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Remote Mine Detection Technologies for Land and Water Environments

Ed Hoover
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

The detection of mines, both during and after hostilities, is a growing international problem. It limits military operations during wartime and unrecovered mines create tragic consequences for civilians. From a purely humanitarian standpoint an estimated 100 million or more unrecovered mines are located in over 60 countries worldwide. This paper presents an overview of some of the technologies currently being investigated by Sandia National Laboratories for the detection and monitoring of minefields in land and water environments. The three technical areas described in this paper are: 1) the development of new mathematical techniques for combining or fusing the data from multiple sources for enhanced decision-making; 2) an environmental fate and transport (EF&T) analysis approach that is central to improving trace chemical sensing technique; and 3) the investigation of an underwater range imaging device to aid in locating and characterizing mines and other obstacles in coastal waters.

INTRODUCTION

Mines are a growing problem of vast proportions [1-3]. In times of war, minefields can critically impact mobility by reducing high-speed maneuverability in hostile environments. In the Viet Nam War from 1967 to 1969 landmines accounted for 14% of all US [4]. In peacetime operations the presence (or threat) of mines can close supply routes, slow convoys of material and personnel, and forestall the opening of civilian facilities and agricultural lands. Unrecovered landmines are the tragic legacy of conflict, continuing to kill and maim civilians long after hostilities cease. In Angola and Cambodia, landmines are used by insurrectionists as weapons of terror against local populations, denying travel on roads and access to agricultural fields. An estimated 100 million or more unrecovered mines are located in over 60 countries worldwide.

The goal for mine detection equipment is to detect <u>all</u> types of mines, with very few false alarms, and at rates appropriate for the situation, be it military or civilian. That goal has not yet been met. While metal detectors, properly employed by trained and disciplined teams can find most mines currently emplaced, survey rates are slow and are plagued with failures. Mine detection continues to be a very difficult and complex problem that will be solved only through systematic analysis and development of complementary sensors, advanced signal processing technologies, and improved support equipment and survey procedures.

DISCLAIMER

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This paper presents an overview of some of the technologies currently being investigated by Sandia National Laboratories for the detection and monitoring of minefields on land and in littoral regions. The three technical areas described in this paper are: 1) the development of new mathematical techniques for combining or fusing the data from multiple sources for enhanced decision-making; 2) an environmental fate and transport (EF&T) analysis approach that is central to improving trace chemical sensing techniques; and 3) the investigation of an underwater range imaging device to aid in locating and characterizing mines and other obstacles in coastal waters.

SENSOR FUSION

Over the years a wide variety of developmental sensors, based on different physical and chemical phenomena, have been examined. These include magnetometers, electromagnetic induction (EMI), ground penetrating radar (GPR), infrared (IR) and/or multi-spectral imagers, X-ray backscatter, X-ray fluorescence, and neutron activation sensors. Unfortunately, no single sensor has demonstrated reliable performance over a range of target types and operational conditions. In fact, the most widely used tool for detecting landmines is still the hand-held, pulsed eddy-current metal detector. In the hands of experienced operators these devices can be quite effective. Landmines buried several inches deep and containing little more metal than a firing pin of 30-50 gm can be detected with this system. Unfortunately, all other metal objects are also detected, resulted in 350-1000 "contacts" for every mine located.

A consensus is therefore building within the mine detection community that new approaches will be required. Either we need to develop better sensors that are more robust in diverse environments, or we need to develop better ways of exploiting the information available from those that we already have. Since there do not appear to be any "magical" sensors on the horizon, most experts now believe multiple sensing technologies combined with advanced data processing methods will be required to solve the dual problems of mine detection and clutter discrimination.

Sandia is examining the use of automatic target recognition (ATR) techniques and principles to enhance detector performance in both stand-alone and multi-sensor scenarios. Novel signal processing methods, data transformations, and pattern recognition metrics are being investigated to maximize the power of individual sensors for discriminating between mines and common non-targets (natural and cultural clutter). The challenge is to identify temporal, spatial, and scalar properties that may be used to detect mines, and to distinguish them from clutter objects. Whenever possible, physical models of sensor response will be incorporated with the measured data. Because the full range of target types and environmental conditions that might be encountered in operation is prohibitively large, attention will be restricted to a limited subset of targets and conditions.

The process by which information is combined is frequently referred to as "data fusion". Fusion can take place at various stages of the processing sequence, and the data to be fused may lie anywhere in the range from raw to highly processed. Different approaches to fusion are appropriate depending on the stage of the processing sequence. For example, if raw imagery from more than one imager is to be combined before input to the final decision-making element of the system, accurate modeling of some complex spatial and temporal relationships between and within images may be required. By contrast, when the data to be merged are already highly processed (e.g., sensor outputs that say how much like a mine the signal is), the modeling task is often relatively simple, and can yield fusion metrics that are powerful and straightforward to interpret.

ATR fusion techniques can be applied to results arising from any of the following: 1) multiple sensors, 2) multiple channels or independent "looks" taken with a single sensor, and 3) multiple ATR algorithms applied to a single data stream. The most elementary approach to ATR fusion uses voting metrics, in which each ATR output is converted to a binary "yes/no" format and final classifications are based on decision rules like "majority wins". In many applications, more sophisticated and effective metrics must be developed.

