A Common Framework of Subsurface Sensing and Imaging

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ABSTRACT

Subsurface sensing and imaging problems arise in a variety of contexts: underground, underwater, inside the human body, and inside a cell or a collection of cells. All of these problems require reconstruction of internal structures or functions from a highly distorted probe or wave sampled outside of an obscuring surface. There is an emerging common framework of physics-based signal processing which will allow progress in any of these areas to be applied to create advances in the other areas. The recognition of the essential similarity of these problems and the development of the common framework is a key to the next generation of environmental and biomedical imaging systems.

Keywords: Subsurface sensing and imaging, tomography, inverse problems, underground, underwater, and medical imaging, 3D microscopy.

1. INTRODUCTION

The problem of imaging under a surface arises is a wide variety of contexts, and these problems are among the most difficult and intractable system challenges known Spread one hundred plastic landmines on top of a farmer's field and they can be safely removed in hours by a worker with a minimum of training. Bury them under one centimeter of soil, and you have a problem that has been the subject of intensive research for over half a century and remains far from solved. State-of-the-art inductive sensors in the hands of an experienced operator can detect non-metallic mines from the signal received from the firing pin and other small metal parts. In typical operation, however, over 300 false alarms are recorded for every mine identified, each requiring lengthy and delicate examination. In the end, operational mine detection systems have little, if any, advantage over probing each square centimeter of the ground with a titanium rod, a process that can clear a field at a rate of 1 meter by 25 meters of ground per person per day. No one has any idea how the three million landmines buried in Bosnia or the 10 million in Cambodia can be removed at any reasonable cost.[1]

De-mining, in common with nearly all subsurface sensing and imaging problems, is an *information* problem. If we knew where the mines were buried, world-wide humanitarian de-mining would require relatively few physical resources. Yet in an Information Age, when the cost of computation and communications is reduced by a sizable fraction each year, the full potential of applying our exponentially expanding information technology sector to subsurface problems has not been realized because of lack of equivalent progress in subsurface detection and identification.

In addition to the technical problems of probes and processing that we will discuss below, we identify two major systems obstacles to progress in subsurface sensing and imaging:
1) the problems of sensor design, modeling, image processing, and recognition have been compartmentalized, viewed as separate disciplines rather than as integrated parts of a *system* optimization problem.
2) the subsurface problems in different media and different length scales are commonly viewed as unrelated problems and addressed with *ad hoc* solutions. Lessons learned in one subsurface technology are rarely applied to other problems, and no overarching theory exists to identify fundamental limitations, predict what can be detected and the optimal way to do it.

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Part of the SPIE Conference on Subsurface Sensors and Applications
Denver, Colorado • July 1999 SPIE Vol. 3752 • 0277-786X/99/$10.00

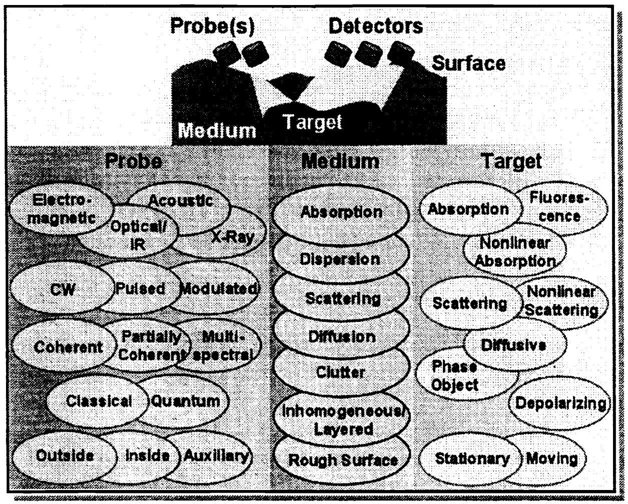


Figure 1. Subsurface problems can be classified on the basis of the probe-medium-target interactions.

