, and SAR bandwidths greater than the "filter" bandwidth waste energy. Bandwidths less than the "filter" bandwidth unnecessarily restrict range resolution, and degrade the S/C ratio. Thus there is an optimum bandwidth if the total transmitted energy is fixed.

The soil's impulse response was used to measure soil response. Figures 5 and 6 give the 3-dB and 10-dB widths of the impulse response for dry sand and San Antonio clay loam with 5% water, respectively, as a function of depth.

Figure 5. Dry sand impulse response

One would expect the optimum bandwidth to be on the order of the reciprocal of the 3-dB width of the impulse response. This should maximize the received S/N ratio. However, since S/C is of more interest, larger bandwidths are probably better.

Figure 6. San Antonio clay loam impulse response (5% water content)

Targets

The targets of interest changed somewhat during the first year as a result of the findings of the Geophysical Underground Structure Team (GUST). GUST was a multi-laboratory team established by DOE NN-20 (then IS-20) to study DOE's role in the detection of underground structures. They recommended that efforts be directed toward objects at depths of 10 to 50 m. This was to avoid duplication of effort, because other agencies had efforts to detect objects at shallower depths. It was also thought that significant nonproliferation targets would probably be at these depths.

The targets of interest are therefore either manned facilities or storage facilities at depths of 10 to 50 m, with manned facilities being the more important and, possibly, the more likely target. Secondary targets at smaller depths which can provide collateral information to support the facility identification are also of interest. Possibilities include identification of buried pipes or power lines which feed the facility and identification of elevator shafts or access tunnels.

Soil Parameter Survey

The properties for a number of soils at 100 MHz are given in the following table [2]. Properties vary greatly, even for a given soil type, due to differences in impurities and moisture content. Thus all figures are approximate. The two-way loss per meter assumes a relative permeability of one.

Table 1. Soil Electromagnetic Properties

<u>Material</u>	<u>Real ϵ</u>	<u>σ (mho/m)</u>	<u>-Imag ϵ</u>	<u>Loss (dB/m)</u>
Air	1	0	0	0
Freshwater	81	10^{-4} to 3×10^{-2}	0.018 to 5.39	0.037 to 11
Seawater	81	4	719	653
Freshwater Ice	4	10^{-5} to 10^{-3}	0.0018 to 0.18	0.018 to 1.8
Limestone (dry)	7	10^{-9}	1.8×10^{-7}	1.3×10^{-6}
Granite (dry)	5	10^{-8}	1.8×10^{-6}	1.6×10^{-5}
Bedded Salt	3 to 6	10^{-5} to 10^{-4}	0.0018 to 0.018	0.014 to 0.21
Permafrost	4 to 8	10^{-4} to 10^{-2}	0.018 to 1.8	0.12 to 18
Sand (dry)	4 to 6	10^{-7} to 10^{-3}	1.8×10^{-5} to 0.18	1.4×10^{-4} to 1.8
Sand (water saturated)	30	10^{-4} to 10^{-2}	0.018 to 1.8	0.06 to 6
Silt (water saturated)	10	10^{-3} to 10^{-2}	0.18 to 1.8	1.1 to 11
Rich Agricultural Land	15	10^{-2}	1.8	8.7
Clay (water saturated)	8 to 12	10^{-2} to 1	1.8 to 180	9.7 to 338
San Antonio Clay Loam (5% water)	5.2	0.011	2	17
San Antonio Clay Loam (10% water)	14.5	0.061	11	51
San Antonio Clay Loam (20% water)	29	0.167	30	93

Radar Cross Section in Lossy Media

Radar cross section is defined in the context of the radar range equation. It is a proportionality constant between the incident power density at the object and the power which would have to be radiated from an isotropic radiator to produce the same power density at the receiver. In extending radar cross section to buried targets, a similar definition is desired. This is complicated somewhat by the interaction with the surface, which causes the cross section to be a function of depth. If this interaction is ignored, as when the object is buried deeply, then cross section is independent of depth and has basically the same meaning as in free space. This was assumed, as was plane wave illumination. The wave in the soil is plane wave only at vertical incidence, but is approximately so for non-vertical incidence because refraction bends the incident wave downward. A third problem, especially for large objects, is defining its burial depth, and hence the soil propagation loss. This is resolved here by defining soil path length as that from the surface to the dominant specular scattering point on the object.

