

## Basic Principles of Seismic Sonar for Buried Mine Detection

**Dr. Thomas G. Muir**

University of Mississippi  
National Center for Physical Acoustics  
Humanitarian De-Mining Institute  
One Coliseum Drive  
University, Mississippi, 38677  
U.S.A.

**Dr. Steven R. Baker**

U.S. Naval Postgraduate School  
Department of Physics, Code Ph  
Monterey, California, 93943  
U.S.A.

[tmuir@olemiss.edu](mailto:tmuir@olemiss.edu) / [srbaker@nps.navy.mil](mailto:srbaker@nps.navy.mil)

### **ABSTRACT**

*The study of seismic interface waves, conducted by the senior author and others at NATO's SACLANTCEN, over the past 30 years, has continued at the University of Texas, the U.S. Naval Postgraduate School, and now; the University of Mississippi, and the Ecole Navale (French Naval Academy), all focusing on the problem of detecting objects buried in soils and sediments. The present paper reviews the physics of what has been learned, in both theory and experiment. Utilizing exploratory measurements to guide the way, it has been possible to formulate a seismic sonar equation, which is similar to the sonar and radar equations, yet quite different. The principles of seismic interface wave propagation have been confirmed and extended to practical matters, including spreading and attenuation in soils and sediments. The principles of target strength for seismic sonar have been established, and some of the major mechanisms have been identified and confirmed, theoretically and experimentally, while others remain to be discovered. Due to the imperfect nature of interface wave generation, and due to the presence of in-homogeneities and false targets in soils and sediments, it has been necessary to develop signal processing methods, to make targets recognizable and enable positive recognition of real targets. These methods have, of necessity, become part of the seismic sonar equation, because they involve the basic vector nature of the propagating seismic interface wave field. This equation is demonstrated by comparison to experiments.*

### **1.0 INTRODUCTION**

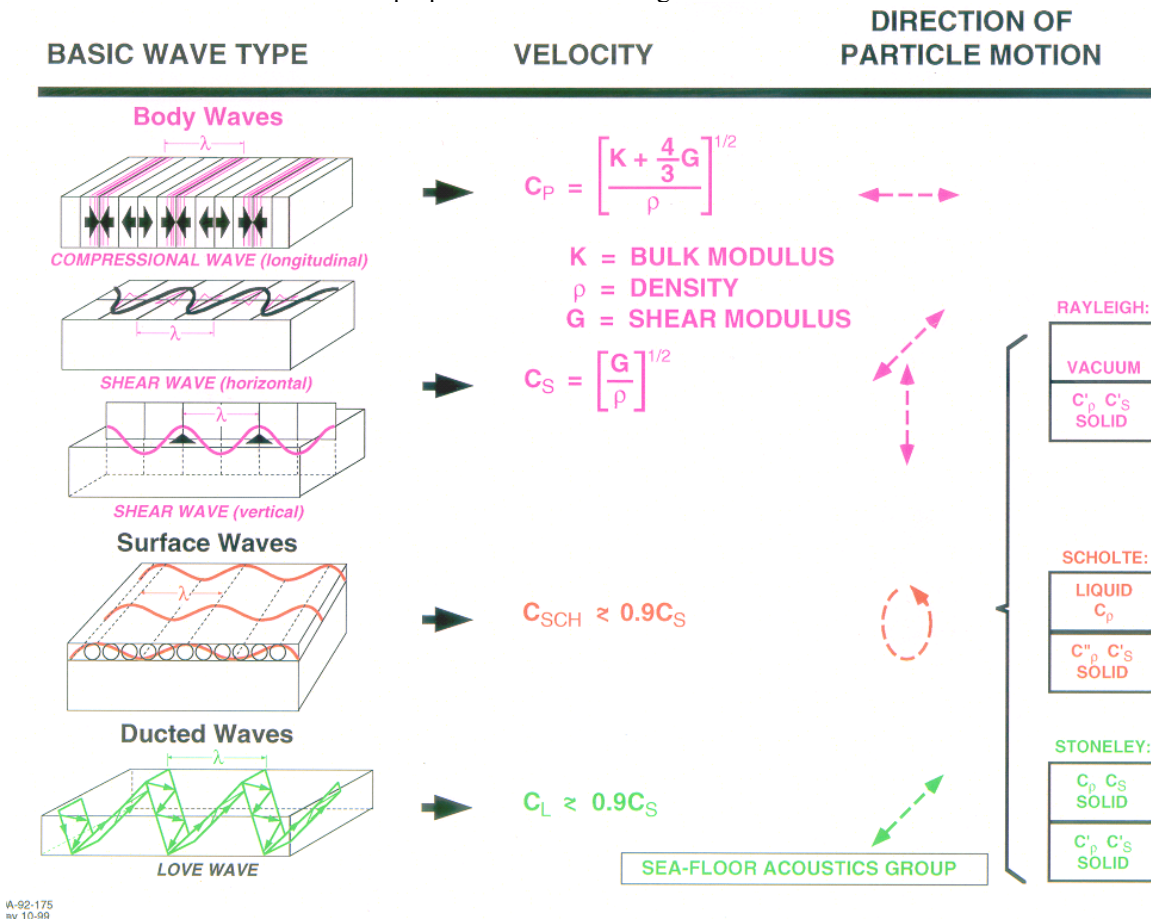
This paper seeks to review the physics of Rayleigh waves and the concept of seismic interface wave sonar; culminating in the development of a new seismic sonar equation, which can be used to isolate the important terms for both further study and eventually, for performance prediction.

