LA-SUB--97-43

27 June 1996

Clutter Sensitivity Test Under Controlled Field Conditions

Resonant Microstrip Patch Antenna (RMPA) Sensor Technology

Subcontract 0214U0015-3C

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Office of Munitions

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EXECUTIVE SUMMARY

Theoretical research, controlled laboratory tests, and these field test results show that nonmetallic (and metallic) shallowly buried objects can be detected and imaged with the Resonant Microstrip Patch Antenna (RMPA) sensor. The sensor can be modeled as a high Q cavity which capitalizes on its resonant conditioñ sensitivity to scattered waves from buried objects. When the RMPA sensor is swept over a shallowly buried object, the RMPA fed-point impedance (resistance), measured with a Maxwell bridge, changes by tens of percent. The significant change in unprocessed impedance data can be presented in two-dimensional and three-dimensional graphical displays over the survey area. This forms silhouette images of the objects without the application of computationally intensive data processing algorithms.

Because RMPA employed electromagnetic waves to illuminate the shallowly buried object, a number of questions and issues arise in the decision to fund or deny funding of the reconfiguration of the RMPA technology into a nonmetallic (metallic) land mine detector. Some of the questions are:

- Can RMPA images distinguish antipersonnel land mines from clutter?
- How does RMPA detection sensitivity change with the orientation of a buried antipersonnel land mine?
- How does soil type (clay and magnetite bearing) change the detection sensitivity?
- What are RMPA's limitations?
- What are the Probability of Detection (P.D.) and False Positive Rates (F.P.R.) along established lanes?
- What land mine detection problem does RMPA address?

and • Can RMPA technology be reconfigured for humanitarian and battle field environments?

To address these questions and issues, a series of clutter field tests was conducted over lanes of buried objects. The objects included nonmetallic antipersonnel and antivehicular land mines, cultural debris, vegetation, various types of soil, and river rocks.

The questions and issues were addressed by burying clutter objects along with land mines and measuring the RMPA response. The objects are shown in Figure 1.

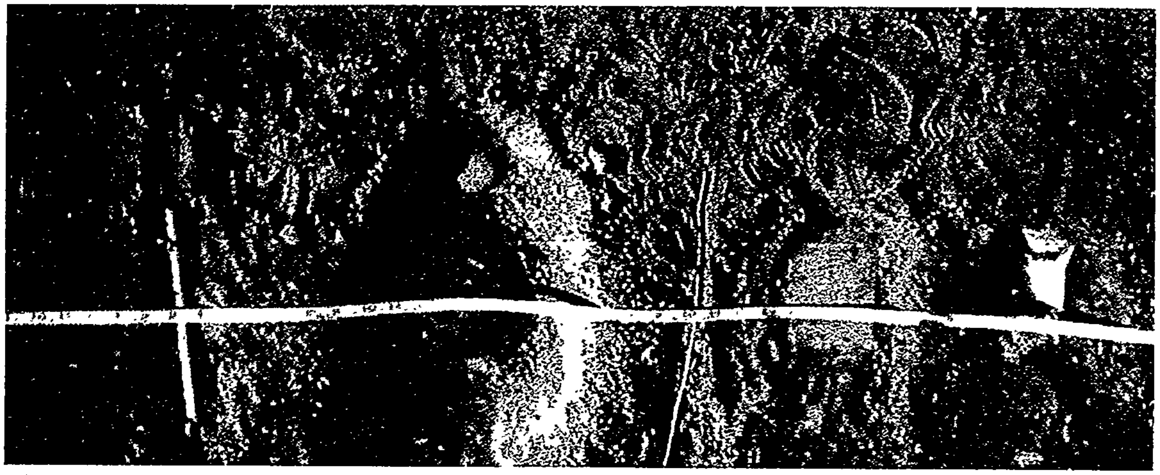

Figure 1 Photograph of clutter objects, antipersonnel, and antivehicular land mines prior to burial.

Starting at the left side of the photograph and proceeding to the right, the objects are:

- 3/4 x 8 inch piece of electrical conduit pipe
- constellation of antipersonnel / antivehicular land mines / river rock
- electrical wire
- 2 x 4 inch pine board
- an aluminum beverage can.

The measured conductance (inverse resistance at resonance) values measured over the image plane are illustrated in Figure 2.