One of the more promising approaches being investigated involves a probabilistic data fusion [5] technique originally developed as part of Sandia's ATR program. As an example of the improvements possible, this technique was applied to electromagnetic induction (EMI) data collected by Parsons Engineering during a recent DARPA clutter study[6]. Thus far, several promising discriminatory features have been extracted from the output of a Geonics EM61-3D, which is a time-domain electromagnetic induction sensor. Because of the complexity and apparent ambiguities that exist in the raw three-axis (x,y,z) data, conventional decision-making algorithms typically have only used the information contained in the sensor's vertical or z-axis coil. The algorithmic technique applied by Sandia utilized all three axes of data in an effort to extract as much of the "useful" information as possible. Adaptive normalization was used to correct for changes in sensor power and background noise level and the three features were combined in the log (p-value) domain.

The side-by-side comparison of these two approaches is illustrated in Figures 1 & 2. In both case areas highlighted in red are those that are most mine-like, but the results achieved using the probabilistic data fusion approach (Figure 2) correlated much better with actual mine emplacements and had far fewer false positives than the results from simply using the z-axis coil (Figure1).

While these results are quite preliminary and far from conclusive, they clearly demonstrate the benefits of incorporating ATR and sensor fusion techniques into mine detection systems. A great deal of research still needs to be done but the potential is clear. Ultimately, this methodology will be extended to multiple sensor types. Single-sensor ATR techniques are most effective with sensors that respond to designated targets in a measurable and reasonably consistent manner. When multiple sensors are to be combined, some orthogonality of principle or applicability is advantageous. Thus, a candidate sensor designed to detect plastic mines might be paired with a metal detector to provide increased coverage of the target space. Combining information from multiple sensors should lead to further reductions in false alarm rates while maintaining or perhaps even enhancing detection probabilities.

EXPLOSIVE DETECTION

Direct sensing of the chemical signature emanating from the explosive components found in landmines has the potential for positively differentiating between real threats and non-explosive objects. In the last two decades, advances in chemical detection methods have brought chemical sensing technology to the foreground as an emerging technological solution. In addition, advances have been made in the understanding of the fundamental transport processes that allow the chemical signature to migrate from the buried source to the ground surface. A systematic evaluation of the transport of the chemical signature from inside the mine into the soil environment, and through the soil to the ground surface is being explored at Sandia to determine the constraints on the use of chemical sensing technology [7].

The chemical signature of explosives in buried landmines is affected by multiple environmental phenomena that can enhance or reduce its presence and transport, and can affect the distribution of the chemical signature in the environment. For example, the chemical can be present in the vapor, aqueous, and solid phases. The distribution of the chemical among these phases, including the spatial distribution, is key in designing appropriate detectors, e.g. gas, aqueous or solid phase sampling instruments, and their optimum use. A fundamental understanding of the environmental conditions that affect the chemical signature is needed to describe the favorable and unfavorable conditions of a chemical detector based survey to minimize the consequences of a false negative. The fate and transport of the chemical signature emanating from the buried landmine is a fundamental property that is poorly understood. As an initial step in the evaluation of the landmine chemical signature, a screening model based on pesticide and Volatile Organic Compound (VOC) movement in soils has been adapted to evaluate landmine chemical behavior.

A conceptual model of the environmental fate and transport processes that impact the movement of landmine chemical constituents to the surface for chemical detection is shown in Figure 3. Chemical vapors emanate from a buried landmine by permeation through plastic case materials or through seals and seams, and from the initial surface contamination of the case. Vapor phase diffusion transports molecules away from the landmine. The vapors may partition into the aqueous phase of the soil water which may then be transported to the surface through advection, driven by evapotranspiration or to depth by precipitation infiltration, and through diffusion driven by concentration gradients. Under extremely dry soil conditions near the ground surface, vapor phases may be directly sorbed to soil particles. When in the liquid phase, chemicals may also sorb to the soil particles. Soil particle sorption can be considered a temporary storage reservoir for the explosive constituents, where they may be released under reversible partitioning reactions, but some proportion may also permanently bound through chemisorption reactions. Transformation and loss of explosive constituents also occurs during microbial degradation and uptake by the roots of certain plant species. The organic chemicals of the explosives in the buried landmine environment can exist in four phases: solid phase of the neat explosive material, vapor phase in the soil air, aqueous phase in the soil water solution, and sorbed onto soil solid phases. The chemical signature begins as a surface coating from production or depot storage and through continuous emission by permeation through the mine case or through leaks in seals and seams. Once the chemicals enter the soil environment, they experience phase transitions, partitioning into the soil air, soil water and sorbing onto soil particles. The impact of temperature and chemical gradients, and precipitation/evaporation will cause movement of the chemical signature. Part of this transport is upward to the soil surface where it is envisioned that chemical detection technology will be employed. Simulation modeling is a technique that can evaluate the impacts of many of the environmental variables that can dampen or accentuate the surface expression of the chemical signature.

A one-dimensional model developed for screening agricultural pesticides was modified and used to simulate the appearance of a surface flux above a buried landmine, estimate the subsurface total concentration, and show the phase specific concentrations at the ground surface. The physical chemical properties of TNT cause a majority of the mass released to the soil system to be bound to the solid phase soil particles. These simulations have found that when the continuous source flux was absent, there was no significant difference in the surface vapor flux or subsurface distribution at the end of the simulation period. This implies that the continuous source flux may be much less important than the initial surface contamination. It appears that the magnitude of the surface vapor flux is directly proportional to the amount of the initial surface contamination. The biochemical half-life is another parameter that is likely to have very different values depending on the location and climatic conditions. Simulations over ten years showed that the steady state surface vapor flux declines steadily when the biochemical half-life becomes smaller than one year. Finally, the importance of heavy precipitation (such as a monsoon season) followed by a dry season was explored. The impact of the heavy precipitation was to lower the surface flux seven orders of magnitude; however, the evaporation period that followed returned the surface flux to approximately the pre-monsoon surface flux.