*Paper presented at the RTO SET Symposium on "Capabilities of Acoustics in Air-Ground and Maritime Reconnaissance, Target Classification and Identification", held in Lercici, Italy, 26-28 April 2004, and published in RTO-MP-SET-079.*

**Basic Principles of Seismic Sonar for Buried Mine Detection**

**1.1 Review of Seismic Interface waves**

Seismic interface waves have long been a topic of study at SACLANTCEN (now, NATO URC), primarily to determine sea floor properties in support of naval sonar. They consist of wave types named after their discoverers; Rayleigh, Sholte, Stonely, Love, Lamb, etc. Theoretically, they involve the solution of the elastic (rather than the fluid) wave equation. A time-honored sketch of their properties is shown in Fig. 1.



**Fig. 1. Some Interface Wave Types Near Boundaries of Elastic Media**

Body waves in infinite media can be either compressional or shear, or both. The compressional waves travel with their particle velocities co-linear with their propagation vectors, but the shear waves can be polarized with perpendicular particle velocities (i.e. horizontal or vertical). Wave propagation velocities depend on the bulk and shear moduli, as shown. When there are boundaries between solids and fluids (as shown in the sketch), the solutions of the elastic wave equation; with the proper boundary conditions, lead to interface waves. Three well known, environmental surface waves are shown; the Rayleigh, Sholte and Stoneley types, and these have particle velocities, uniquely polarized in elliptical orbits. There are many more types, including the horizontally polarized Love waves (also shown), which travel in low velocity ducts. In Arctic ice, there are Lamb waves, and the floating sheets of ice undulate. There are also unique surface waves on munitions, both in the atmosphere (missiles and projectiles) and in the sea (torpedoes and insonified mines), as well as on buried landmines, which also resonate in plate and ring modes. There are also the myriad perturbations, all depending on the boundary conditions, that give rise to refracted and reflected compressional and shear waves. The surficial Rayleigh wave in soils or sediments has one of the slowest propagation velocities of them all, and this offers a unique utility, as its pulsed signals can often be separated from the other wave types in the time domain.

## 1.2 Review of Rayleigh Wave Physics

We begin with the results of solutions of the elastic wave equation (see, for example Ref. 1), which although strictly valid for an isotropic half space, have been used to guide seismic sonar research for landmine detection<sup>2-14</sup>. Here, the Rayleigh wave (see Fig. 2.), is characterized by 1) propagation along the soil/sediment or air/water boundary with cylindrical spreading in range ( $\sim 1/\sqrt{R}$ ), as well as (generally exponentially) decaying amplitude with increasing soil depth, 2) elliptical soil particle motion in the vertical (depth-range) plane, 3) continuity of the vertical particle displacement ( $U$ ) at the interface, passing through a maximum with depth, 4) discontinuity of the horizontal particle displacement ( $W$ ) at the interface, decaying and passing through zero, and increasing through an amplitude peak at a larger depth, only to decay exponentially with greater depth, 5) no low frequency cut-off, and 6) a propagation velocity very close ( $\sim 0.9$ ) to the bulk shear velocity in the soil/sediment. At the interface and just beneath it, the motion of the soil/sediment particles in the vertical plane is retrograde (counterclockwise), as shown. With increasing depth, and after the horizontal displacement passes through its first zero, the elliptical motion becomes prograde (clockwise).

