Inductive and Capacitive Sensor Arrays for *In Situ* Composition Sensors [1][2]

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Abstract—Advances in electromagnetic sensor design provide the potential for high resolution imaging of subsurface objects and material properties at the microscopic (micrometer) and mesoscopic (meter) scales. With quasi-static, capacitive and inductive sensor arrays, objects are detected, identified, and imaged via their perturbations to the applied electric and magnetic fields, rather than through time delays of reflected electromagnetic waves as in ground penetrating radar. Building on the successful application as nondestructive quality assessment and monitoring tools as well as land mine detectors, several sub-surface *in situ* sensors are enabled by this technology. Examples include: an electronic 3D microscope, enabling examination of cell level structures and composition; examination of near surface structures such as, soil moisture, permafrost dynamics, soil properties with depth, root growth carbon sequestration, Martian surface aquifers, and buried deposits of carbon dioxide or methyl hydrides.

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1. Introduction

An *In situ* Sub-Surface Composition Sensor is an extension of observational research into the quasistatic frequency range and represents a fundamentally new observation regime. Multiple frequency measurements using both inductive and capacitive sensing techniques, along with unique sensor geometries, provide new characterization capabilities for both bulk materials and hidden objects. As an example, dielectric spectroscopy can be used to detect and identify subsurface objects when the dielectric properties vary with frequency. Sensor array designs with controlled spatial distribution provide property imaging and depth profiling capabilities, which can enable significant increases in mission performance while reducing costs of scientific measurements

The range of practical science applications for quasi-static capacitive and inductive sensor arrays is quite extensive. Using spectroscopic (multiple frequency 1Hz - 30MHz) measurements provides for materials characterization and categorization (see Figure 1). Our aim in this paper is to answer:

- What are quasi-static, capacitive and inductive sensor arrays?
- What are the possible applications and instrument concepts?
- Why is it important scientifically to observe detailed composition distributions within a volume via *in situ* sensors?
- How can these observations be accomplished?
- What has been done to date?
- What are possible future directions?

In particular, using sensor arrays to measure sub-surface composition on micrometer to meter scale sizes will be discussed. Items that are under study include: resolution capabilities, composition sensitivity, power requirements, robustness, and potential for causing or receiving interference. The near term applications are near sub-surface

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exploration, on solar system bodies. Potential longer-term applications are in life science, astrobiology, pedology, geology, hydrology, and medical diagnostics.

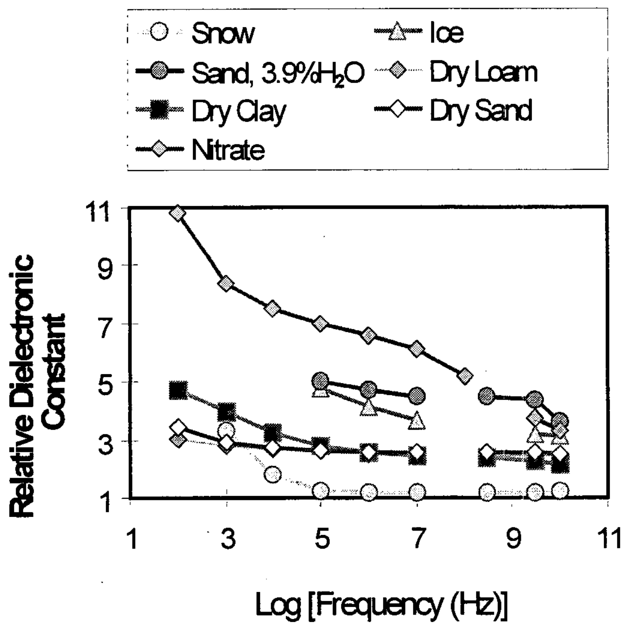
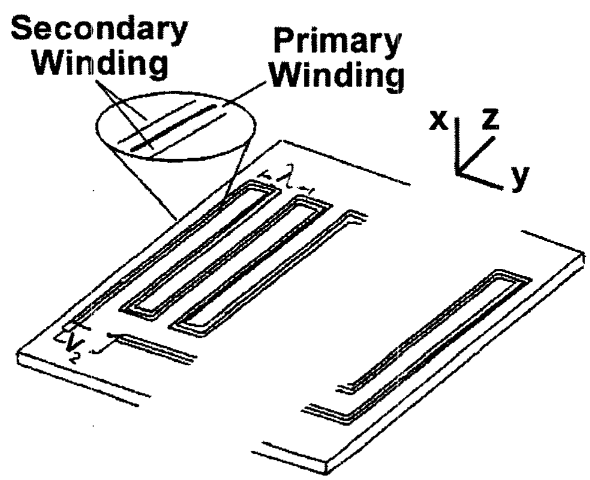


Figure 1. Variation in Dielectric Constant (from literature, e.g., Von Hippel)[1] for various materials of interest in the EQS regime.