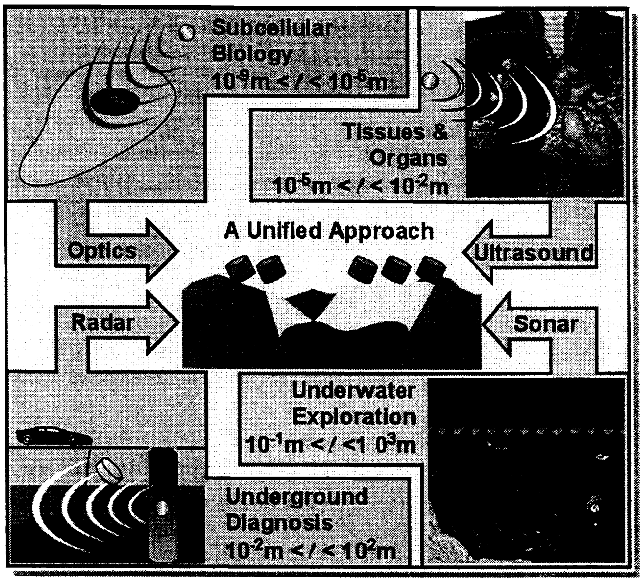


Figure 2. A unified physics-based approach can unite subsurface problems from many domains at different length scales.

The subsurface sensing and imaging problem is to extract information about a subsurface target from scattered and distorted waves received above the surface. Imaging techniques, whether ultrasound sensors in tissue or electromagnetic probes in soil, can be described by the properties of probe wave, the wave propagation characteristics of the medium and surface, and the nature of target/probe interaction as shown in Figure 1.

The framework of Figure 1 describes not only underground imaging, but also underwater imaging, medical imaging inside the body, and 3D biological microscopies inside a cell or collection of cells. A unified theory of subsurface sensing and imaging, as illustrated in Figure 2, should encompass all of these applications and permit progress in one domain to be transparently applied in other domains with similar elements in the taxonomy of Figure 1.

For example, diffusive wave optical imaging for medical diagnosis and crosswell radar/EMI tomography for geophysical exploration both involve extracting an image of, or information about, anomalous regions (e.g., diabetic lesions under the skin or oil-bearing rock formations under the ground; see Figure 3). Although the problems occur on vastly different length scales, both require solution of the frequency-domain diffusion equation in the presence of an inhomogeneous, layered medium, and a need to filter large data sets from multiple transmitters and receivers that are, nevertheless, sparse compared to the information set sought. Attacking these two problems within the same framework allows the synergy of the two solutions to be exploited. Thus, even the critical differences between the two problems (lossy *vs.* lossless propagation, Poisson *vs.* Gaussian noise statistics, the diffusion equation as a limit of the radiative transfer equation *vs.* the diffusion equation derived by neglecting the displacement current in Maxwell's Equations) become a basis for more complete understanding of the unified problem, rather than just an obstacle to applying the same specialized algorithm to each problem.

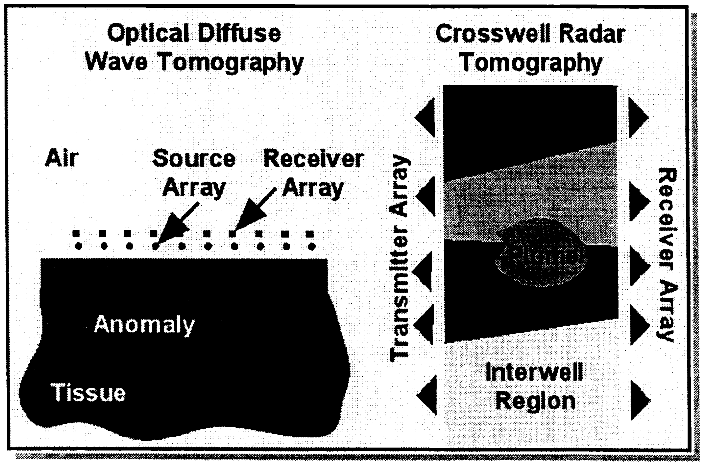


Figure 3. The physical/mathematical framework of diverse problems can be very similar.