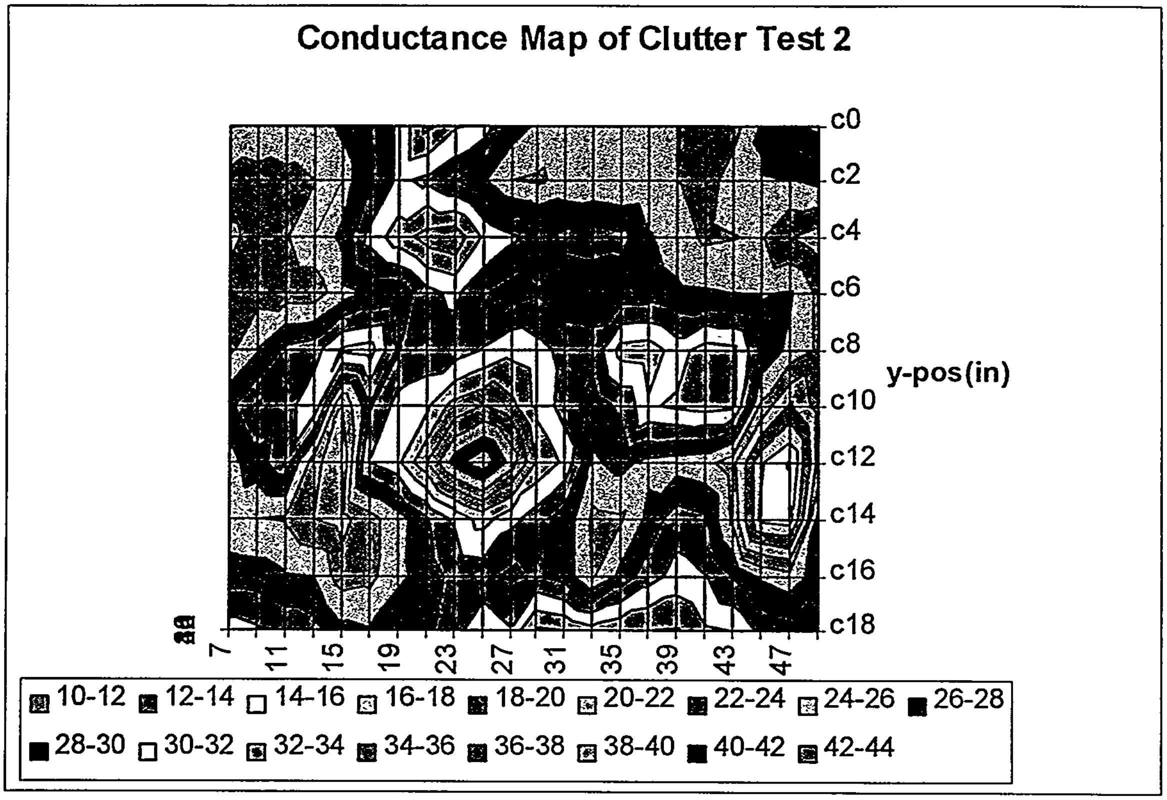

Figure 2 Plan view of measured conductance values over survey area.

The silhouettes of the conduit pipe appear to be eight inches long and the diameter of the antivehicular land mine is near six inches. The diameter of the silhouette of the antipersonnel mine is near three inches. The silhouette of the aluminum beverage can suggests that the object is oblong with a width of two inches and length of three to four inches. All of the silhouettes are reasonably close to the actual size of each of the objects. The river rock and pine board are not evident in the image. A three-dimensional presentation of the measured data is illustrated in Figure 3.