The simulations conducted thus far have only been used for initial conceptual designs of chemical pre-concentration subsystems or complete detection systems. The physical processes modeled required necessary simplifying assumptions to allow for analytical solutions. Emerging numerical simulation tools will soon be available that should provide more realistic estimates that can be used to predict the success of landmine chemical detection surveys based on knowledge of the chemical and soil properties, and environmental conditions where the mines are buried. Additional measurements of the chemical properties in soils are also needed before a fully predictive approach can be confidently applied.

UNDERWATER RANGE IMAGING

Near-shore hydrographic reconnaissance and shallow water mine countermeasure operations are functions currently performed by teams of divers and/or divers and marine mammals. Mine countermeasures involve the detection and identification of both mines and mine-like targets. In hostile areas, divers can expect to encounter various moored contact mines, bottom influence mines, and anti-invasion mines. Some of the newer bottom influence mines have plastic or composite outer cases with case profiles that are very effective at blending into the bottom. Marine growth can make these weapons difficult to detect, and because of the presence of influence triggering mechanisms, they are a threat to military divers as well as landing craft. Mines and obstacles become even more problematic in the surf zone. Here, the mine threat includes all of the numerous pressure-plate and tilt-rod mine variants available on the international market, as well as obstacles such as hedgehogs, concrete blocks, stake jacks, steel tetrahedrons, and both single- and triple-stranded concertina wire. In addition, waters near shore are often optically turbid with overall clarity dependent upon variables such as bottom type, proximity to rivers, bays, and inlets, rainfall history, proximity to civilization, and time of year.

Range-gated imaging systems generally give an operator the capability to see targets at much longer distances in scattering media than possible with other types of active systems or with the unaided eye. However, any system depending on image contrast for target recognition will have limited effectiveness in viewing targets with geometry and surface coloration/texture that closely matches that of the background. Spectral contrast is lost due to varying rates of color attenuation and the use of a monochromatic source. Low signal-to-noise ratio is an issue when concerned about small form-factor hazards such as concertina wire in the water volume. Non-diving applications, such as imaging mines in the water volume through a wavy air-water interface, also present problems that have required complex solutions with conventional gated imaging systems.

An alternate approach is to use a system that forms a three-dimensional image on the basis of range rather than a two-dimensional image based on reflected energy. Formation of the "range-image" is a function of the ability to unambiguously determine the distance between each element of the detector and the points on the target that are in that particular element's instantaneous field of view. Thus, image contrast associated with a given target is more a function of its 3-D geometry and position relative to the background than of reflectivity and surface texture.

In the spring of 1998 Sandia National Laboratories, Nichols Research Corporation, and the Navy's Coastal Systems Station (CSS) performed a short sequence of feasibility experiments in a test tank at CSS [8]. Images were gathered at several different turbidity levels, and it was found that 3-D volume targets in the range images were often recognizable beyond the point where there was sufficient image contrast to recognize the target in the standard 2-D image.

Scannerless Range Imager

The scannerless range imaging device used in the underwater feasibility tests is basically an imaging lidar that forms a range image through a unique series of hardware modifications and processing techniques that eliminate using either mechanical or electrical beam steerage processes. It was originally developed at Sandia National Laboratory, and the technology was patented in 1990 by the Department of Energy [9]. The basic system elements consist of a light source and a receiver that utilizes an image intensified CCD (ICCD) array as the detector. The source can be either continuous wave (CW) or pulsed, but operates in floodlight mode in either case to ensure operation as a total field of view system. Range information is generated through a sequence of processes that starts with the synchronous modulation of both the light source and intensifier gain at RF frequencies. Energy reflected from the target (or within the volume) is collected by the receiver, and the phase information captured through the mixing of the return signal with the modulated intensifier gain prior to being recorded by the CCD array on a pixel-by-pixel basis. Thus, phase information is captured simultaneously for each pixel in the array. An on-board digital signal processor is used to compare two or more frames of reflectance data generated with different modulation schemes and extract the range information for each pixel. The images are then output as a standard video signal. Reflectance imagery is thus available at normal video rates, and the range imagery available at near normal video rates. The latest camera/DSP combination makes the system capable of one- to three-inch range resolution and a high range-image pixel rate. The use of a Gen II or Gen III image intensifier also enables the implementation of conventional range gating techniques to minimize the effects of backscatter and enhance the signal to noise ratio for targets located within the gated volume.

The range imager used in the underwater feasibility experiments was a breadboard configuration assembled from available components by Sandia National Laboratory. Basic components were the receiver, the source, power supplies and control electronics, and a desk-top computer. The receiver consisted of a Kodak digital camera with 1534 by 1024 pixel CCD array coupled to a slow response image intensifier with a 50 ns rise time for the gate and a minimum 100 ns gate width. Standard 25 mm and 50 mm photographic quality lenses were used to collect and focus the return signal. The source was a frequency-doubled Nd:YAG laser operating at 532 nm and coupled to a diverging lens and a diffuser element. The mine-related targets imaged were a PDM-1 mine simulant (tilt-rod surf zone bottom mine), a painted 21-inch diameter aluminum sphere to simulate volume mines, and a 20 foot length of triple stranded concertina wire. The test geometries used are shown in Figure 4 and above water photos of the 21-inch sphere, the PDM-1 mine simulant, and the bundled concertina wire are shown in Figure 5.