2. The Technology and Its Basic Capabilities

Unlike radar-based imaging technologies, such as ground penetrating radar (GPR), quasistatic imaging technologies operate at small spatial dimensions compared to the wavelength of traveling waves at the operating frequencies. Thus, the electric and magnetic fields are effectively decoupled. Magnetoquasistatic (MQS) devices, such as metal detectors, that impose magnetic fields satisfy the diffusion equation in conducting media and Laplace's equation in air or poorly conducting soils. Electroquasistatic (EQS) devices satisfy Laplace's equation. In Laplacian or diffusion decay, the amplitude of the magnetic and electric fields decay exponentially with distance from the drive windings or electrode. As a result nearby objects are imaged and identified via the distortions to the applied fields rather than through time delays of the reflected waves as in the case of GPR. Both sensor technologies can be operated in the continuous wave (over a wide range in frequency 0.001Hz to 100MHz) or pulsed mode, although efforts to date have focused on the continuous wave mode. In addition, sensors can be fabricated from lightweight conformable materials that should be storable in a compact format for transit and deployment in the "field".

The eddy-current (inductive) sensor technology is based on the Meandering Winding Magnetometer (MWM™) geometry and the interaction of magnetic fields with test materials. MWM sensors consist of a spatially periodic meandering primary winding for creating the magnetic field and meandering secondary windings located on opposite sides of the primary for sensing the response. The secondary elements respond to perturbations in the magnetic field caused by the presence of conducting and/or magnetic materials and variations in these properties. The windings are typically mounted on a thin and flexible substrate, producing a conformable sensor. The sensor was designed to produce a spatially periodic magnetic field in the material under test (see Figure 2), which permits the sensor response to be accurately modeled and dramatically reduces calibration requirements.



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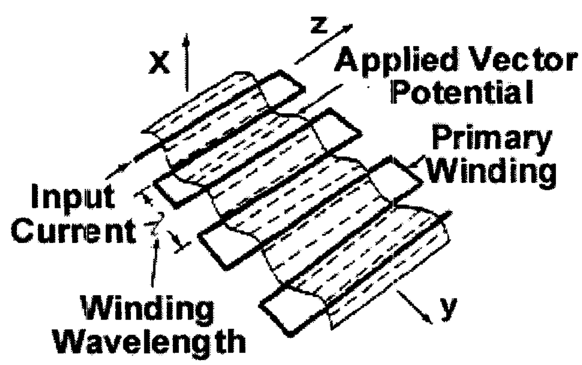
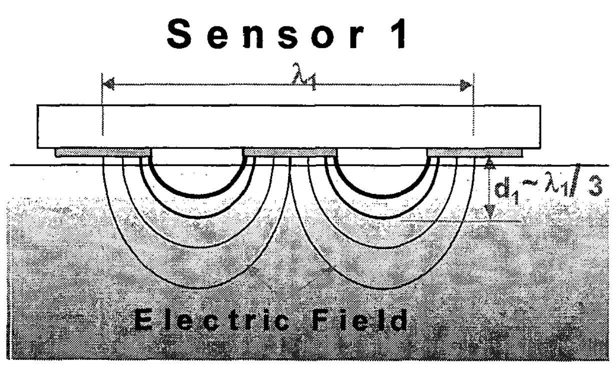


(b)

Figure 2: (a) A Meandering Winding Magnetometer (MWM™), (b) a "sinusoidal" magnetic vector potential for the dominant Fourier mode of the MWM.

The dielectrometer (capactive) sensor technology is based on the interdigitated electrode dielectrometer (IDED) geometry and the interaction of electric fields with test materials. IDED sensors consist of a pair of intertwined electrodes that can be thought of as two parallel plate electrodes laid flat to lie in a single plane to cause a fringing electric field region that penetrates into the unknown dielectric (see Figure 3). One set of electrodes are driven by a sinusoidally time varying voltage to create the electric field while the voltage or current at the second set of electrodes serves as the sense response. Since the depth of penetration of the electric field into the material at a given frequency is proportional to the spatial repetition of the periodic electrodes. Small electrode gap sensors primarily respond to changes of material properties near the sensor-dielectric interface while larger gaped sensors respond to changes farther from the sensor interface. Therefore, multiple wavelength sensors can be used to measure spatial profiles of dielectric properties. As with the MWM sensors, the IDED sensors can be micro fabricated onto flexible substrates and can be accurately modeled when in the presence of layered materials. IDEDs can be used to study moisture concentrations at the micro and meso scales.