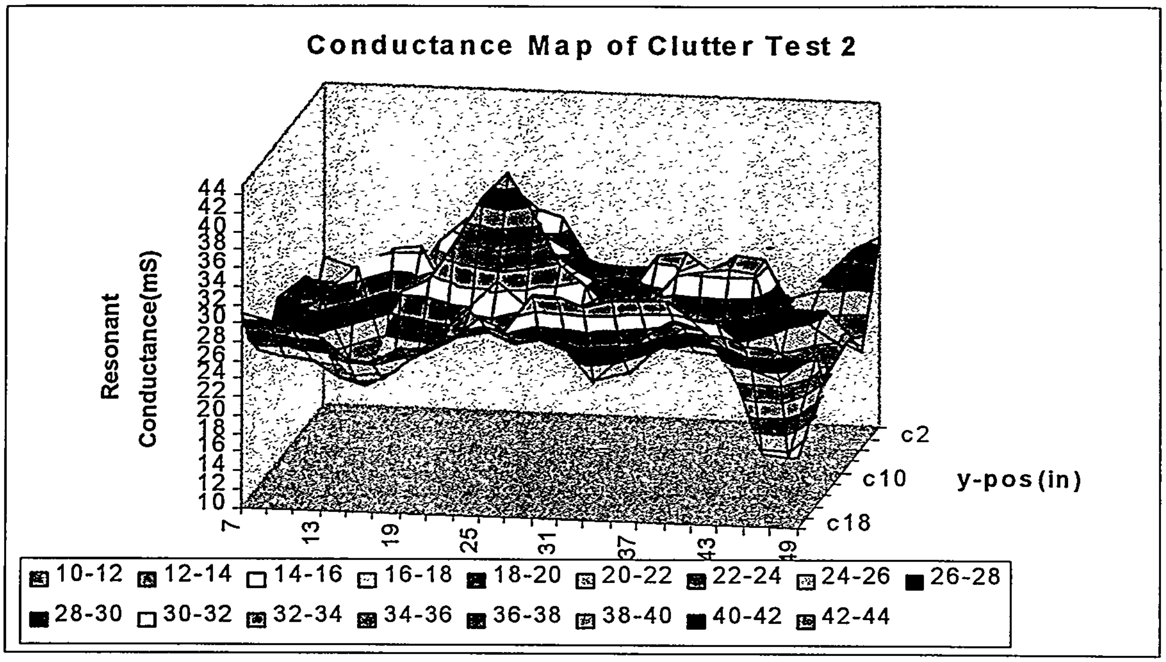

Figure 3 Survey area map of measured conductance in milisiemens acquired over buried object.

The significant feature in the three-dimensional presentation is that the conductance values decrease over metal objects and increase over nonmetallic objects. This difference may be used in identifying metal and nonmetal objects.

The objects were covered with clay bearing soil. When water was released over the antipersonnel land mine, the detection sensitivity increased. This occurred because the electrical contrast between the soil and the antipersonnel land mine increased.

We find that the detection sensitivity of the antipersonnel land mine changed from 32% to 22% when buried with a 45 degree tilt. This change in sensitivity occurred because the object scatters rather than reflects EM waves. Adding magnetite to the soil did not change the detection sensitivity.

A series of tests was conducted to determine antipersonnel mine detection sensitivity versus burial depth. We found that when antipersonnel mines are buried at the surface, the RMPA impedance decreases (conductance increases) as RMPA approaches and departs from the antipersonnel mine. It reaches a minimum value over the mine. At burial depths of one and two inches, the impedance decreases when RMPA is swept over the antipersonnel mine. The standing wave above the air-soil interface depends on the scattered wave generated by the object. The standing wave also depends on the operating frequency of the RMPA.

Several river rock tests were conducted in clay soil. One inch diameter rocks overlying the land mines increased the detection sensitivity. Tests conducted over river rocks (≈ two inch diameter) buried at depths of 0, 1, and 2 inches caused the conductance to decrease slightly. Tests over disturbed soil simulating burial at 1 and 2 inches changed the conductance value by a small amount.

Limitations:

The RMPA downward traveling primary wave is phase coherent with the air-soil reflected wave and the scattered wave from the buried object. The vector sum of the waves forms a standing wave above the air-soil interface. The RMPA feed-point impedance appears to be dependent on the standing wave.

We found that the detection sensitivity reaches a maximum value when RMPA is near the air-soil interface and periodically at one-half wavelength intervals above the interface. Minimum detection sensitivity occurs at a quarter wavelength above the air-soil, interface. RMPA will be most effective as a close-in man-pack instrument; however, it can also be used with less detection sensitivity in stand-off applications. The stand-off height needs to be controlled or measured in the instrumentation. Designing RMPA with a multifrequency capability would allow the detection sensitivity to be switched from minimum to maximum at any given stand-off height. A multifrequency design would increase the detection sensitivity of the RMPA instrument.

I INTRODUCTION

Preliminary theoretical studies and controlled laboratory/field tests provided direct evidence that the Resonant Microstrip Patch Antenna (RMPA) could detect and image shallow buried nonmetallic and antipersonnel (AP) land mines. Los Alamos National Laboratories and the NASA Johnson Space Flight Center (electromagnetics branch) participated in the verification and validation. The work focused on antipersonnel land mines because they are more difficult to detect with the current state-of-the-art technologies. NASA used theoretical modeling of electromagnetic (EM) wave propagation at the air-soil interface and experimental measurements to investigate the antipersonnel land mine detection sensitivity. Los Alamos National Laboratories (LANL) used theoretical methods to investigate the physics underlying the RMPA detection process. LANL participated in controlled field experiments to answer specific questions concerning the detection and imaging capability of RMPA. By way of background, the physics of the Resonant Microstrip Patch Antenna (RMPA) sensor is similar to downward-looking radar. RMPA technology capitalizes on its high Q resonant cavity detection process. Both the resonant frequency and impedance (resistance in ohms or conductance in milisiemens) of the high Q resonant cavity significantly change when the RMPA sensor is swept over a buried antipersonnel mine. The resonant parameters are measured at the feed-point of the RMPA sensor with a Maxwell bridge and associated microcomputer-controlled electronics. While the resonant frequency changes by approximately 1%, the resonant impedance changes by tens of percent. The exact change depends upon the operating frequency, burial depth of the object, and the electrical parameters (conductivity [σ], dielectric constant [ϵ], and permeability [μ]) of the soil and the buried object. The difference in electrical parameters is called contrast. The significant change in resonant impedance when the RMPA sensor is swept over an antipersonnel land mine allows images to be formed directly from unprocessed data. This is important when considering the computational requirements in the identification problem.