Experimental Results

Data collected on the three dimensional targets illustrate the unique possibilities of the SRI sensor for underwater imaging applications. Figure 6 is a side-by side comparison of the reflectance and range images in clear water for the PDM-1 mine simulant resting on the bottom 17 feet away from the receiver. Measured absorption (a) and beam attenuation (c) coefficients are provided as well. The intensity map on the left side of the figure is clearly recognizable as the mine simulant, because shadows and differences in reflectivity from some of the target's features produce a high degree of contrast. The hemispherical housing and tilt-rod stand out, with cleanly defined edges as would be expected. Another feature that stands out very cleanly is the cable attached to the vertical tilt-rod to facilitate target removal at the end of the tests.

Imaging performance under low visibility conditions is also of great interest because the combined effects of attenuation and backscatter are difficult to overcome. Although the breadboard sensor used in these feasibility tests was not optimized for turbid water operations, an effort was nevertheless made to qualitatively examine the performance of the range imager in low-visibility conditions. Figure 7 shows image data taken of the PDM-1 simulant with a coil of concertina wire suspended from the surface and making contact with the top of the target underneath.

A close look at the images reveals that the outline of the bottom target can just barely be seen in each one, and the target would probably not be recognizable under field operating conditions. However, the concertina wire, which is just discernable in the intensity image, is clearly identifiable in the range image. This characteristic of the SRI would be valuable to divers, since nets, cables, and similar clutter in the water volume are entanglement hazards that divers avoid if possible. As a matter of fact, the SRI proved to be very effective at imaging volume targets in general, because the inclusion of the extra dimension of the 3-D targets provided a means of increasing the effective signal to noise ratio in the presence of backscatter.

Evidence of the sensor's ability to discriminate targets in the range image at distances beyond what was possible in the intensity image is presented in Figure 8. The target is clearly identifiable in both images from the 17-foot data, however, there is more contrast in the range image than the intensity image. Cables are also clearly visible in the range image, but cannot be seen in the intensity image. The biggest difference is observed in the 33-foot data in the lower image pair. Here, the laser power had to be boosted, and the intensity image washed out in the volume backscatter, but the target in the range image was still recognizable as a moored target with cables attached to the bottom.

These initial feasibility tests indicate that substantial benefit might be gained by adapting this technology to operate in the underwater environment. A qualitative assessment of imaging performance against 3-D targets seems to indicate that, all other things being equal, the range image provides a substantial signal to noise advantage over a reflectance image in turbid environments or when looking through a modulated surface. One characteristic that presents a potential advantage to the diver is the high level of contrast observed when imaging normally low contrast objects such as wire or cable in the water column. Since the technique can be used with a continuous source, it offers the potential to design small, low-cost systems that might perform adequately under some conditions and circumstances, and which, would offer and size and weight benefits over range-gated imagers. The results presented here are strictly qualitative in nature and future work is planned to better assess how well the SRI would perform in an optimized system configuration. The system employed during the tests had a gate width much too long to be useful at the ranges for which the data was taken, while a shorter gate width might be expected to improve performance considerably.

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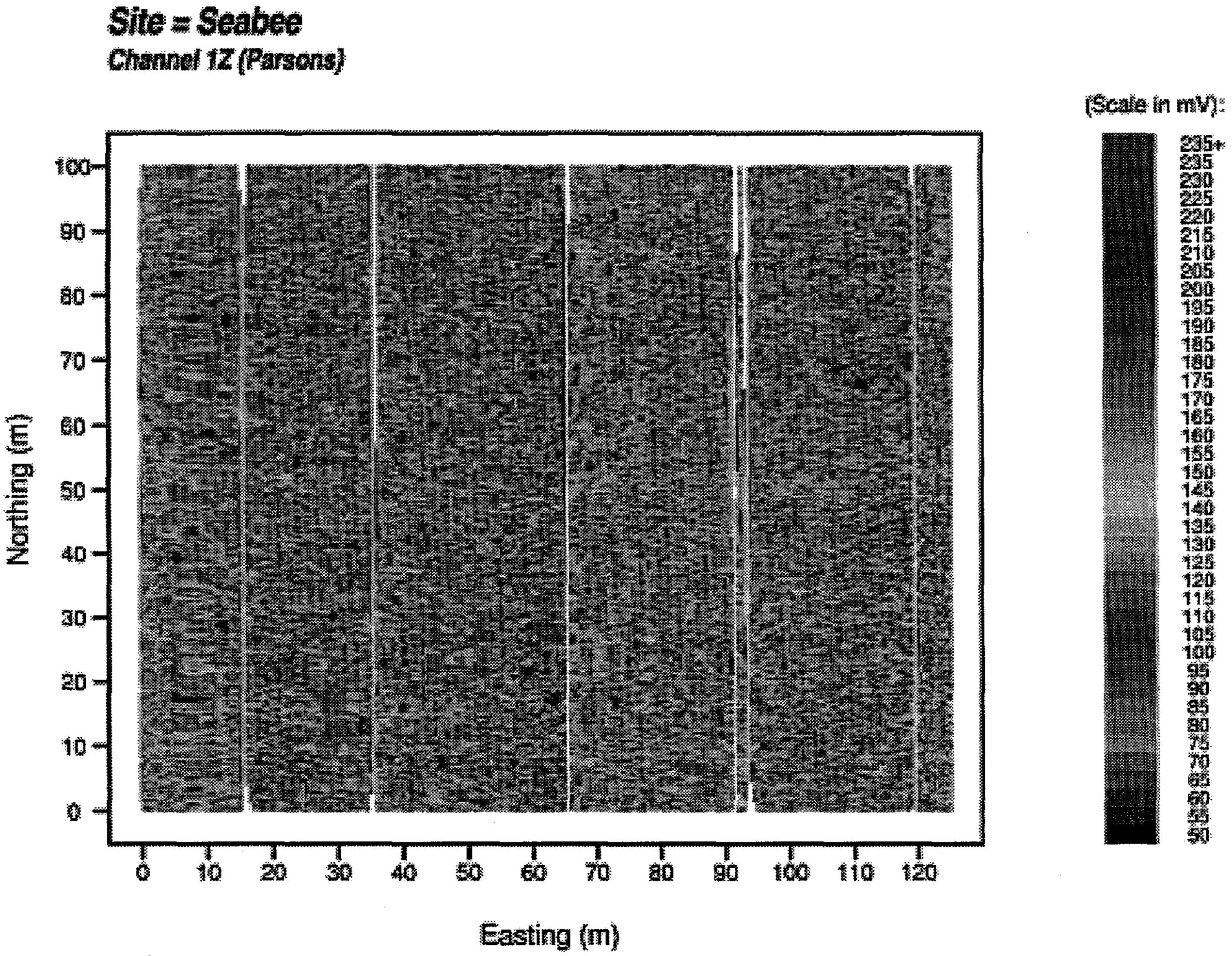