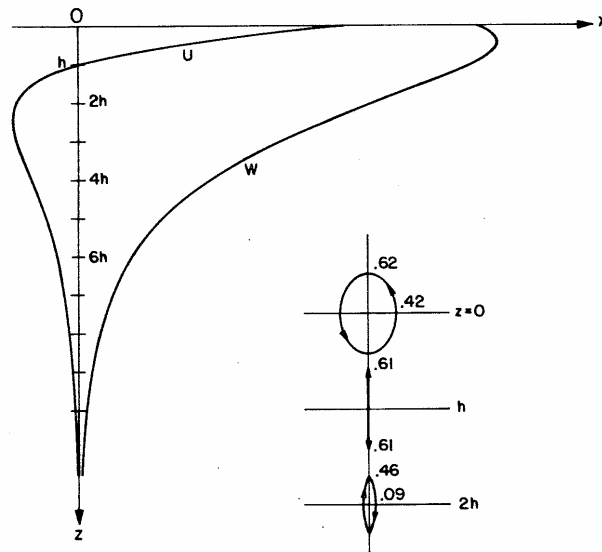


Fig. 2. Depth Dependence on Displacement Amplitude and Particle Motion (from Ref. 1)

The parameter  $h$ , depends on the Poisson ratio of the soil or sediment and is typically  $h \sim 0.1\lambda$ , where  $\lambda$  is the Rayleigh wavelength (after ref. 1). The range parameter  $R$  is either along or parallel to the  $x$  axis.

Attenuation of Rayleigh waves in wet, sandy beach sediments can be remarkably low. At frequencies around 100 Hz, with typical wave velocities of 100 m/sec, it is only about 0.13 dB ( $\sim 0.15\%$ ) per wavelength of travel<sup>8</sup>. In wet to dry soils it can be higher, and quite variable, depending on soil moisture, temperature, etc. Soils also tend to have more inclusions or heterogeneities, which cause environmental backscattering (clutter). These heterogeneities also cause scattering out of the beam, which together with absorption (conversion of Rayleigh wave energy to heat) is an irreversible loss. Surficial soil properties are typically more variable than sea floor sediments because soils are directly exposed to the prevailing weather. Sea floor properties have been documented for sonar applications (see, for example, Ref. 2), and it is known that the shear wave velocity generally increases with depth (due to overburden compaction), while the shear wave attenuation decreases with depth, but increases nonlinearly with frequency.

## Basic Principles of Seismic Sonar for Buried Mine Detection

Knowledge of these effects for various unconsolidated soil types is presently inadequate to support seismic sonar for landmine detection. However, there are many parallels with sea floor effects. Overburden compaction and the increase of shear wave velocity with depth is known to lead to frequency dispersion, which has been observed in seismic sonar research<sup>6</sup> and has been delineated<sup>15</sup> for very low frequency beamforming of Sholte waves on the sea floor. Although dispersion exists, it has not been a major problem at frequencies used to date in seismic sonar for landmine detection<sup>2-14</sup>.

### 1.3 Seismic Sonar Concept

The method involves generating a Rayleigh wave with an array of vibrational sources, called shakers, which sends a beam of interface waves, in a pulse of short duration to the area of the target, where they are reflected, as shown in Fig. 3.