The radar cross section is then defined by referencing the incident-illumination power density to the dominant specular point on the object and factoring the soil propagation loss from the cross section. This loss is then included in the radar range equation as a separate factor. The radar cross section is then defined by [3]

$$\sigma_{\mu\epsilon} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{|e^{Im(k) \cdot (R-a)} \vec{E}_s|^2}{|e^{Im(k) \cdot a}|^2}$$

where a is the distance from the coordinate-system origin, typically located within the object, to the dominant specular point.

Unfortunately, the above definition is very difficult to evaluate except for simple geometries. It has been applied to a metallic sphere, flat plates, and cylinders, and could be extended to other simple geometries. This study showed that the free space cross sections scaled by the wavelength in soil are reasonable approximations for buried objects [3].

Preliminary Data Acquisition

A rail-SAR test was performed to provide preliminary data to guide the LDRD. The objectives of this test were to (1) explore ground-penetration phenomenology, (2) measure pertinent parameters, and (3) evaluate SAR ground-penetration capability. A low-frequency rail-mounted SAR developed by MIT was used to collect the data. Identical test objects were buried in two soil types (native soil and dry sand), and SAR data were taken and processed.

The rail-SAR system was provided by Dennis Blejer of MIT. This system can transmit up to 801 equally spaced frequencies (across the selected band) at a peak power of 100 mW. The maximum depression angle is 30 degrees. The maximum usable rail length is 8.4 m, and the maximum height is 12 m. Two antennas were used, one horizontally polarized and the other vertically polarized. Measurements with both linear polarizations (HH and VV) and with cross polarization (HV and VH) are possible. Each antenna has a beamwidth of approximately 100 degrees and covers the entire test frequency range. Data was taken at 401 equally-spaced frequencies over the range from 50 to 1050 MHz. This missed the four exclusion bands (73.0-74.5, 121.4-121.6, 156.7-156.9, and 242.8-243.2 MHz) in this range.

The test imaged two areas with targets buried in disturbed soil. The targets consisted of pipes, barrels (55 gallon drums), and corner reflectors. Two 15 m x 15 m x 2 m deep pits were dug. One was refilled with native soil and a wedge-shaped berm was placed on it using soil from the other pit. Targets were buried at the desired depths in the berm as it was built. The other pit was filled and bermed with sand in the same manner. Each pit had the same matrix of targets, arranged in three rows. The row nearest the SAR had a 2 inch diameter by 13 m long horizontal metal pipe 0.5 m below the surface. The next (middle) row had a plastic barrel, a metal barrel, and a 1 m triangular corner reflector, each with their tops just below the surface. The next (farthest) row had two metal barrels, one with its top 0.5 m below the surface, and the other with its top 1 m below the surface in native soil and 1.5 m in sand. All barrels were horizontal. Above-ground corner reflectors were also placed over the test objects on some tests to provide calibration in amplitude and location.

Measurements were taken at the maximum antenna height (12 m) and then repeated at different heights to simulate a two-dimensional aperture. The spacing in height was constrained primarily by system clutter (antenna ringing), with nominal values being about 25 cm. Both HH and VV polarization data were taken. Cross-polarization data (HV and VH) were also taken for selected configurations.

The results were somewhat disappointing. The only object seen in the native soil was the metal barrel near the surface (its top was about an inch below the surface). This barrel, the one buried 0.5 m, and the corner reflector were the only objects seen in the sand. The effective depth of the corner reflector (depth to its effective scattering point) was about a meter. Neither the pipe, the plastic barrel, nor the deepest barrel could be seen in either soil type. Three-dimensional processing did not change this outcome. This implies that the improvement with three-dimensional processing was not enough to reveal any other targets.

It should be noted, however, that the bandwidth for these tests was much more than the optimum for these soils. Thus much of the radiated energy was so severely attenuated in the soil as to be useless. Decreasing the bandwidth while keeping the total transmitted power constant may improve results.