Figure 1. Results from using simple algorithm and only the z-channel data.

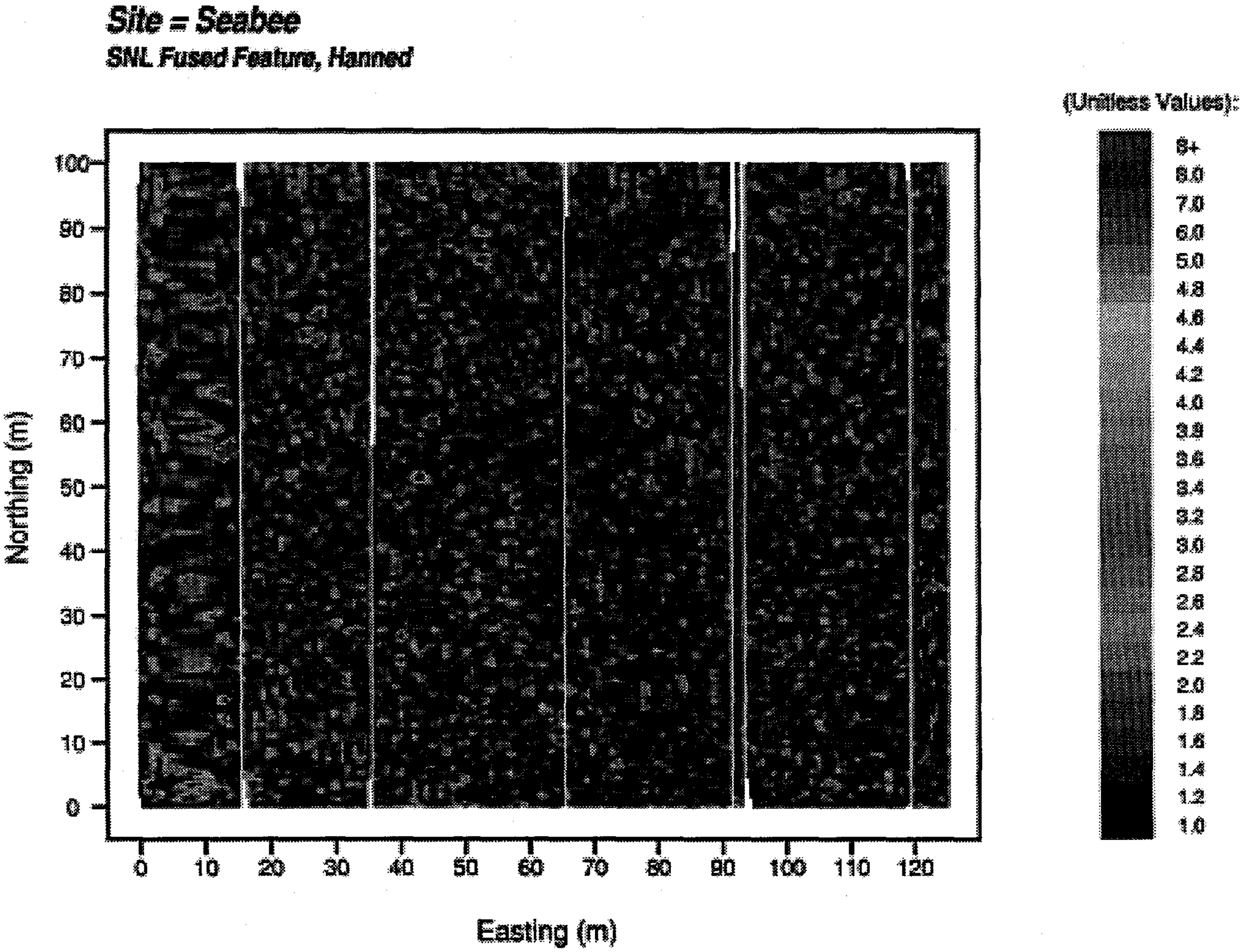


Figure 2. Results achieved using a modern probabilistic data fusion technique and all three axes available.