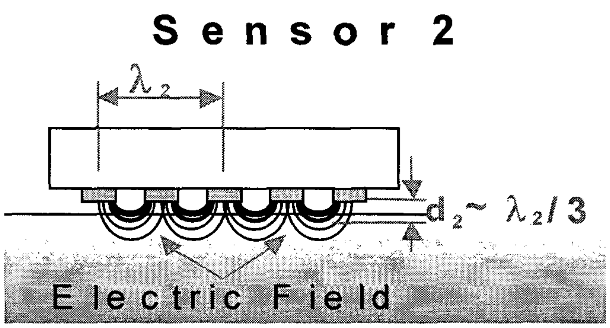
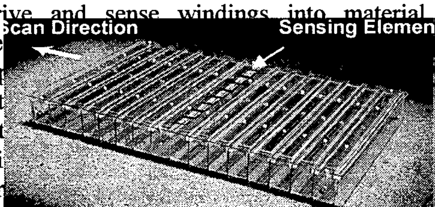


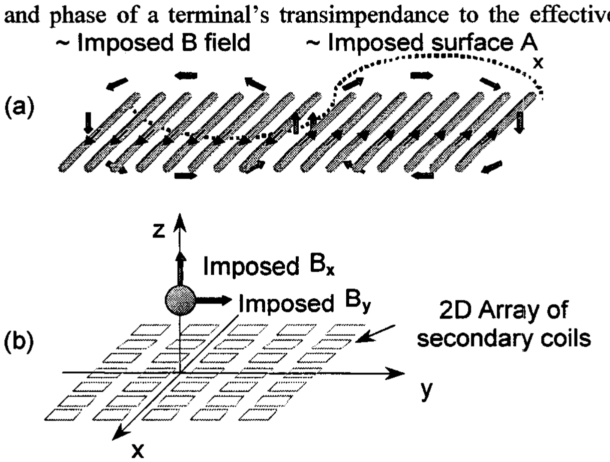
Figure 3. Variation of electric field depth of penetration with spatial wavelength for an interdigitated electrode dielectrometer (IDED) sensor with different spatial wavelengths, λ.

For rapid imaging applications, arrays of sensing elements within a single sensor footprint can provide real-time images of material property variations. This is particularly useful for characterizing property profiles (such as coatings, process-affected zones, or soil conductivity) and the detection of objects or flaws (such as cracks, roots, or land mines). These sensor arrays use novel winding or electrode geometries that promote accurate modeling of the response. This eliminates many of the undesired differences in the response of the sensing elements in existing arrays, such as the cross coupling between individual array elements. For example, an MWM-Array has demonstrated accurate measurements of depth and size for objects of known shape when applied to the detection of landmines and unexploded ordnance [2]. In this array, the inductive drive winding is configured to create one spatial period of a sinusoidally shaped magnetic vector potential so that the associated magnetic field also has sinusoidally shaped vertical and horizontal components (see Figure 4). The magnetic fields are essentially uniform across the primary so that secondary elements placed across the width of the array are exposed to the same magnetic field. This facilitates imaging of property profiles and objects as the array is scanned across the surface. A 2-dimensional array of secondary elements can also be placed within the footprint of the primary winding to create an image without scanning.

Similarly, capacitive sensor arrays have demonstrated the capability to detect both metal and plastic objects, measure moisture profiles as a function of depth, monitor independently both permittivity and air gap thickness for noncontact property measurements, and discriminate between material types. Scanning arrays provide the unique capability to segment the electric field sensed by the array sensing elements to create quantitative images. Other arrays use segmented electrode to provide sensitivity to field components with different depths of penetration into the ground (see Figure 5a). This facilitates profiling of material properties with depth. These arrays also support dielectric spectroscopy to differentiate material types and conditions, such as moisture content.

Converting the measured the terminal impedance between the drive and sense windings into material properties require[...] can be accomp[...] parameter estimat[...] real-time propert[...]er method for esti[...]generating measur[...]riables to variations in two of the material or geometric properties, and then using a table look-up algorithm to obtain real-time material properties. These grid measurement methods use a database of sensor responses to map the measured signals into the properties of the material. The database is derived prior to the data acquisition, using a "forward model" of the sensor response with either a continuum or a finite element model for the sensor and specific problem of interest. The measurement grids are two-dimensional databases that relate two measured parameters to two unknowns. The magnitude and phase of a terminal's transimpendance to the effective





conductivity and liftoff (the distance of the material to the plane of the windings) is an example (see figure 5b). Novel measurement environments will require solving the inversion problem directly.

(c)

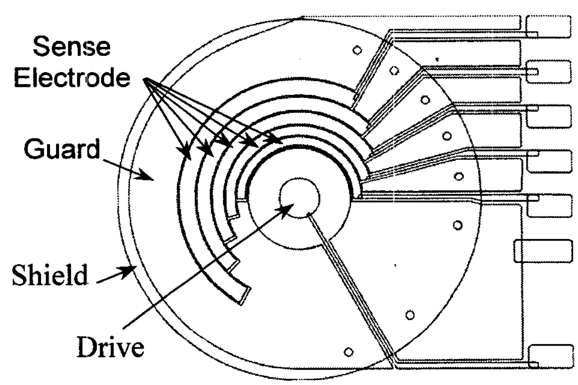
Figure 4. (a) MWM-Array drive winding design and schematic representation of current and field distribution around the primary, (b) 2-dimensional array of MWM-Array sensing secondary coils, (c) photograph of an MWM-Array with indicated secondary sensing elements.