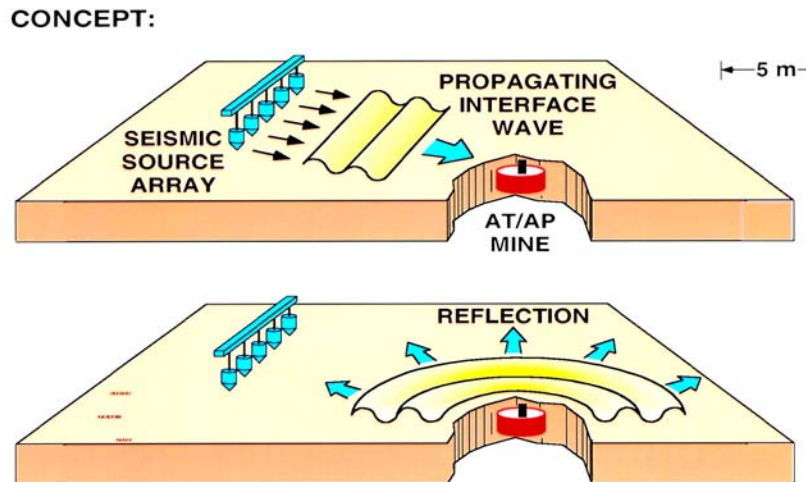


Fig. 3 Seismic Sonar Concept

The echoes then return to an array of three-axis receivers, called seismometers. Range to the target is computed from the Rayleigh wave velocity for two-way travel, while target bearing is estimated by using Rayleigh waves in narrow beams.

## 2.0 SEISMIC SONAR

Seismic Sonar can be operated in either forward-looking or side-looking modes (see Fig. 4); or in both, or other modes.

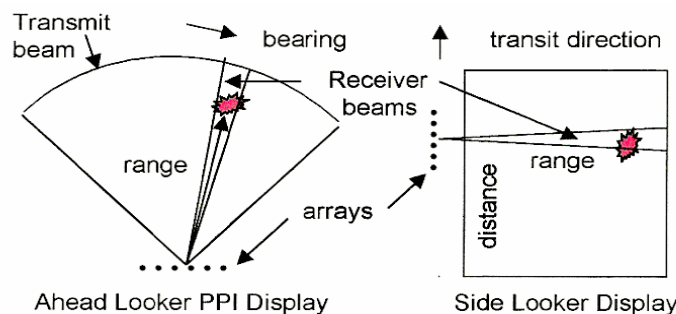


Fig. 4. Seismic Sonar Modes of Operation for Search

In principle, seismic sonar is quite similar to acoustic sonar used in naval and civilian applications, although there are significant differences. Thus, the principles of beam forming, used in acoustic array theory can be used in seismic sonar. In experiments conducted on a sandy beach, we have previously shown that the spatial coherence of the medium does not severely limit the attainment of narrow seismic sonar beams,<sup>9,12</sup> and we have also shown that beamforming is attainable in this environment<sup>10-11</sup>. In acoustic sonar, an echo amplitude contrast provides a suspected target of interest, and this is also the case in seismic sonar. Signal processing to verify target type has more possibilities in seismic than acoustic sonar, due to the vector, two-component nature of Rayleigh waves. When a suspected target is detected, due to echo amplitude contrast; the echo can be examined in detail through simultaneous time-frequency-amplitude analysis using methods such as developed by Gabor, or by Wigner-Ville. It has been shown<sup>14</sup> that this provides a capability to characterize the target as either man-made (landmines, paint cans, etc.) or natural (rocks, tree stumps, etc.). This capability has the potential for realization at standoff ranges considerably greater than are provided by other buried mine sensors.

## 2.1 Seismic Sonar Detection; Some Examples, using Detection Signal Processing

We first illustrate the seismic detection of objects from amplitude contrasts in reflected echoes, which is a time-honored method, dating back to Paul Langevin's first ocean acoustic sonar experiments in the early 1900's. The present problem involves seismic methods for the detection of objects in near-surface, unconsolidated soils and sediments, which is a different problem from that of stratigraphic profiling for deep oil and gas deposits in consolidated formations as used in the oil industry. For detection of targets in a micro-seismic time series, Vector Polarization Filtering<sup>3-5, 7-13</sup> is quite useful. Here, the two components in the echo (vertical and horizontal) are 90 deg. out of phase, which calls into play the theory and function of the complex variable, enabling the assignment of real and imaginary values to these signal components. When this is done, it is possible to compute the complex power in the signal echoes, which contain both real and imaginary parts. Since seismic waves in sediments contain numerous wave types (acoustic, diving shear, multiple reflections, refractions, etc.), and since these wave types interfere with Rayleigh waves, it is possible to separate the Rayleigh wave echoes from this "noise," by capitalizing on the vector nature of the echo field. This requires the detection of both the horizontal and vertical components in the echo field, and then computing the complex power in the echo. For a single time-series echo train in a sonar beam, the complex power computation can be expressed as,