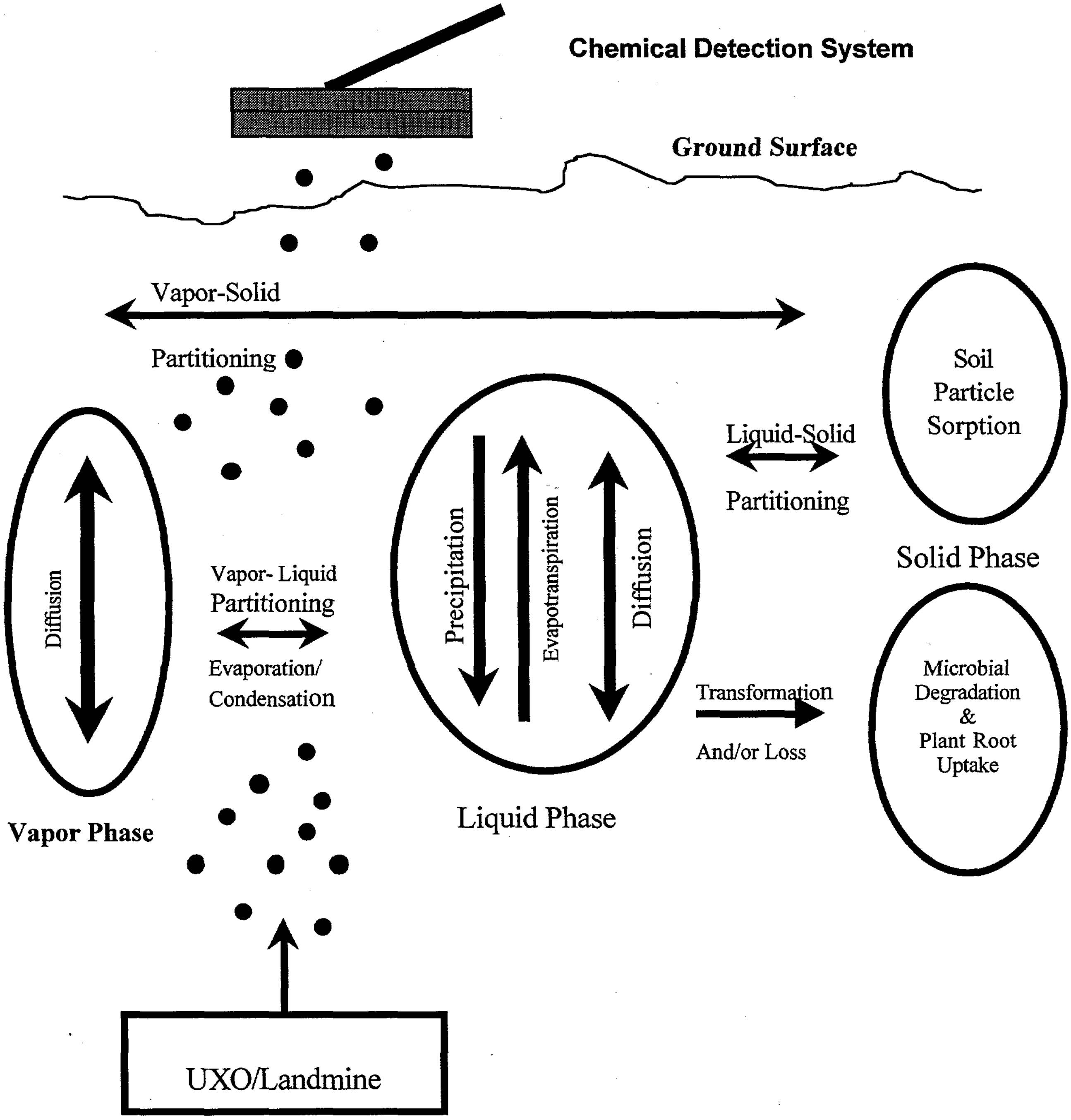
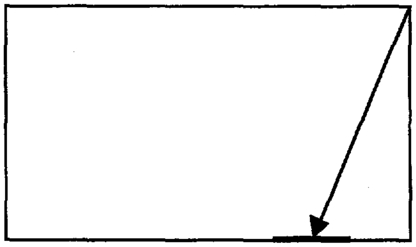
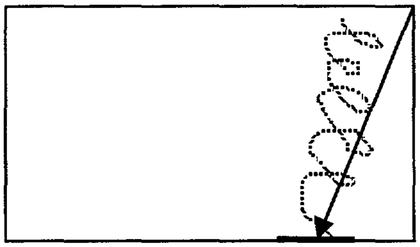


Figure 3. Conceptual diagram of environmental fate and transport simulation process.