3. Instrument Concepts and Possible Applications

Two basic instrument concepts, microscope on a chip and time resolved mapping of complex sub-surface (or internal) composition and structure are of interest. We will discuss the basic instrument design concepts and known operational environments for the MWM and IDED sensor arrays in each of the spatial scales (micro and meso).

Fundamental Questions

One of the fundamental questions that lie at the core of space science is "Does life in any form, however simple or complex, carbon-based or other, exist elsewhere than on planet Earth" [5]. To answer this question we must use a whole host of complimentary tools including those that allow us to practically examine the sub-surface environment. A non-destructive approach offers significant advantages for both the initial identification of likely samples but also the surrounding ecosystem.



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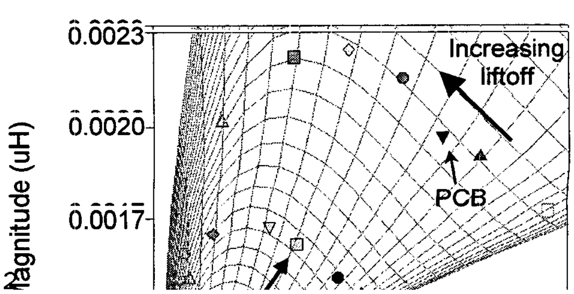


Figure 5. (a) A dielectric sensor with multiple sensing elements within the same sensor footprint (b) A permittivity-liftoff grid with representative measurements as the air-gap spacing between the sensor and insulating, rigid test samples is varied.

The applicability of this technology is in two major areas. The first as a complementary tool providing basic subsurface mapping (cm to m) for core sampling, tunneling, drilling, or digging activities for sample study and return missions as well as for development of natural *in situ* resources (i.e., locating water on Mars), the second as direct measurements of the physical properties under study. In essence, a site assays both in the mineralogical and biological senses. Interestingly, this direct measurement sensor array technology could be incorporated in to the drilling and tunneling equipment to provided additional information in the *in situ* local environment.
In situ, sub-surface, examination is applicable to several areas including: the identification of samples to return to Earth, detection of organic compounds, and measurement of a sub-surface physical characteristics both chemical composition as well as possible biological material. The potential for simple, robust, storable, constructs of the sensor arrays makes them ideal for use in the wide range of environments of interest to the NASA Space Science Enterprise.

Within the NASA Origins program [6] progress on several fundamental questions can be made using these sensor arrays. In particular the questions of "How does life begin and develop", "Does life exist elsewhere in the universe", and "Whether there is (or once was) life elsewhere in our solar system". Exploration of the subsurface probably offers the only credible opportunity to find extant life on either Mars or Europa [5]. The needs for *in situ* surveys of exogenous organic matter and composition analysis of comets and asteroids; non-disruptive high resolution studies of microbial ecosystems and associated communities; direct evidence for liquid water on Mars; and surveys of composition and morphology in the 10 m to 4 km scale is well established by the Space Science Strategic plan.

In the longer term, the NASA Strategic plan [7] calls on the Space Science Enterprise to obtain scientific information in support of human exploration of space. In particular, to investigate the composition, evolution, and resources of Mars, the Moon and small bodies through *in situ* measurements and sample return missions. This would then be followed by the identification of locales and resources for future human exploration, use, and development of space.

Instrument concepts

The application of quasi-static capacitive and inductive sensor arrays represents a fundamental breakthrough in sub-surface sensors. This technology is applicable across multiple mission concepts both near term and far. This fundamental nature is demonstrated by the very broad range of and scale over which the technology operates. The development of this novel *in situ*, sub-surface instrument technology is applicable to multiple research domains from microscopic *in vivo* biological studies to macroscopic geological structures.

Building on the successful application of capacitive and inductive sensor arrays as nondestructive manufacturing quality assessment and condition monitoring tools and as land mine detectors [2] several sub-surface *in situ* sensors are enabled by this technology. At the microscopic (Micrometer) scale is a Microscope on a Chip, in essence an electronic 3D microscope with no optics. This has the potential of enabling the examination of cell level structures and composition, and the identification of particular biological molecules. A more modest capability for compound identification in the surrounding environment such as a submersible vehicle or as a part of a drill shaft is also possible.

On the mesoscopic (meter) scale examination of near surface structures such as root distribution, carbon sequestration, deep sea, tidal or intertidal communities, soil moisture content and distribution, permafrost dynamics, and soil physical and chemical properties with depth in possible [3,4]. For Micromissions and Outer Solar System Missions the sensor arrays can be micro fabricated onto flexible substrates, thus, reducing mass requirements as well as allowing for integration of the arrays into the structural components.