Preliminary Algorithm Development

Radar Echo Model

The first step in algorithm development is to derive an expression for the phase history as a function of position in the scene [2]. The first step in doing this is to derive an expression for echo delay time (τ), which is

$$\tau \approx \frac{2}{c} \left[\|R\| + Re \left(d\eta \sqrt{1 - \left(\frac{\cos \Psi}{\eta} \right)^2} \right) \right]$$

where R is the slant range, η is the soil's complex refractive index, and ψ is the depression angle. Since η is a function of frequency, τ is a function of frequency. A frequency-dependent time delay is identified as dispersion. This is illustrated in Figure 7, which plots effective range versus frequency for San Antonio clay loam with 5% water content. The same derivation also yields the power attenuation in the soil as

$$G \approx \exp \left[\frac{4\omega}{c} Im \left(d\eta \sqrt{1 - \left(\cos \frac{\Psi}{\eta} \right)^2} \right) \right]$$

where d is the target's depth. The expression for time delay also leads to the following expression for phase history:

$$\frac{2(\omega + \Delta\omega)}{c} \left[((\sin\psi) \Delta\psi + \cos\psi) (s_x \Delta\alpha - s_y) + (d - s_d) \eta \left(1 - \frac{\cos^2\psi}{2\|\eta\|^2} \right) \right]$$

Figure 7. Effective Radar Range.

where

$$\Delta\omega = \gamma(t - \tau_o)$$

where γ is the chirp rate and τ_o is a time offset for the local oscillator, and

ψ = depression angel to the central reference point (CRP)

α = azimuth angel to the CRP

$\psi + \Delta\psi$ = depression angel to the target

$\alpha + \Delta\alpha$ = azimuth angel to the target

(s_x, s_y, s_d) = vector from CRP to the target

d = focal point depth

and where x and y are the along-track and cross-track directions, respectively.

Thus, if $d = s_d$, apertures in aspect angle (azimuth) resolve in the y dimension and apertures in frequency (ω) resolve in the x (range) dimension. Also note that the refraction index scales only the depth dimension, so that buried objects will appear at greater depths, but at the correct x,y location. This also means that resolution in the x and y dimensions are primarily unaffected by target depth or soil dielectric properties.

Three-Dimensional Processing

The above model also demonstrates that, if a two-dimensional aperture is used, then all three dimensions can be resolved. In this case, aspect angle still resolves in the x dimension, but now apertures in depression angle (the second dimension of the 2D aperture) resolve in the y dimension and apertures in frequency resolve in depth. Thus the three dimensions are approximately independent, and can be processed independently.

Three-dimensional processing was illustrated by computing a number of 3D impulse responses (IPRs) [2]. As expected, the 3D-IPR has sidelobes in all three dimensions. Of these, sidelobes in the depth dimension is considered to be more serious.

Sidelobe Optimization

Sidelobes of surface or shallow targets can overshadow the mainlobes of deeper targets. However, typical window functions are real, and hence yield even IPRs. For our purposes, it would be better to have lower sidelobes in the "down" direction, even though this means increasing sidelobes elsewhere (the total volume under the IPR is constant). Also, since there is a limit to how deeply targets can be detected (the depth horizon), there is nothing to be gained by suppressing sidelobes below that depth. Thus the ideal sidelobe shape would exhibit an exponential taper (matched to propagation loss in the soil) in the down direction as far as the depth horizon. A buried target with a radar cross section equal to the surface clutter cross section would then not be obscured by the clutter sidelobes, regardless of the target's depth.

The window function which produces this sidelobe structure was named the "loss-compensated" window function. It is, of necessity, complex, and can be thought of as a digital filter ($\mathbf{w}$) operating on the input data ($\mathbf{x}$) to produce the desired output (y), or

$$y = \mathbf{w}^T \mathbf{x}$$

where the T denotes the transpose. The filter was found by a mean-squared-error fit to a specification. First, a set of L normalized (between zero and one) frequencies $\{f_i\}$ were selected. For each frequency, a gain d_i and a phase ϕ_i were specified. A cost c_i was also specified that indicated the relative desire for meeting the gain and phase specifications. The c's were empirically determined in an iterative procedure to achieve the desired result. The result of the optimization yields