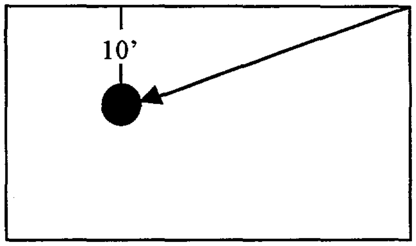
Figure 4. Position of underwater targets relative to the source and receiver for the underwater tests. Targets are (a) PDM-1 mine simulant, (b) PDM-1 and concertina wire, and (c) 21-inch painted aluminum sphere.



(a) Slant range 17 feet



(b) Slant range 17 feet



(c) Slant ranges of 17-33 feet

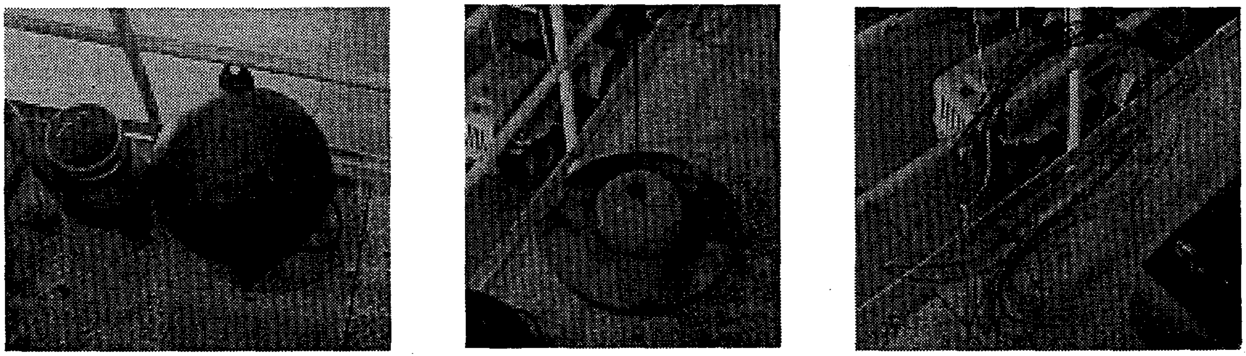


Figure 5. Above water photos of the primary targets used in the tests; 21-inch sphere (left), PDM-1 simulant (center), and concertina wire (right).

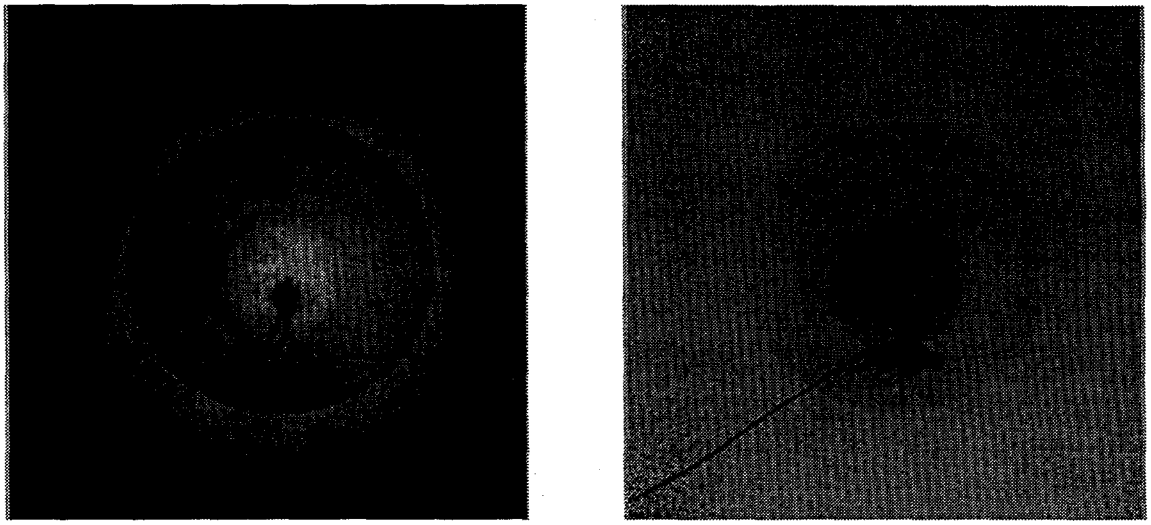


Figure 6. Reflectance image (left) and range image (right) for PDM-1simulant sitting on the bottom of the SDV test tank at a range of 17 feet from the receiver. Water was clear with (a) = 0.001 m^{-1} and (c) = 0.085 m^{-1}.