Finally, the identification of natural resources, their location, extent, distribution, structure, and composition is possible. Examples of this use would be identifying the extent and depth of permafrost across regional scales or locating and mapping of Martian aquifers or buried deposits of carbon dioxide or methyl hydrides [3,4].

Possible Environments

Three main areas of mineralogical assay of comets and asteroids could benefit from a low power, low mass sensor Hyper-Spectral Volumetric sensor. The first area of investigation is the basic physical properties of the body. The internal structure and distribution of materials, and the extent of differentiation will contribute to our understanding of solar systems formation and evolution.

The second main area is in commercial mining and manufacturing in space. Good compositional assessments of small solar systems bodies will be critical to the eventual viability of resources utilization. Knowing which asteroid or comet has needed raw materials will be critical to the financial success of commercial raw material mining and manufacturing in space [9,10].

Finally, the third area is in the realm of planetary defense. The NEAR mission has shown that the knowledge of the internal structure of a potential Earth impacting asteroid or comet is critical to a realistic risk assessment and to any possible mitigation plan, such as course adjustment [11].

Observations of global planetary or Earth system are critical for the success of NASA's Earth Science Enterprise, the Astronomical Search for Origins, and Solar System Exploration science themes. Characterizing and monitoring the global systems requires observing systems that are space-based, surface-based, and *in situ* [12]. Remote sensing scientists have especially been challenged to profile below a planet's surface into the sub-surface (soil or ice). With the exception of technologies such as ground penetrating radar, which tends to be cumbersome and site specific, the major success, even on Earth, in characterizing sub-surface properties has been the use of certain radar techniques to identify moisture content in the top few centimeters of the soil [13]. In general, tools such as the Normalized Difference Vegetation Index [14] or other indices of vegetation growth have had to serve as surrogate measurements to identify soil properties [15]. Given the distinct lack of observable vegetation this approach is not feasible on other solar systems bodies.

The soil system, or Pedosphere, plays a critical role in the functioning of the Earth system in that it regulates flows of matter and energy through each of the other geospheres [16]. A similarly critical role is expected for the Pedoshere on other bodies as well. Thus, measuring and monitoring soil properties over space and time will provide insight into ecosystem changes especially in response to global change and land use.

Several essential *in situ* measurements could be made with the inductive and capacitive array sensors. These measurements are not just for one location or depth but for larger volumes and areas as well. Examples of required measurements [3,4] from several research domains that would be possible using the proposed sensor arrays include:

- *In situ* observations of snow depth and water equivalence; depth and structure of river and lake ice; and soil moisture and salinity over time
- Soil properties such as the amount and depth of organic carbon, nutrient content, bulk density, mineralogy, particle size distribution, porosity, iron and aluminum oxide content, depth and extent of permafrost, and rooting depth are possible with this sensor technology.
- Hydrologic properties such as ground water storage fluxes, suspended sediment, and the associated transport of biogeochemicals are of significant interest

4. OBSERVED INSTRUMENT CHARACTERISTICS

Preliminary measurements with the scanning arrays have been performed. This includes numerous measurements at JENTEK's indoor landmine/unexploded ordnance (UXO) test facilities, described in [17], as well as limited measurements performed over the calibration portions of the Fort A.P. Hill test lanes. These measurements were performed under a Phase II SBIR for the Army, which ended in October 1999.

Inductive Sensor Arrays

Representative scan images taken with the prototype MWM-Array and an eight element secondary array are shown in Figure . These images were taken over sections of the calibration portions of the Fort A.P. Hill test lanes and clearly indicate the low metal TS50 and VS50 anti-personnel mines and the metal M21 anti-tank mine. The estimated landmine locations are in good agreement with the nominal positions, but incorporating a position encoder into the scanning array should improve the consistency of the measured image position of the landmine. The large image size of the M21 required the concatenation of several scans as a single pass of the MWM-Array scanned approximately 30 cm across the lane and extra scans were required on either side of the landmine so that the sensing elements on the far side of the array would not respond to the presence of the mine. A larger array (2 m by 1.6 m) has been fabricated at JENTEK, as described later. This imaging capability has also been demonstrated for a variety of landmines and UXO's buried in indoor and outdoor test lanes at JENTEK, as illustrated in figure 7. To date high resolution images are obtained with slow scan rates of order 0.1 m/s but reasonable images are also obtained at high scan rates greater than 0.5 m/sec. Instrumentation improvements that exploit the parallel processing capability of the data acquisition should provide for faster scan rates (over 1 m/s) and images more suitable for shape filtering. This instrumentation should be available for testing at Fort A.P. Hill in the summer of 2001.