Although RMPA technologies reached a mature development status in the real time measurement of uncut coal, its reconfiguration and application in nonmetallic land mine detection needed critical review and consideration. Since RMPA is based upon Electromagnetic wave Detection and Imaging Technologies (EDIT), a number of technical issues must be addressed in the detection and identification of nonmetallic land mines. The probability of detection (P.D.) and False Positive Rate (F.P.R.) are critical performance evaluation factors in humanitarian demining and the battle field environment. Clutter in the form of vegetation, cultural debris, and spent battle field objects have a significant impact on P.D. and F.P.R.. Ideally, the detection system would discriminate against buried clutter objects and detect only land mines. Realistically, it is far better policy to detect every buried object and form images for use in identification. Since image forming is a critical factor in the P.D. and F.P.R. problems, high resolution images must be achieved without computational intensive data processing. The detection system must have a straightforward user interface and be capable of operating beyond the lethal kill distance limit from a land mine.

This project addressed the issues and concerns described above by setting up lanes of clutter objects and nonmetallic land mines buried in clay soil. The clutter field tests were designed to enhance our understanding of the detection physics and investigate the limitations of RMPA. Since the RMPA sensor technology is based upon the detection of scattered (not reflected) electromagnetic waves from buried objects, the first series of questions that naturally arises relates to how the scattered wave depends on orientation (scattering cross section) of the land mine, the type of soil (bearing clay or magnetite), moisture, sensor stand-off height above the soil and object burial depth. The next series of tests were concerned with the Probability of Detection (P.D.) and False Alarm Rate (F.A.R.). Can antipersonnel land mines be detected in soil featuring a wide variety of clutter objects? If clutter objects were detected, could they be identified in an image forming process? If image forming is required in the identification process, what is the resolution and computational complexity? What kinds of clutter objects were not detected? Finally, can detection limitations be resolved in the design of the instrumentation and imaging process?

The first series of tests addressed the issue of detection sensitivity versus stand-off height, burial depth and orientation. A mathematical model of the RMPA detection process was developed and found to be in agreement with measured data. This model is useful in qualitatively understanding the relationship of detection sensitivity to stand-off height, burial depth and orientation of the antipersonnel land mine. Our analysis suggests that RMPA resonant frequency and impedance are related to the time average energy density of the standing wave as a function of height above the air-soil interface. The standing wave is caused by the primary EM fields being phase-coherent with the reflected fields from the air-soil interface and the scattered wave from the buried object. The standing wave is periodic in ½ wave length distance intervals above the soil interface. At 850 MHz, detection sensitivity achieves maximum value when the stand-off height is close to zero and periodically at 6.8 inches (17 cm) intervals. At 850 MHz, the loss tangent of the soil is very small. When the soil is illuminated by the RMPA primary fields, dielectric displacement currents predominate in the soil. Dielectric constant plays a major role while soil conductivity plays only a minor role in determining the intensity of the reflected wave at the air-soil interface at 850 MHz. About 30 percent of the primary field is reflected at the interface. The moisture in the soil causes the dielectric constant to increase. Since the wavelength is 13 inches, it is long compared to the diameter (3 inches) of the antipersonnel land mine; scattering predominates in the detection problem. Scattering causes the orientation of the land mine to be a minimal factor in the detection problem. Orientation would be a significant problem if reflections predominated the EM wave propagation problem in the vicinity of the antipersonnel land mine.

II CLUTTER TEST SITE

2.1 DESCRIPTION OF CLUTTER TEST SITE:

The clutter test site is located on ranch land in the foothills of the Sangre de Cristo Mountains in northern New Mexico. The test site is shown in the photograph shown in Figure 4.