2. PHYSICS-BASED SIGNAL PROCESSING

It is rarely the case that we cannot get any information from the subsurface region. The concealing media, while not transparent, can usually be penetrated to a considerable depth by a variety of acoustic and electromagnetic wave probes. The problem is that the target signal is distorted by complex absorption, dispersion, diffraction, and refraction of the wave through the media and obscured by surface reflection, subsurface clutter, and scattered energy from unknown inhomogenieties on many scales. The signal received, y, depends on the target information x and various signal-dependent clutter and nuisance parameters z through the function C which describes the physics of the probe-wave generation, propagation, and target and clutter interaction:

$$y = C(x,z) + n \qquad \textbf{(1)}$$

The inverse problem of un-encoding the signature of the target object x from the received signal y in the presence of unpredictable clutter signals due to z and noise, n, is the challenge of subsurface sensing and imaging.

Since the mapping from the target to the sensor depends on unknown information about the subsurface media and target, the inversion from the scattered wave to the target properties is a nonlinear mathematical problem.[2,3] The use of appropriate physical models of the probe/surface/media/target/ receiver interaction (C in Equation 1) to assist in the solution of that inverse problem is what is referred to as physics-based signal processing (PBSP). PBSP has been identified in a seminal 1998 review article as a key to progress in image formation in complex media.[4] Physics-based reasoning through the entire image understanding process and goal-directed processing will produce algorithms which are robust to modeling errors and generate accurate reconstructions of the critical information.

The fundamental problem of subsurface sensing and imaging is to differentiate the target of interest from irrelevant clutter and scatter, to distinguish a landmine from roots, stones, shell-casing, or ground-surface reflections. In the pulse-reflection ground-penetrating radar (GPR) simulation in Figure 4, for example, the signal from the plastic cylinder in the lower figure is obscured by the rough-surface reflection in the upper figure. The task is to extract the signal from the complex scattered field of random surface irregularities. In principle, if the surface profile and the soil dielectric properties were precisely known, one could subtract the background from the received signal to extract the target signature, but a full 3D calculation of the scattered field for a single pulse could take on the order of 10 hours on a 450 MHz desktop Pentium computer. Problems where the target distinguishing features are comparable to the clutter size, such as demining, are among the most challenging subsurface problems that exist.

One of the primary differentiating features is *shape*. Since resolution in the far-field is limited to order of the wavelength, it is desirable to use probes with wavelengths smaller than the size of identifying features. Unfortunately in most subsurface modalities, absorption increases with increasing frequency (smaller wavelengths). For example, the attenuation of medical ultrasound increases at the rate of 1dB/cm for every megahertz of frequency. Arterial plaque, which can be resolved by inserting catheters containing 30 MHz (λ = 50 μm) ultrasonic probes, cannot be noninvasively imaged from outside the body because the