Preliminary measurement scans have also been performed on several anti-personnel mines. The position of the landmines indicated by the image is in good agreement with the nominal position calculated from GPS measurements as indicated by the cross-hairs. Figure 6a shows a representative scan over VS50 and TS50 landmines buried to a depth of one inch in gravel. Although the VS50 is detectable, the TS50 is near the threshold of detectability for this 1st prototype MWM-Array. This is not surprising since this MWM-Array was initially designed for the detection of metal mines, not for low metal content mines. Modifications to the sensor design and electronics are being implemented by JENTEK Sensors to increase sensitivity for the detection of low metal content mines.

Capacitive Sensor Arrays

Numerous measurements performed with a capacitive sensing array and landmines buried in a laboratory sandbox established the base capability of this measurement approach. Figure 8 shows images for an M14 landmine buried at several depths, with sensitivity to the presence of the landmine lost at a depth of approximately 3 cm. With a nominal air gap liftoff distance of 2 cm, the total depth of sensitivity is approximately 5 cm below the sensor, which is consistent with the approximation that dielectric sensors have a depth of sensitivity of roughly one-quarter of a wavelength, which is 20 cm for this capacitive sensor. Figure 8 shows several images for an M14 buried to a depth of 1 cm for several scan rates. While the image is distinct at speeds up to 0.5 ft/sec., it degrades noticeably at scan rates greater than 1 ft/sec. Advances in the speed of the data acquisition and instrumentation electronics are expected to provide for higher scan rate without degradation, which would be suitable for real-time measurements in the field.

The potential material discrimination capability of the capacitive sensing array is illustrated in Figure 6 for a measurement scan over a VS50 and an M14. The M14 has a lower permittivity than the surrounding soil that causes a decrease in the local capacitance. The metal containing VS50 has a higher effective permittivity than the surrounding soil that causes an increase in the local capacitance. The effects of surface roughness are also illustrated, as the surface was hand-smoothed. Although both landmines are detectable, the undulations in the sand surface affect the sensor response and motivate the use of grid methods for compensating for the soil property variations.

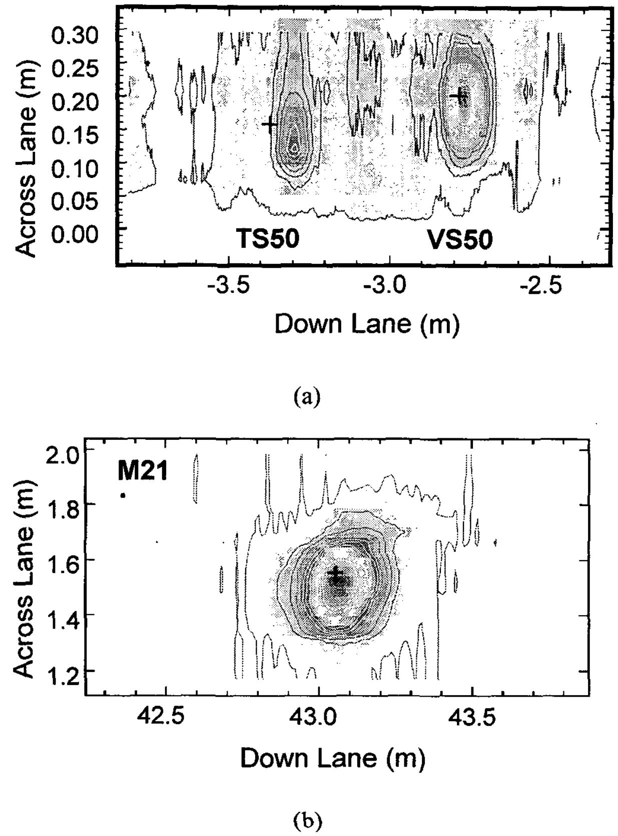


Figure 6. Preliminary scans over (a) low metal content anti-personnel mines and (b) an anti-tank mine.

To illustrate the use of measurement grids to perform non-contact dielectric property measurements, consider the new sensor geometry and grid of Figure 5. The circular multiple wavelength electrode sensor, shown in Figure 5a, is suitable for the characterization of layered dielectric materials and the detection of objects and/or flaws in dielectric materials. A time-varying electrical voltage is applied to the drive electrode, which creates a fringing electric field that couples to the other conductors through the material under test (MUT). The currents to segmented sensing electrodes are then measured, so that the ratios of the currents to the applied voltage (transadmittance) can be related to the properties of the MUT. Guard and shield electrodes minimize stray coupling to the sensing electrodes. The multiple sensing elements provide sensitivity to multiple depths of penetration and different spatial wavelengths for the imposed electric field. The smaller diameter sense electrodes are sensitive to the portions of the electric field with small penetration depths, while the larger diameter sense electrodes respond to the portion of the electric field that have large penetration depths. Thus, the use of multiple sensing elements allows the spatial profile of dielectric materials to be measured.