$$\mathbf{w} = \mathbf{a} + j\mathbf{b}$$

where

$$\mathbf{b} = j [(\mathbf{R} + \mathbf{R}^T) - (\mathbf{R} - \mathbf{R}^T)(\mathbf{R} + \mathbf{R}^T)^{-1}(\mathbf{R} - \mathbf{R}^T)]^{-1} [(\mathbf{P} - \mathbf{P}^C) - (\mathbf{R} - \mathbf{R}^T)(\mathbf{R} + \mathbf{R}^T)(\mathbf{P} - \mathbf{P}^C)]$$

$$\mathbf{a} = (\mathbf{R} + \mathbf{R}^T) [(\mathbf{P} + \mathbf{P}^C) + j(\mathbf{R} - \mathbf{R}^T)\mathbf{b}]$$

and where C denotes complex conjugate, $\mathbf{R}$ is the $n \times n$ cross-covariance matrix, and $\mathbf{P}$ is the $n \times 1$ auto-covariance vector. The elements of $\mathbf{R}$ are given by

$$r_{i,k} = \sum_{l=1}^L c_l^2 \exp [j2\pi f_l (k-i)]$$

and the elements of $\mathbf{P}$ are

$$p_i = \sum_{l=1}^L d_l c_l^2 \exp [-j(2\pi f_l i + \phi_l)]$$

Phase History Data Interpolation

A major problem with low-frequency SAR is the existence of exclusion bands and RF interference in the SAR bandwidth. Exclusion bands can be avoided with chirp signals by gating off the transmitted signal as it sweeps through the bands. Notch filters can be used to remove interference, but add extraneous phases. Both approaches result in "holes" in the phase history data (PHD), i.e., periods of time in which the return from a given range is missing. The PHD holes will degrade the impulse function. Cancellation loops can remove interference without creating holes, but can do nothing for exclusion bands. A study was conducted to determine if the impulse degradation due to holes could be mitigated by interpolating the PHD data.

The effect of PHD holes on the impulse response was taken to be the 20-dB width of the main lobe and the minimum peak-to-sidelobe ratio. The 20-dB width was found to not be greatly affected by holes and, in general, to decrease as hole width increased. This is a result of the hole transferring some of the main-lobe energy to the sidelobes. The most sensitive effect of holes is then peak-to-sidelobe ratio. Typical results are given in Figure 8 for a Taylor 35 dB weighting with $n\text{-bar} = 4$ and for a data length of 2048 samples. (The points plotted are for widths of 8, 16, 32, 64, 128, 256, and 512 samples.) The hole was located in the center of the phase history data, where the weighting caused it to have the greatest effect. It is evident that holes much wider than eight samples give unacceptable degradation of the impulse response.

Three approaches for filling the holes were tried:

The simplest approach for filling the hole is to just insert another part of the data. The result is that the impulse response is inevitably made worse. The spliced data adds degradation of its own without removing that resulting from the hole. Thus more sophisticated approaches are necessary.

Figure 8. Effect of phase history holes on the impulse response.

The second approach used the higher frequency terms of a Fourier series to approximate the missing data. Minimal improvement (less than one dB) was obtained.

The third approach used a linear-prediction-coefficient estimator. The data points are predicted one at a time using the prediction equation

$$S_n = \sum_{i=1}^p a_i S_{n-i}$$

where p is the number of coefficients in the prediction and the a 's are complex coefficients selected to minimize the mean-square-error (mse). The phase history data is used to find a set of coefficients, and then the above equation is used to calculate an estimated data set, one point at a time. The interpolation worked very well for the first point (the one for which the optimization is made). However, the interpolation error grows very rapidly beyond that point. The resulting effect on peak-to-sidelobe ratio is again minimal (less than one dB), probably because only the first one or two points are valid. The rapid growth of the interpolation error (in spite of the small error in the first point) results from the calculated coefficients (a 's) being larger than one. This implies that the interpolation contains terms that nearly cancel, which in turn increases sensitivity to errors.

This leaves us without a satisfactory way to interpolate holes. It will be difficult to achieve enough bandwidth without overlapping exclusion bands. Unless an interpolation technique can be found, exclusion bands will place a severe constraint on sidelobe level.