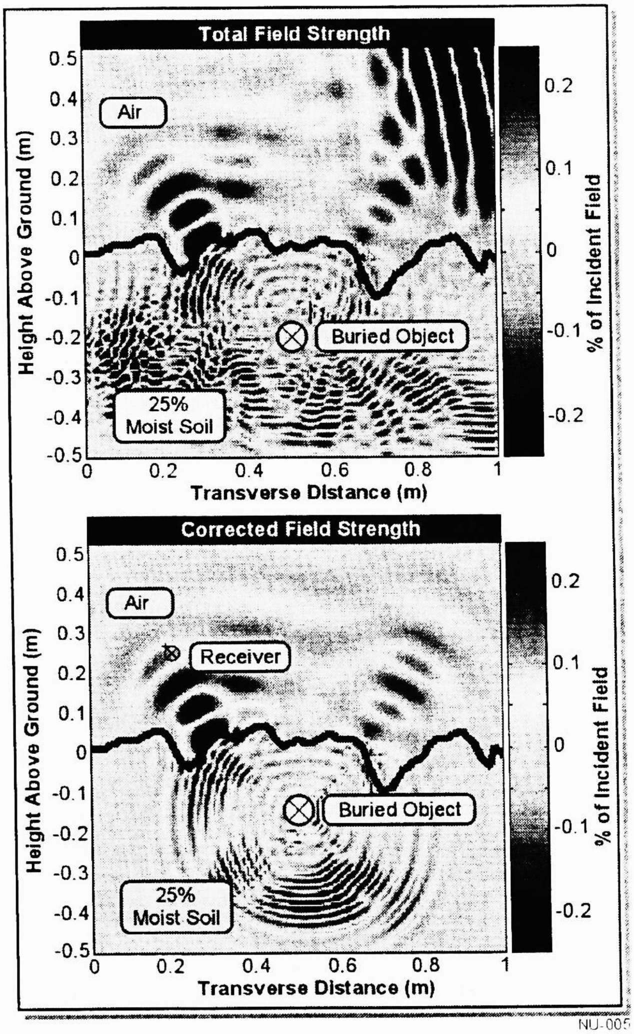


Figure 4. Clutter from rough-surface reflection in the top frame obscures the signature of the buried object in the bottom frame in this pulse GPR simulation.

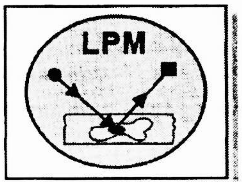
attenuation is too severe (about 30 dB per centimeter of depth at 30 MHz). This range/resolution trade-off is a fundamental limitation on many subsurface modalities including underground seismic imaging and underwater sonar imaging.

Alternatively, probes which are sensitive to target *material properties*, such as to material spectral response (color), conductivity, or magnetic susceptibility, can offer advantages for target differentiation. For example, medical imaging probes such as magnetic resonance imaging or nuclear medicine molecular tags which are sensitive to target chemistry can be used to differentiate targets on the basis of *physiology* (functioning) instead of *anatomy* (structure). Imaging the subtle physiological differences between cancerous cells and normal cells would be a medical breakthrough.

Nonlinear material properties are used for subsurface discrimination in two-photon microscopy[5,6,7] or ultrasonic harmonic imaging. Harmonic imaging can yield diagonostically useful information on the 25% to 30% of the population that cannot be imaged well by ultrasound due to high clutter levels, distortions, and artifacts. Although harmonic imaging is already commercially available, the physical mechanisms behind it are poorly understood.

3. INFORMATION EXTRACTION STRATEGIES

Despite the bewildering variety of imaging modalities and techniques covered in the Figure 1 taxonomy, subsurface problems can be organized into a relatively small number of *information extraction strategies* which use similar algorithmic tools. Three broad information extraction strategies are discussed here.



Localized probing and mosiacking (LPM) concentrates the probe wave on a local subsurface region by focusing or time-gating and then assembles these individual pieces of information into an information mosaic. Common to these techniques are problems of concentration, aberration, and registration which may use tools as simple as a lens or as complex as three-dimensional image matching and reconstruction. For example, medical reflection ultrasound and confocal microscopy both collect scattered energy from a subsurface target voxel. In both cases, precise focusing assumes a uniform homogeneous wave velocity, rarely the case in subsurface imaging, and resulting aberrations impede accurate imaging. LPM techniques are subject to obstruction by opaque objects (e.g., bones), and because reflection geometries are sensitive to high spatial frequencies (interfaces) LPM techniques are poor at detecting low-contrast or phase-only objects.

Wide-scan, high resolution LPM imaging usually requires mosiacking of multiple frames. Figure 5 shows an image of an ocean-floor hydrothermal vent assembled in this way by our collaborators at Woods Hole Oceanographic Institution. Errors in image registration and composition techniques contribute to errors on the scale of meters in the large-scale representation of imaged objects, reducing their utility in quantitative oceanography. The use of high-resolution sonar maps to register the optical images is a multi-modality path to the desired capability for high-resolution mapping of hundreds of thousands of square meters with an accuracy of centimeters.