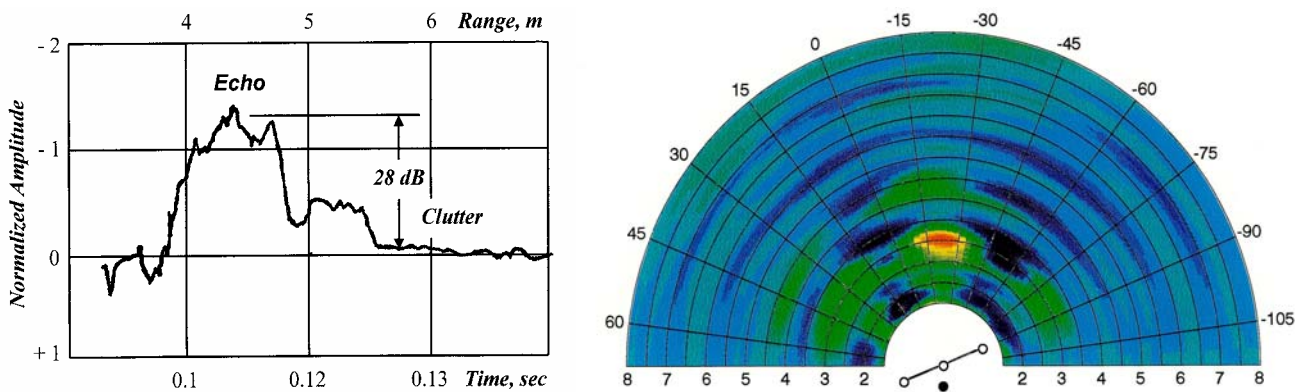
$$P_{rv}(t) = V_v^*(t) \cdot V_r(t),$$

where  $V_v^*(t)$  and  $V_r(t)$  are the complex signals obtained from the Hilbert transforms of the real, vertical and horizontal (radial) components of the Rayleigh wave echo, and \* denotes complex conjugation. From the complex power, one must select the imaginary part, because it alone contains the Rayleigh wave echoes, and not the interfering acoustic waves and other random echoes, such as heterogeneous clutter.

Examples of amplitude contrast detection, using this method<sup>13</sup> are illustrated in Fig. 5. Here a 20 lb. anti-tank (practice) mine was buried some 10 cm below the surface of a clay soil and centered at the focus of a buried array of ten, commercially available, shaker sources, at a lateral range of 4.5 m. (Recently, we have developed vibrational sources having ten times the power output and bandwidth, that couple directly to the soil surface, from rolling stock, requiring no burial of anything.) The vibrational sources<sup>6, 9-14</sup> used here were of the moving mass type, each of which utilizes a heavy magnet to oscillate in the field of an electromagnetic coil, directly coupling energy to the soil, through Newton's third law. The shaker array was laid out on a circular arc, with a radius of 4.5 m., enabling it to be focused at the radial center. The receivers consisted of an array of eight three-axis seismometers of geophone (velocity) sensors, buried flush with the soil surface, and co-located with the sources. The shakers were excited with sinusoidal impulses, centered at 100 Hz, producing short packets of damped oscillations in the soil. As we have shown<sup>3-4, 6-14</sup>, a vertically driven sediment or soil produces easily recognizable two-component Rayleigh waves, starting at distances of about 5 wavelengths from the source. In the present experiments, Rayleigh waves so generated, propagated to the target, were reflected, and were received by the seismometer array. The received signals were amplified, digitally recorded, and processed by the Vector Polarization Filter Process, discussed above.