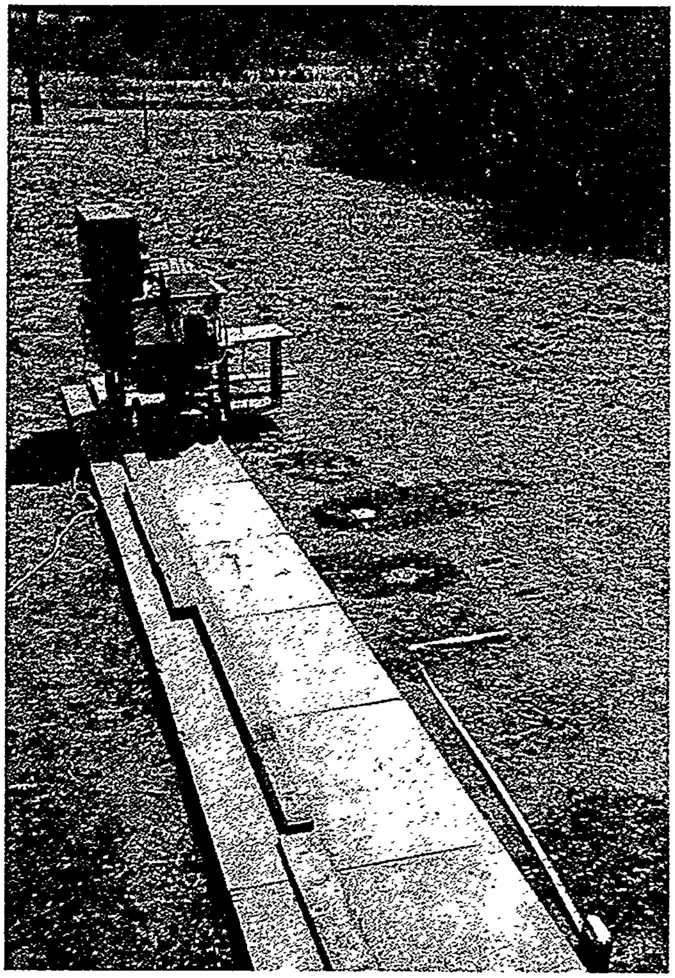

Figure 4 Instrumentation and survey lane of buried objects.

Nonmetallic land mines and clutter objects were buried along the survey lane. The instrumentation included an HP4191A RF Impedance Analyzer and the resonant Microstrip Patch Antenna (RMPA) sensor. The RMPA was mounted on an extendable wooden boom assembly which could be extended to cause the RMPA sensor to follow a specific Y survey line.

The RF Impedance Analyzer was calibrated at the RMPA feed-point, causing the measurement load plane to be located at the feed-point. This allows the impedance measurements to be made at the RMPA sensor feed-point.

The instrumentation was moved along the travel-way, stopping and measuring at two inch intervals.

The following buried objects, from back ground to foreground, are shown in the photograph in Figure 4:

- 4" x 4" aluminum plate with a two-inch bracket
- antipersonnel land mine
- 5-inch diameter Lucite cylinder
- antivehicular land mine
- air filled maple syrup bottle
- 3/4 inch diameter plastic pipe
- shell casings
- river rocks.

Clay soil was used to cover the objects in Figure 4. The clay soil was originally the floor of the Cretaceous period sea that covered most of the central part of the United States.

The vegetation tests were conducted next to an oak brush tree illustrated in Figure 5.

Figure 5 Photograph of the oak brush tree vegetation test.

The tree roots and clumps of grass were in the foreground.

2.2 INTERPRETATION OF MEASURED DATA

Interpretation of electromagnetic wave detection and imaging data is both an art and a science. The science part of the interpretation problem utilizes physics and mathematical formulations to understand how the measured values depend on the electrical parameters of the objects and the surrounding soil. The difference in electrical parameters is called contrast. Modeling will describe how the resonant impedance changes for a wide range of soil parameters and burial depths. The art depends on the skill and training of the countermines personnel.

The RMPA concept was originally formulated by David Chang in his doctoral dissertation at Harvard University under R.W.P. King. Later, Chang and Wait developed the theory which described the admittance variation of a single loop of wire over a layered half space. Their research indicated that a resonant loop of wire could be used in sensing changes in the physical parameters (depth of each layer from the wire loop) and electrical parameters (conductivity {σ}, permitivity {ϵ}, and permeability {μ}) of the layers. Chang and Wait also developed analytical expressions for the changes in resonant frequency and input impedance of the wire loop due to changes in the physical and electrical parameter changes of the layers.

Laboratory investigations by Raton Technology Research, Inc. (RTR, Inc.) and

NASA Johnson Space Center, showed that a RMPA exhibited similar resonant frequency and admittance changes as that of the wire loop in the Chang-Wait analysis. The vertical cross section of the RMPA sensor is shown in Figure 6.