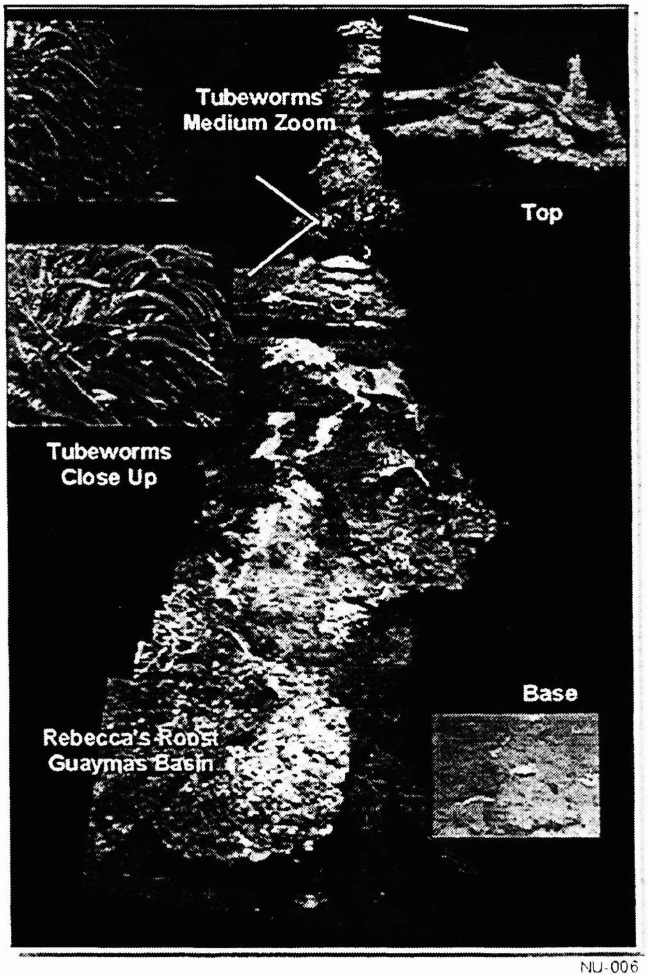
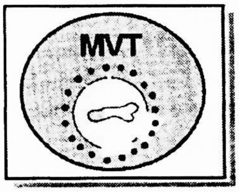


Figure 5. High-resolution underwater optical image of an ocean-floor thermal vent is assembled by 3D photo-mosaicking techniques. (Photo courtesy of Woods Hole Oceanographic Institution.)



In contrast to LPM where the sensor information is spatially isolated, in *multi-view tomography* (MVT) correlated information from multiple sensors is combined mathematically to create a virtual map of the physical properties of the target. These systems all involve mathematical inversion of integral equations through linearization, regularization, and integral transforms. Examples include x-ray CAT scanning, diffraction tomography, and synthetic aperture radar.

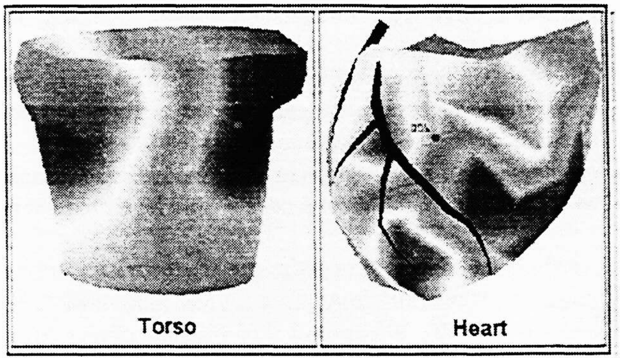


Figure 6. In Cardiac Electrical Imaging (CEI), near-field MVT inversion yields the electric potential on the heart from measured voltages on the torso.

If multiple view angles are possible, MVT techniques can image obstructed/occluded objects and yield quantitative maps of wave velocity as well as absorption, allowing imaging of phase-only objects. For wavelengths that are short compared to feature dimensions, as in CAT scans[8,9], Radon convolution-backprojection algorithms combined with Fast Fourier Transforms (FFT) can achieve 3D feature imaging.

Diffraction tomography[10] is the technique of image reconstruction and resolution enhancement by multiple-view imaging when the wavelength is comparable to feature size. The development of the theory of diffraction tomography by the linearization and Fast Fourier Transform (FFT) inversion of the wave diffraction equations using the filtered back-propagation algorithm was pioneered in the early 1980s.[11,12] Diffraction tomography has been successfully applied for seismic imaging of near-surface objects, including fossil dinosaur bones[13] and to ultrasonic imaging[14,15,16]. Applications of diffraction tomography with limited or obstructed field-of-view or with higher-order, non-linear models is at the forefront of the state-of-the-art.