## Basic Principles of Seismic Sonar for Buried Mine Detection



**Fig. 5. Seismic Sonar A-scan and PPI Displays: Amplitude Contrast with Vector Polarization Filtering**

The large anomaly in the plot at left, around 0.1 and 0.12 sec arrival time is the echo from the buried mine. Its amplitude, in comparison to the background clutter, is some 28 dB (a ratio of 25:1), facilitating detection some 5m away from the seismic sonar device. When displayed on a normal ahead looking, scanning sonar, Plan Position Indicator (PPI) the amplitude contrast appears as a distinct “blip.” (The PPI display shown was actually taken from another experiment<sup>3,4</sup>, which had a much lower echo to clutter ratio, and is included here for demonstration purposes only.)

### 2.2 Seismic Sonar Equation for Detection

During WWII, a number of scientists in several countries developed mathematical models for underwater sonar, both for performance prediction and research. Simplified sonar equations evolved, as much for these reasons as to enable the identification and separation of terms for further study of unique effects; such as attenuation, target strength, etc. This ensured that specialized groups could study these effects in detail, while adding to the general knowledge of sonar. We are now at a similar point in the development of seismic sonar, so it is worthwhile to take a cue from the past. Of course, the seismic sonar problem is more difficult than acoustic sonar, because of the vector nature of interface waves, and their strong vertical variability in soils and sediments, as well as their own, unique sensitivity to environmental variations. It is worthwhile to initiate a simplified seismic sonar equation for detection, leaving classification as a topic for future study.

There are many ways to formulate sonar equations, especially in terms of units and the choice of parameters. The classic, active sonar equations were first formulated for the transmission of an acoustic pulse in the form of a time-gated tone, and the receive signal was similarly treated. The decibel notation was used, and the useful concept of power was imposed on the transduction from electrical to acoustic energy. That was appropriate because there was usually a known efficiency in the transfer of electric to acoustic power. Such is not the case for seismic sonar operating in soils and sediments, where the problems of coupling efficiency, related to boundary conditions are now quite poorly understood.

To simplify the problem, we choose to begin with a **source level** term,  $L_S$ , which is the Raleigh wave **energy density**, already created at a soil or sediment interface, as if by preferential excitation, which can be written in decibel notation as,

$$L_S = 10 \log [ \rho ( V_r^* \cdot V_v / 2 ) ],$$

Where  $\rho$  is the density of the soil or sediment, and  $V_r$  and  $V_v$  are the radial and vertical components of the Rayleigh wave velocity, and \* denotes complex conjugation. Here, the dynamic variables,  $V_r$  and  $V_v$ , may be expressed in any form; peak, mean, rms, etc., as long as the dynamic variables in the rest of the equation are similarly expressed. They can also be expressed in the time domain, i.e.  $V_r(t)$ . It is implied that  $L_S$  is a vector quantity, and that taking the imaginary part exclusively yields the Raleigh wave, should other (acoustic) wave components be present, which is often the case.

**Basic Principles of Seismic Sonar for Buried Mine Detection**

The next term to be considered is the **spreading loss**,  $S.L. = 20 \log R^{1/2}$ , where R is range to the target, from the standard distance of 1 m from the center of the source. S.L. is multiplied by 2 for two-way propagation (to and from the target).

Following spreading, we must consider the **attenuation loss**, A.L., consisting of absorption (energy conversion to heat) and scattering out of the beam; and is an empirical number, experimentally determined. Little is known about the attenuation of Rayleigh waves in different types of unconsolidated soils and sediments, at different frequencies. One measurement (by Hall<sup>8</sup> at a frequency of 90 Hz, in a sandy beach at Monterey California) gave an **attenuation constant** A of 0.13 dB / m. Here, the **attenuation loss**, will be defined as  $A.L. = A \cdot R$ , which = (2) A·R, for two-way losses.

Next we must consider the **target strength**. Its classic definition for sound waves is  $T.S. = 20 \log ( p_r / p_i )$ , where incident pressure,  $p_i$  and reflected pressure,  $p_r$  are referred to 1 m from the target center. This could be extended to the seismic sonar case as  $T.S. = 10 \log [ ( V_r^* \cdot V_v )_r / ( V_r^* \cdot V_v )_i ]$ , also referred to 1 m. This procedure is based on experiment; and is empirical, but quite practical, within limits. It has been used to measure the target strength of test targets<sup>8</sup>, which yields numbers in the neighborhood of -25 dB for anti-vehicular mine shapes.