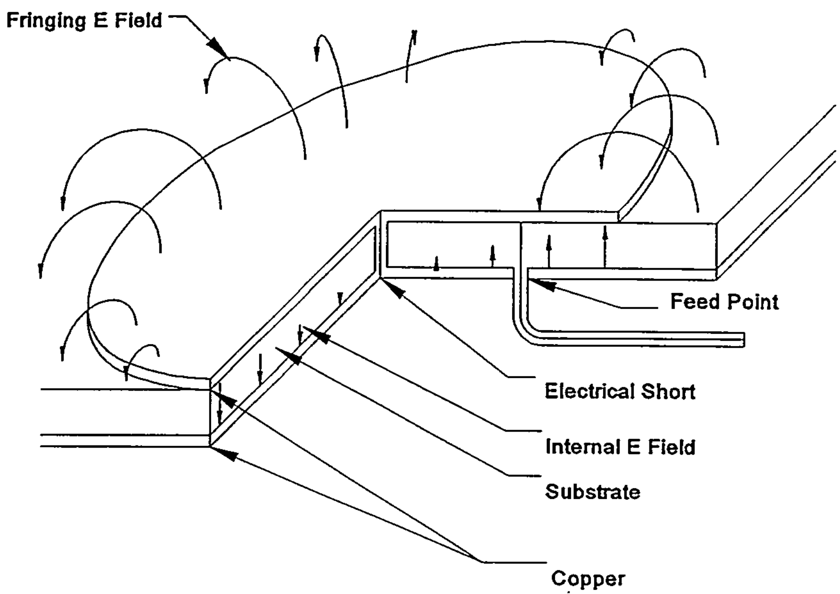

Figure 6 Vertical cross section of the RMPA sensor including the electric field lines.

The RMPA sensor can be modeled as a high Q cavity which capitalizes on its resonant sensitivity, such that a distinct advantage is obtained over a nonresonant EM wave sensor. The high Q cavity is formed by the circular copper patch and the ground plane. The E-field within the cavity is excited/sensed by a vertical "probe" at the feed point. The TM_{11} mode E-field within the cavity and the fringing E-fields are illustrated in Figure 6 above. The magnetic (H) fields are not shown; however, they are orthogonal to the E-fields. The fringing E-fields (and H-fields) play an important part in the RMPA. The fringing EM fields are the coupling mechanisms between the internal cavity fields and external fields. The EM fields between the antenna and the target cannot be characterized solely by near field, induction zone, or far field representations. All three contribute to the RMPA response.

Figure 7 illustrates the physics of the RMPA sensor.

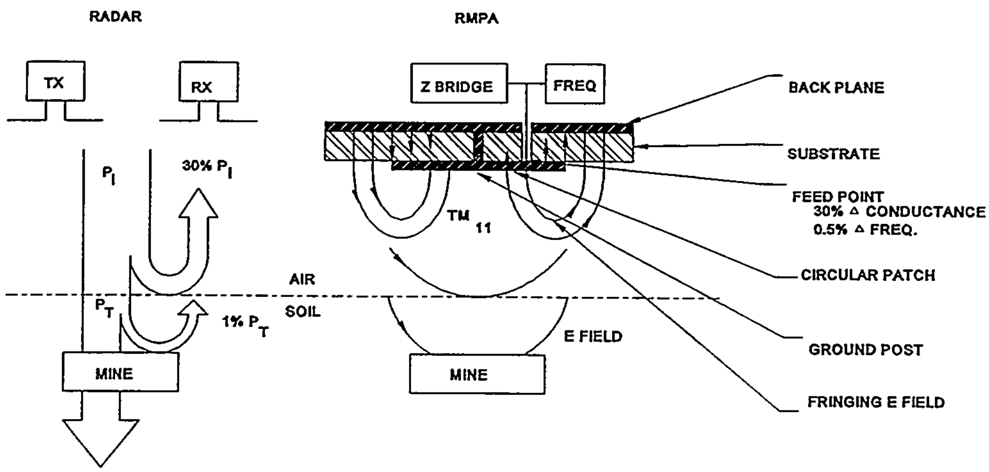

Figure 7 A cross section of a buried land mine detection problem. For comparison purposes, a GPR system is illustrated on the left and RMPA is illustrated on the right.

In a continuous wave (CW) GPR or RMPA system, the primary field energy propagates downward from the antenna. Approximately 30% of the incident energy is reflected at the soil-air interface.

The single high Q RMPA transmits primary EM fields and senses the reflected and scattered fields through its altered resonant condition. A continuous wave is emitted from RMPA that is partly reflected and partly transmitted at the air-soil interface. The transmitted portion of the wave is scattered (not reflected) from the mine due to the discontinuity in conductivity and dielectric constant. The scattered wave is again partly reflected and transmitted at the soil-air interface. Since the primary continuous wave is coherent with the secondary waves, a standing wave occurs in the air space of the soil-air interface.