When the wavelength is long compared to feature size, *near-field* tomographic techniques can still yield useful information in geophysical or medical applications. In Electrical Resistance Tomography and Electromagnetic Induction Tomography, quasi-static probes and models are used to image contaminants in soil and groundwater and leaks from storage tanks on scales much smaller than the electromagnetic wavelength.[17,18] Applications in medical imaging include Electrical Impedance Tomography[19] and Cardiac Electrical Imaging [20,21,22]. Figure 6 shows the electric potential on the heart imaged from the measured potential on the torso by Cardiac Electrical Imaging. The potential benefits of the enhanced information gained by this technique over standard electrocardiograms (ECGs) are enormous. ECGs have a rate of false diagnosis of myocardial infarctions ("heart attacks") as high as 30% which results in unnecessary health-care costs in the U.S. estimated at $4 billion per year [23], while up to 25% of actual heart attacks go unnoticed until evidence of cardiac damage is detected in annual checkups.

Multi-spectral discrimination (MSD) adds the element of frequency discrimination to the spatial resolution sought by LPM and MVT giving a 4-dimensional map (3-space plus frequency) of the object. Combinations of MSD with LPM are common (a color photograph or hyperspectral image are examples). Joint methods for MSD and MVT have received little attention. MSD information extraction methods focus on material dispersion, parameter estimation, image registration, and fusion. Multi-sensor fusion can be viewed as an MSD problem involving, in some cases, probes that differ in modality (acoustic and optical, for example) as well as frequency.

For example, the work illustrated in Figure 7 shows that subtractive imaging at two nearby optical wavelengths can map specific chemical concentrations, such as oxygenated /deoxygenated hemoglobin (Hb).[24] This use of optical spectroscopy to detect chemical indicators of physiological function *in vivo* is promising for diagnostic discrimination. The rich spectral interaction of IR-VIS-UV light with biological molecules, however, causes absorption and strong scattering in tissue [25,26,27] and makes the localization of emergent light difficult. Diffusive Wave Imaging[28,29] in strongly scattering media is the focus of much current research, including optical coherence tomography [30,31,32] and CenSSIS work in *dual-wave* acousto-photonic imaging which seeks to improve spatial resolution from centimeters to millimeters for precise quantitative diagnosis.

Satellite hyperspectral imaging of the Caribbean Basin has been used to determine the health of coral reef ecosystems and measure coastal erosion[33]. Reflected light is strongly scattered in the water column, by the ocean surface, and by the atmosphere, distorting the frequency spectral information as well as the position of underwater objects. This problem is similar to medical diffusive imaging except on a length scale that differs by orders of magnitude. The physics of both are modeled by the radiative transfer equation (RTE) [34]. However, in diffusive medical imaging, the ratio of absorbed to scattered light is assumed to be small leading to the diffusion equation, while in ocean scattering Beer's law is often applied by assuming the ratio is large. In reality, the physical situation in both cases may be intermediate, and there is a need for more rigorous forward models and more robust inversion algorithms. Current spatial resolution from space-based platforms is approximately 1 meter; processing techniques that take advantage of accurate physical models may improve the resolution limit to 10 centimeters.

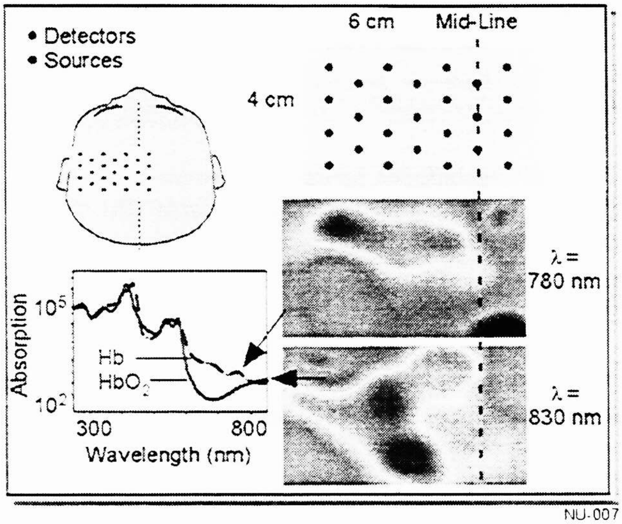


Figure 7 MSD analysis of diffusive optical waves images areas of activity (high blood oxygenation levels) in infant brain.