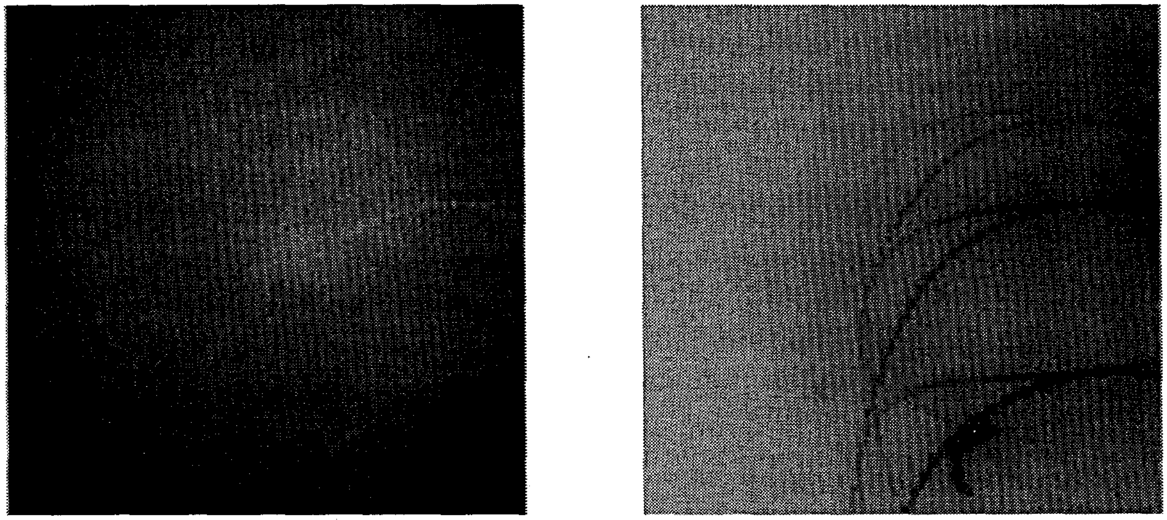


Figure 7. Reflectance image (left) and range image (right) of PDM-1 simulant and suspended concertina wire in turbid water with $a = 0.11\ m^{-1}$ and $c = 0.65\ m^{-1}$.

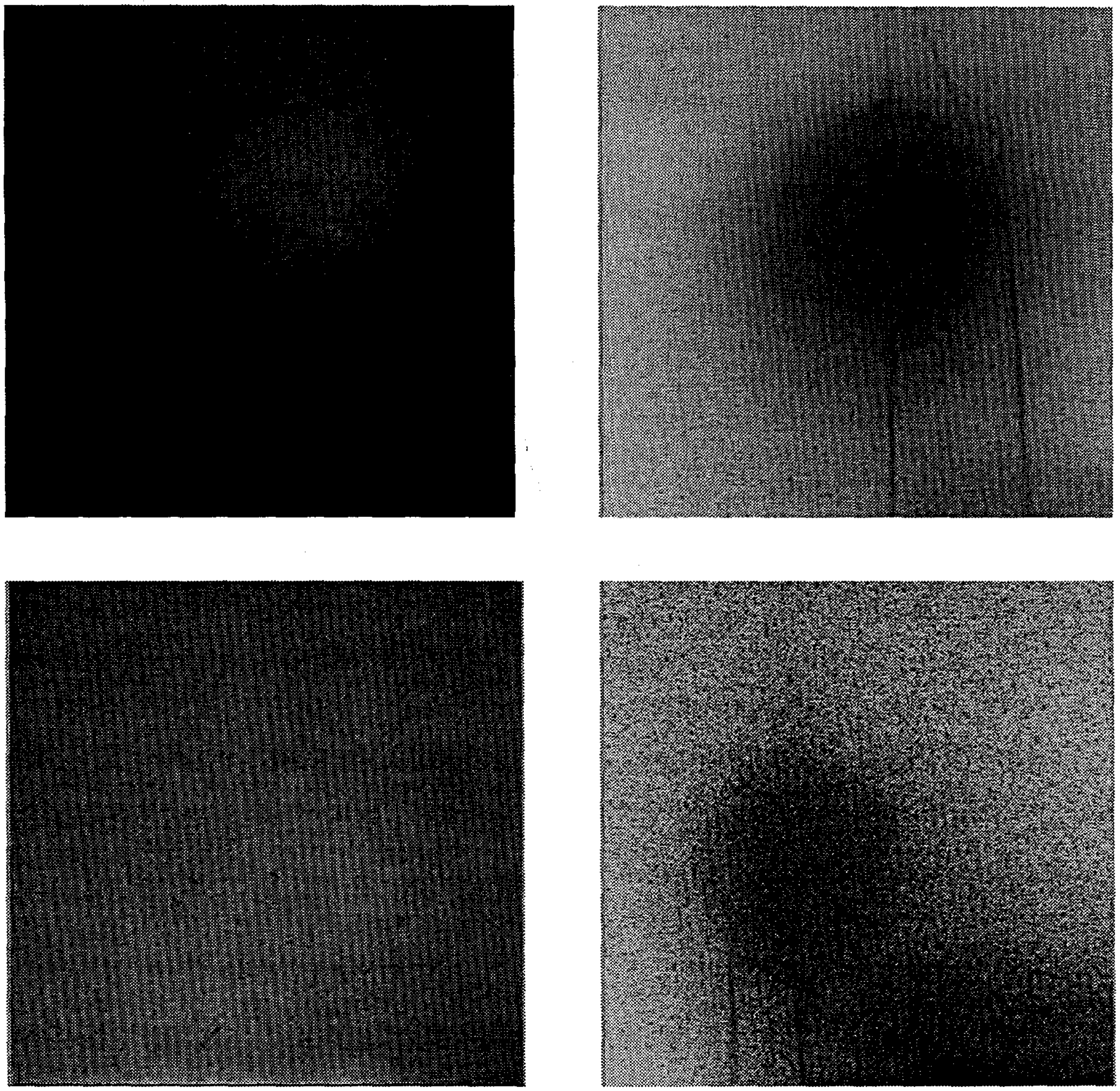


Figure 8. Image pairs with reflectance image on the left and range image on the right for 21-inch sphere at distances of 17 feet from the receiver (top pair) and 33 feet from the receiver (bottom pair). The sphere was suspended 10 feet below the water surface in each case. Water was moderately turbid with $a = 0.07\ m^{-1}$ and $c = 0.26\ m^{-1}$.