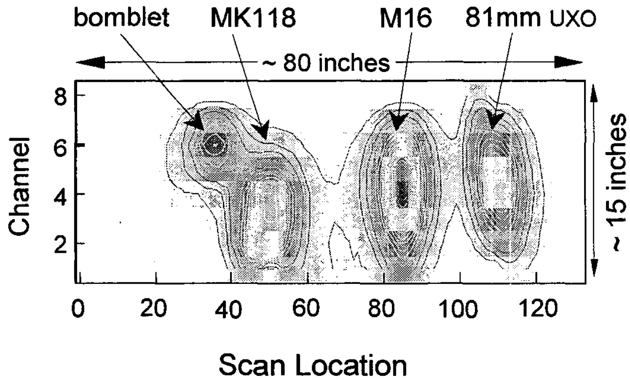


Figure 7. Representative scan images over several landmines and UXO objects buried at JENTEK's indoor landmine/UXO test facility [17]. The bomblet, MK118, M16, and 81mm UXO are buried at 2.5", 3", 5", and 3" respectively.

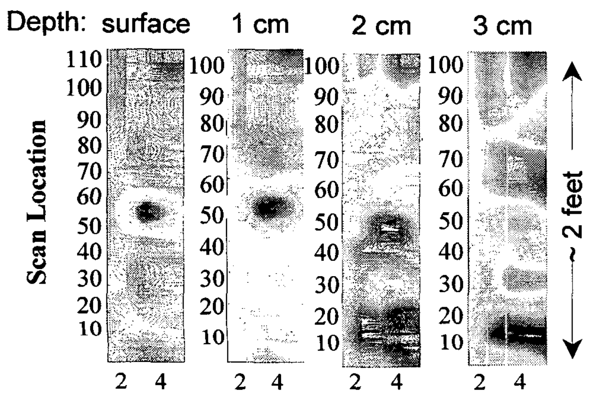


Figure 8. Scan images of the capacitive sensing array over an M14 landmine buried at several depths in a sandbox.

The measured transadmittance was converted to property values using measurement grids. A representative grid for measurements on insulating materials is shown in Figure 5b. In this case, the magnitudes of the transadmittances from two of the sensing elements are used to create the grid. The grid illustrates the dependence of the sensed magnitudes on the dielectric constant of a material with a known thickness and the air gap between the MUT and the sensor. Sets of data points for two different materials, each 1.58 mm thick, are plotted on the grid of figure 5b as the air gap was varied. The first material is Lexan™, which has a dielectric constant of approximately 3.2, while the second material is a printed circuit board substrate material, which has a dielectric constant of approximately 4.6. The flat and rigid sample materials were suspended above the face of the sensor to simulate non-contact measurements of the materials with various liftoffs or air gaps. For each material, the sample points approximately follow lines of constant dielectric constant, which illustrates the use of multiple wavelengths to provide non-contact measurements of the material dielectric constant. This approach can also be applied to buried object detection to compensate for variations in the soil properties or surface undulations.

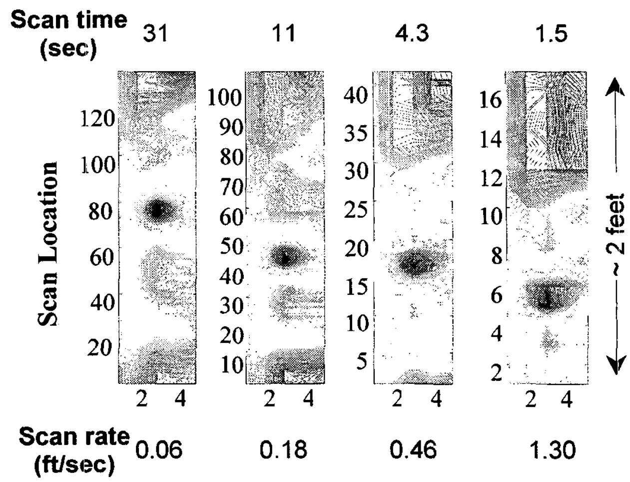


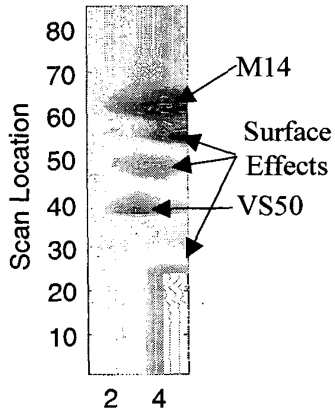
Figure 9. Scan images of a capacitive sensing array over an M14 landmine buried to a depth of 1 cm with a 2 cm standoff between the sand and the sensor.

5. Ongoing Developments

While these sensing arrays have demonstrated an imaging and discrimination capability that have the potential to greatly improve the ability to detect landmines and UXO, numerous improvements are required before a field-deployable technology will be available. These improvements include the development of high resolution, wide area scanning arrays, enhanced instrumentation, the use of multiple excitation frequencies, and enhanced clutter suppression algorithms.