4. RESEARCH NEEDS AND BARRIERS TO PROGRESS

Progress in subsurface sensing and imaging approaches within these information extraction strategies has been documented in the feature articles in a recent issue of Science ("*Imaging: New Eyes on Hidden Worlds*")[35]. Key elements in these advances include the increase in computation power, the application of new mathematical algorithms and advanced sensing strategies, the exploitation of wave coherence, and the fusion of multiple sensing modalities (e.g., microwave and infrared) to extract increasingly detailed information from physical systems.

Still, the need for new technologies is clear. The General Accounting Office has stated, "the dimensions and potential costs of cleaning up our environment are so great that, without innovative technologies, we may find the solution cost prohibitive and impacting on our ability to address other national needs." By using current technologies, the costs of remediating Superfund and Resource Conservation and Recovery Act sites, Federal facilities, and other known hazardous waste sites may total $750 billion over the next 30 years[36]. Humanitarian de-mining remains an unsolved problem. No current imaging technique can adequately detect precancerous cell masses in soft tissue or noninvasively diagnose arteriosclerosis, and there is no way to collect and correlate the images from different modalities to automatically identify incipient health problems.

Barriers to such advanced civil-environmental and biomedical detection systems lie both in unsolved fundamental research problems and in lack of adequate technology tools. Some of the major barriers are:

Barrier 1: Fundamental knowledge is lacking about nonlinear interactions, dual-wave sensing mechanisms, and coherent imaging in scattering media. While linear acoustic and electromagnetic interactions can be modeled and characterized by well-understood linear response functions, advanced imaging techniques using non-linear or dual-wave (*e.g.*, acoustic/optical) probes require fundamental investigations to determine appropriate physical models.

Barrier 2: The present formulation of coherent inverse scattering is inadequate to quantitatively image objects in highly-scattering random inhomogeneous and cluttered environments. In these situations the non-linear character of the inverse problem defeats tomographic reconstruction and adequate alternatives do not yet exist.

Barrier 3: Recognition strategies for obscured and limited-view subsurface applications are not well developed, and we have no theory for combining different sensor inputs to optimize the information obtained.

Barrier 4: Forward modeling of large complex scattering geometries is too slow for real-time inverse-processing applications.

Progress is required in both efficient approximate forward solvers and in hardware/software implementation of processing.

Barrier 5: There are few widely-available test facilities with sufficient flexibility and sensor reconfigurability to permit the optimization of sensor modality/configuration and processing strategies based on recognition and decision objectives.

Barrier 6: Techniques for rapid processing, cataloging, storage and retrieval of large image databases are not sufficiently developed. Data and metadata standards will need be instituted so that processing algorithms can be routinely tested on experimental results from diverse experimental domains.

5. CONCLUSION

The pieces are in place for a major advance in the field of sensing and imaging. The development of a common framework and unified disciple of subsurface sensing and imaging promises to allow the field to emerge as a co-pillar of the Information Age, along with computation and communications. We can look forward to systems-level advances such as integrated, field-tested, algorithmic and computational tools for the entire range of subsurface problems, and standards and criteria for the use of multiple sensing modalities to achieve subsurface sensing system goals. These, in turn, will open the door for the next generation of systems for environmental sensing underground or under the water, medical imaging and automatic diagnosis inside the body, and biological microscopy to reveal fundamental processes inside living cells.

ACKNOWLEDGEMENTS

We would like to acknowledge the invaluable assistance of our many CenSSIS colleagues in developing the concepts presented in this paper. In particular, we would like to thank Bahaa Saleh for the concept of Figure 1, Eric Miller for Figure 3 and the related discussion, Hanu Singh and Jon Howland of Woods Hole Oceanographic Institution for Figure 4, Charles DiMarzio and David Boas for Figure 6, and Dana Brooks for Figure 5. We are especially in the debt of David Castanon for his elucidation of the concept of information extraction strategies. Valuable communications with Ron Roy, Robin Cleveland, and Tom Szabo are gratefully acknowledged.

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