The return signal to the RMPA serves as an inductive and capacitive mutual coupling between the buried object and the RMPA.

The return signal is coupled through the fringing field and alters the E-field at the feed-point. The RMPA microprocessor-controlled electronics changes the frequency until the measured impedance is real. The resonant impedance measured at the feed point can change by a significant amount when the RMPA is in the presence of a land mine.

GPR relies on a low Q antenna(s) to measure the voltage changes which are proportional to the reflected and scattered fields. Resonant conductance changes at the high Q cavity feed point appear substantially larger than corresponding GPR voltage changes. Therefore, RMPA has a significant increase in sensitivity to scattered fields.

The real (R) and imaginary (X) values of the RMPA feed-point impedance were measured over a range of frequencies with an HP 4191A RF Impedance analyzer. The measured data is presented in Figure 8.

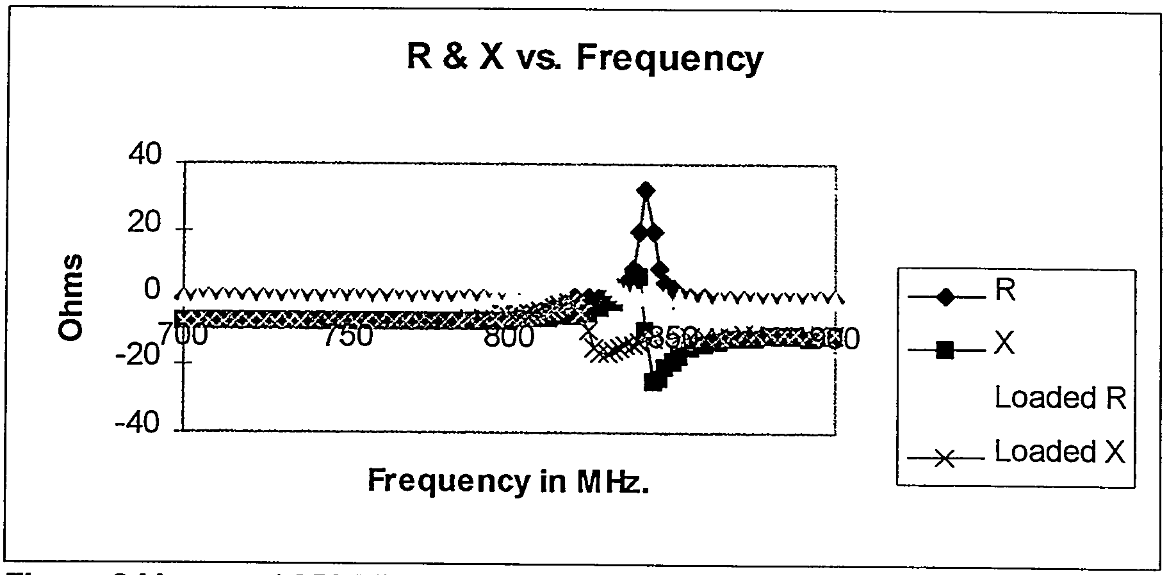

Figure 8 Measured 850 MHz RMPA sensor feed-point impedance vs. frequency.

The impedance was measured with the RMPA sensor radiating into free space and into soil. The real (R) component (resistance) of the feed-point impedance versus frequency curve illustrates the resonant characteristics of the high Q cavity. The resistance rapidly changes on each side of the resonant frequency. The imaginary component (x) rapidly changes in the neighborhood of resonance.

When the RMPA sensor radiates downward into soil, the resonant frequency and real/imaginary components of the feed-point impedance change.

The feed-point impedance at resonance depends upon the feed-point radial distance from the center grounding post. The real part of the resonant impedance increases with radial distance from the center.

The feed point resonant frequency and impedance dependence on the electrical parameters have been determined with a commercial software program (Sonnet). A Green's function analysis of the circular patch antenna with multiple layers was also used in modeling. The analytical software programs determined that the resonant frequency and impedance exhibited a damped sinusoidal variation as the sensor stand-off height or burial depth was varied. Studies suggested that the time average energy density of the standing wave closely followed both the modeling and measured data.