A mechanical consideration of **target strength**, based on the cross sectional area intercepted by the mine, its mechanical properties, as well as the Rayleigh wave depth profile; is expressed as  $T.S. = 10 \log [ K (m,e) \cdot A_r \cdot F(z) ]$ , where  $K (m,e)$  is a constant depending on the mass of the target and its elasticity,  $A_r$  is the effective cross sectional area upon reflection,  $F(z)$  is a dimensionless Rayleigh wave **depth factor**, to account for the variance of Rayleigh wave amplitude and phase with depth (see Fig. 2). The depth factor is a complicating geometric term, but it could be computed and applied in a straightforward manner. This approach could be of importance for large mines that subtend significant portions of the exponentially decaying Rayleigh wave field, beneath the surface.

Seismic sonars are backscatter or clutter limited, in that the target strength of natural inclusions in the soils or sediments also scatter Rayleigh waves back to the sonar receiver, at levels higher than that of the ambient seismic noise. This means there is a target strength of the clutter, governed by the environment itself and by the size and effective depth of the resolution cell, the latter being limited by the exponential decay with depth of the Rayleigh wave. These are even more complicated dependencies, about which little is known, so we must again take an empirical approach, and define a **clutter target strength** as,

$$T.S. \text{ clut} = S.S. \cdot ( 10 \log [ R \Delta\theta \cdot V_R (\Delta t/2) \cdot F(z) ] ),$$

where S.S. is a **scattering strength** constant for the particular soil or sediment interface type, R is range,  $\Delta\theta$  is receiver beamwidth (in radians, small angle approximation),  $V_R$  is the Rayleigh wave group velocity,  $\Delta t/2$  is half the pinglength, and  $F(z)$  is defined above. Although backscattering (clutter) has been observed, it has not been sufficiently quantified, so practically nothing is known about the **scattering strength** constant and how it varies with soil and sediment type, frequency, etc.

We are now ready to begin assembling a **seismic sonar equation**, as follows:

$$L_S - (2) S.L. - (2) A.L. + T.S. + P.G. = L_E$$

Here, the term P.G. identifies the **signal processing gain**, expressed in decibel notation, as obtained from procedures like that of section 2.1, above. The term  $L_E$  is the **echo level energy density**,  $= 10 \log [ \rho ( V_r^* \cdot V_v / 2 ) ]$ , where the prime denotes an echo quantity. One can use the same equation to determine the **clutter level energy density**,  $L_C$ , which can be determined by measurement or by scaling in performance prediction.

When this is done, a term called the recognition differential, **R.D.**, which gives the number of decibels between the target signal and the clutter, and can be calculated as  $L_E - L_C$ . The **R.D.** term has been measured in only three experiments; one on a sand beach in Corpus Christi, TX<sup>3-4</sup>, one on a sand beach in Monterey, CA<sup>9-10</sup>, the third in a red clay soil in Oxford,

## Basic Principles of Seismic Sonar for Buried Mine Detection

---

MS<sup>13-14</sup>, (shown in Fig. 5, above). The scattering strength of the environment for these experiments has not yet been obtained from the sonar equation we have constructed here. Scattering strength is best determined from dedicated measurements, using equipment specially designed for that purpose. The same is true for attenuation, target strength, etc. These are topics of on-going research.

### SUMMARY AND PERSPECTIVE

The physics of Rayleigh waves has been reviewed for its use in the detection of landmines buried in soils and sediments. The concept and application of seismic sonar has also been reviewed. A rudimentary sonar equation was developed to model this process, so that the important terms can be isolated for further study. Once these terms are better understood, the sonar equation can be used for analysis and performance prediction. It is anticipated that the seismic sonar equation introduced here, will undergo evolution with time, to better model and describe the process of landmine detection.

### ACKNOWLEDGEMENTS

Work supported by the U.S Army Research, Development and Engineering Command, Night Vision and Electronic Sensors Directorate, and the U.S. Marine Corps Systems Command.