Clutter Estimation

Another approach for suppressing clutter is to use more bandwidth than is needed to form the image and to use the additional information to estimate the clutter so it can be cancelled. This takes advantage of the frequency dependence of propagation in the ground. This dependence restricts the amount of bandwidth that can be used for imaging underground targets, but it also means that returns for higher frequencies come essentially from only the surface, and not from sub-surface targets. Having an image that contains only surface returns makes it possible to at least partially cancel clutter in the sub-surface image.

The technique investigated here uses twice the bandwidth usable for forming the image. Two images are then formed, one from each half of the bandwidth. The image from the lower half of the bandwidth will contain both surface and sub-surface returns; that from the upper half of the bandwidth will have very little sub-surface return. It is anticipated that bandwidths on the order of ten percent will be used for each half. It is then reasonable to assume that the statistics for the surface clutter in the two images are the same. If the bandwidths do not overlap, the clutter in the two images can also be assumed to be statistically independent. Finally, it is assumed that the surface clutter magnitude is Rayleigh distributed. Then simply subtracting the image magnitudes gives a residual clutter with a zero mean. This reduces the mean square magnitude from

$$2 \alpha^2$$

to

$$\alpha^2 (4 - \pi)$$

where α is the Rayleigh parameter. This is an improvement of 3.7 dB. The price paid for this improvement is increasing the computational requirements by essentially a factor of two (since two images must be formed) and reducing the signal to receiver noise ratio (S/N) by 6 dB. The reduction in S/N results from the same transmitter energy being spread over twice the bandwidth and from the noise powers increasing by 3 dB when the images are subtracted.

It is also possible to further suppress clutter by repeating the above process and integrating the results. Assume that a sequence of n pulses is transmitted and received, each being the superposition of two chirps, one covering the lower bandwidth (for imaging sub-surface targets) and the other covering an equal bandwidth at a higher frequency. Further assume that there is no overlap in the upper bandwidths for the n pulses. Finally, assume that the sub-surface returns in the lower bandwidth are highly correlated over the n pulses. Then repeating the above process for each pulse (forming two images and taking the difference in their magnitudes) and integrating the results over the n pulses will increase the power signal-to-clutter ratio (S/C) by n . This is an additional improvement of $10 \log n$ dB. This also further increases the computational requirements by a factor of n . If this process is done instead of a pulse presuming, then the loss in the power signal-to-noise ratio (S/N) is only $10 \log n$ dB. The overall gain in S/C is thus

$$3.7 + 10 \log n \text{ dB}$$

the overall loss in S/N is

$$10 \log (2n)$$

and the increase in computational requirements is a factor of $2n$. In effect, there is almost a dB-for-dB tradeoff between S/C and S/N. This severely limits the extent to which clutter can be suppressed with this technique. However, in some situations, improvements on the order of 10 to 15 dB may be reasonable.

Recommendations

The recommendation of the Geophysical Underground Structure Team (GUST) that DOE efforts be restricted to targets buried from 10 to 50 meters greatly complicates the problem and dictates that all possible options be considered in the second year. The objective for the second year should be to establish as firmly as possible whether soil penetrating SAR holds any promise for such depths.

Not only should all possible options be considered, but second year efforts should also look for any "Achilles' heels" that might be exploited. One possible Achilles' heel was identified in the first year. It involves using pipes and/or power lines attached to deeply buried facilities to conduct energy to and from the facility with greatly reduced loss. Energy would be induced into the pipes before they turn down toward the facility, would propagate down them to the facility, would reflect off the facility, and then would propagate back to the surface, where it would re-radiate. The reflected energy would be identified using a technique called "time-domain reflectometry."

The Doppler history of the reflected return will be the same as the surface return where the signal entered the ground, but its range will be larger. Thus its Doppler history will be different from surface returns at its range. Also, the azimuth depth-of-focus can be made comparable to the range resolution by making the azimuth resolution fine enough (about half a wavelength). Then Doppler history provides a second way to discriminate in range. The return signal would be processed first for range. Then a set of images would be formed by processing the returns from each range with a set of Doppler histories that focus at different ranges. Finally, the returns would be processed to resolve in azimuth. Any signals from ranges other than that corresponding to the surface would be taken as an indication of a buried facility. Since it should be possible to also image the pipes or wires that serve as the signal pickup, they could be used as further confirmation.

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