High Resolution, Large Scale Arrays

The use of sensor arrays provides the capability of creating two- and possibly three-dimensional object images, which is a fundamental requirement for spatial image processing. Although preliminary imaging efforts, under both laboratory and field test lane conditions, have been limited to plotting of magnitude or phase of the transimpedance as a function of position, ongoing efforts are focused on developing higher resolution imaging arrays and more sophisticated imaging algorithms to discriminate object features and shape. When combined with the grid measurement methods, estimates of the object properties from each of the elements in the array provides a large amount of redundant information that could be used to improve property estimates and ultimately, to construct three-dimensional object images.



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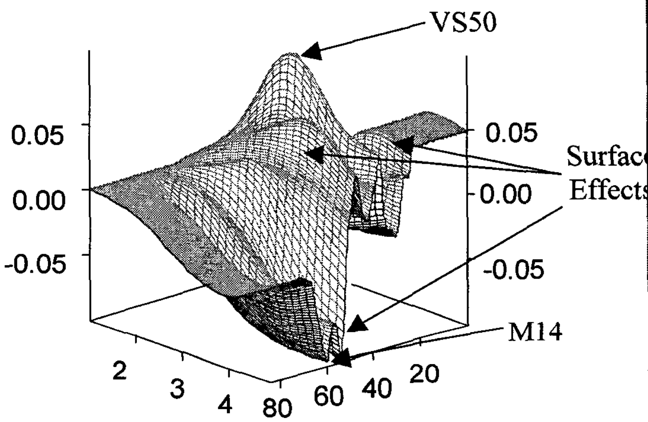
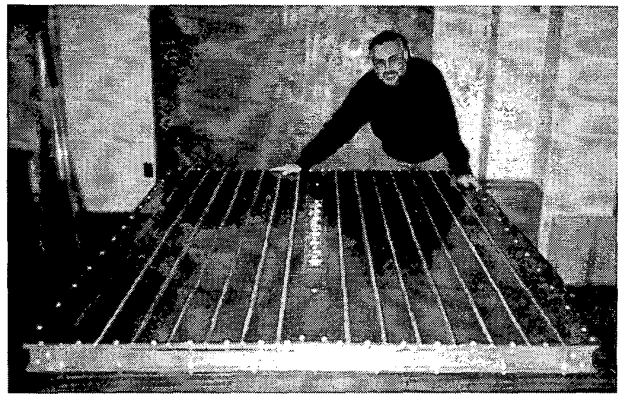


(b)

Figure 10. (a) Scan image and (b) surface plot of the differential capacitance over a VS50 and M14 landmine and a hand-smoothed sand surface.

In addition to the high-resolution elements for creating images, wide areas can be scanned rapidly using large-scale arrays. One such array that uses the shaped field approach is shown in Figure 11. This array has a 2 m by 1.6 m primary winding and currently has a single row of eight secondary elements. Additional elements distributed across the width and length of the array will eventually provide a higher resolution imaging capability both when the array is scanned and when the array is stationary.



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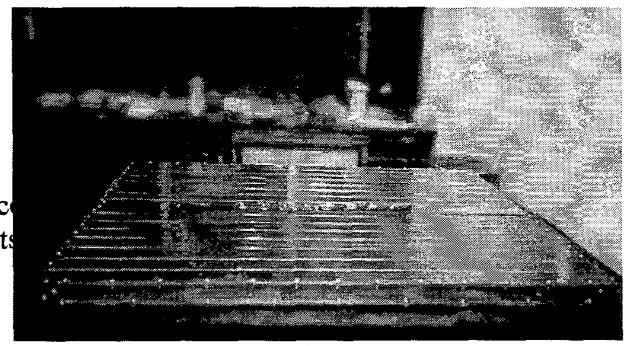

(b)

Figure 11. Large scale MWM-Array for creating high-resolution inductive images of buried objects over wide areas.

6. Summary

The identification and distribution of surface and subsurface materials are of vital importance to answering the Space Science questions of where to look for life and its signatures. Quasi-static capacitive and inductive sensor arrays have the potential of radically altering the search for life.

Application of this technology will make significant contributions in several scientific research areas. In particular: active *in situ* sensors for bio-signatures, and physical and chemical properties. The application of array technologies and extensions into the quasistatic frequency range of dielectric spectroscopy represents a fundamentally new observation regime. Sensor array designs with controlled spatial wavelengths provide property imaging and depth profiling capabilities. Although it is still quite early in the development of applications for sub-surface composition sensors the initial results show both promise and problems. The promise is detailed non-disruptive 3-dimensional material characterization or assays. The biggest problem is the daunting task of the necessary inversion of terminal impedance into material properties for arbitrary samples.

Further work will concentrate on extending the restricted application of landmine and UXO detection to the general application of arbitrary material characterization appropriate for field investigations on earth and the other planets.

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