### REFERENCES

- [1] A. Ben-Menahem and S.J. Singh, *Seismic Waves and Sources*, Springer-Verlag, 1981.
- [2] T. G. Muir, T. Akal, M.D. Richardson, R.D. Stoll, A. Caiti, and J.M. Hovem, "Comparison of techniques for shear wave velocity and attenuation measurements," in *Shear Waves in Marine Sediments (Proceedings of the 1990 NATO Conference in Lerici, IT)*, 293-294, Kluwer Academic Publishers, 1991.
- [3] Thomas G. Muir, Eric Smith, and Preston S. Wilson, "Seismo-acoustic sonar for buried object detection," *Proceedings of the Symposium: Technology and the Mine Problem*, p. 7-97 to 7-102, U.S. Naval Postgraduate School, Monterey, CA, 93943, Nov. 1996.
- [4] Eric Smith, Preston S. Wilson, Fred Bacon, Jason Manning, John Behrens, and Thomas G. Muir, "Measurement and localization of interface reflections from a buried target," *Journal of the Acoustical Society of America*, **103(5)**, p. 2333-2343, May 1998.
- [5] Eric Smith, "Scattering of interface waves from pointlike objects," *Journal of the Acoustical Society of America*, **103(5)**, pp. 2344-2353, May 1998.
- [6] Fred E. Gaghan, Jr., *Discrete-mode source development and testing for new seismo-acoustic sonar*, M.S. Thesis, supervised by S.R. Baker and T.G. Muir, U.S. Naval Postgraduate School, Monterey, CA, 93943, March 1998.
- [7] Sean M. Fitzpatrick, *Source development for a seismo-acoustic sonar*, M.S. Thesis, supervised by S.R. Baker and T.G. Muir, U.S. Naval Postgraduate School, Monterey, CA, 93943, December 1998.
- [8] Patrick W. Hall, *Detection and target strength measurements of buried objects using a seismo-acoustic sonar*, M.S. Thesis, supervised by T.G. Muir and S.R. Baker, U.S. Naval Postgraduate School, Monterey, CA, 93943, December 1998.
- [9] Kraig E. Sheetz, *Advancements in buried mine detection using seismic sonar*, M.S. Thesis, supervised by T.G. Muir and S.R. Baker, U.S. Naval Postgraduate School, Monterey, CA, 93943, December 2000.



---

**Basic Principles of Seismic Sonar for Buried Mine Detection**

---

- [10] Jeremie Guy, *Seismic sonar developments for the detection of buried landmines*, Senior Year Thesis, College of Chemistry, Physics, and Electronics, Lyon, FR, done at the U.S. Naval Postgraduate School, Monterey, CA, 93943, December 2000, under supervision by T.G. Muir, S.R. Baker, and M. E. Zakharia.
- [11] Jeremie Guy, Kraig E. Sheetz, Steven R. Baker, and Thomas G. Muir, "Beamforming in the sand," *Proceedings of the Fourth International Symposium on Technology and the Mine Problem*, U.S. Naval Postgraduate School, Monterey, CA, 93943, September, 1999.
- [12] Kraig E. Sheetz, Jeremie Guy, Steven R. Baker, and Thomas G. Muir, "Spatial coherence of interface waves in surf zone sediments," *Proceedings of the Fourth International Symposium on Technology and the Mine Problem*, U.S. Naval Postgraduate School, Monterey, CA, 93943, September, 1999.
- [13] Aurore Gril, and Emanuel Gestat de Garambe, *Investigation of seismic interface waves for land mine detection*, Senior Thesis Report, Ecole Navale (French Naval Academy), 29 240 Brest Armées, FR, May 2003.
- [14] Thomas Muir, Manell Zakharia, Aurore Gril, and Emanuel Gestat de Garambe, "Landmine detection with seismic sonar," in *Proceedings of the SPIE Defense and Security Symposium 2004*, Orlando, FL, 13-15 April, 2004, International Society for Optical Engineering.
- [15] J.A. TenCate, A. Kristensen, A. Caiti, E. Michelozzi, and R. A. Koch, "Beamforming on Seismic Interface Waves, with an Array of Geophones on a Shallow Sea Floor," *Institute of Electrical and Electronic Engineers, Journal of Oceanic Engineering*, Vol. **20**, No. 4, p. 300-310, October, 1995.

**Basic Principles of Seismic Sonar for Buried Mine Detection**

---