The energy density formulation is analytic and provides an insight into the dependance of RMPA measured values on the physical and electrical parameters of the land mine detection problem. The time average energy density is given by:

$$\mu = \frac{Re}{2}\left[E \cdot E^{x}\right] = 1 + R^2 - 2R\cos 2kZ + \frac{2A(1-R)}{\sqrt{\epsilon}d+Z}\cos\left(2kZ - \sqrt{\epsilon}kd + \Delta\right) + \frac{2(1-R)A}{\sqrt{\epsilon}d+Z}\cos\left(\Delta - \sqrt{\epsilon}kd\right) + \left[\frac{(1-R)A}{\sqrt{\epsilon}d+Z}\right]^2$$

where ϵ = the relative dielectric constant of the soil

R = the soil-air interface reflection coefficient

d = the burial depth

A = the scattering amplitude

k = the wave number

and, Δ = the scattering phase shift

The energy density versus height above the soil is illustrated in Figure 9.

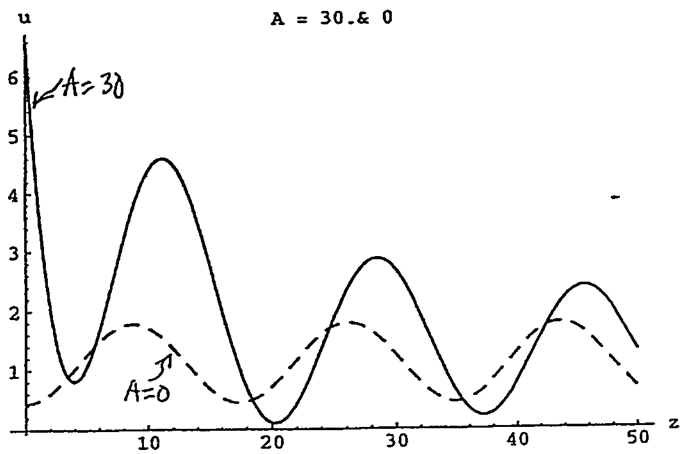

Figure 9 Energy density versus sensor height above the soil air interface (after Bob Kelly, LANL).

The dashed curve illustrates the energy density without a buried target. (A = 0). It illustrates the interference of the incident and soil-air reflected waves. The solid curve is the energy density (system response) as a function of RMPA sensor height above the soil-air interface. The land mine is buried at a depth of 4 cm. The solid curves suggest that the maximum sensitivity occurs when RMPA is in close proximity to the soil-air interface. When the elevation reaches 4 cm, the detection sensitivity would be near zero. The detection sensitivity reaches another maximum near 11 cm.

The energy density also depends upon the burial depth. The period is approximately the wavelength in free space divided by $\sqrt{\epsilon}$.

The energy density has been calculated for RMPA sensor heights of 4 cm (1.57 inches) and 11 cm (4.33 inches) above the air-soil interface. The change in energy as a function of burial depth is illustrated in Figure 10 for an antenna height of 4 cm.

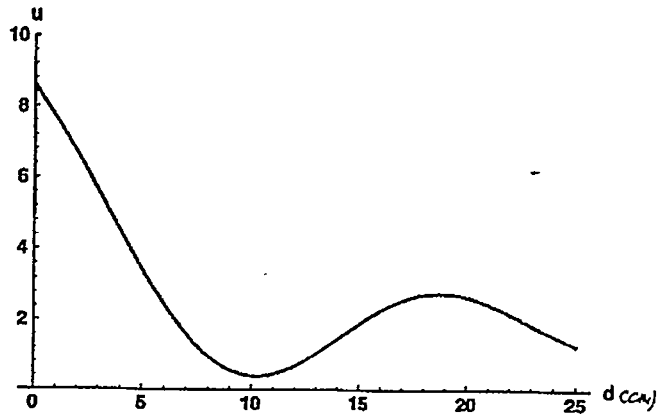

Figure 10 Energy density versus burial depth for an antenna height of 4 cm at a frequency of 850 MHz. The soil relative dielectric constant is assumed to be 4.

The energy density reaches a minimum value at a burial depth of 10 cm. (3.94 inches). At this depth the resonant impedance reaches a maximum value. As the burial depth increases to 18 cm (7.08 inches) the energy density reaches a maximum value and the impedance reaches a minimum value.

The analytic expression defining RMPA response suggests that a mufti frequency system is required. The multi-frequency system would enable the standing wave pattern to change by one fourth wavelength, shifting any minimum response to a maximum response. The phase shift (Δ) used in the analytical expression will be different for nonmetallic and metallic objects. The measured resonant conductance shows that under certain test conditions, the conductance change over nonmetallic land mines is greater than the change over metallic land mines. A system built with multiple-frequencies could capitalize on the change to identify the difference between metallic and nonmetallic objects.

III DESCRIPTION OF CLUTTER TEST RESULTS

3.1 MEASURED RMPA CONDUCTANCE VERSUS STAND-OFF HEIGHT

The detection sensitivity versus stand-off height is illustrated in Figure 11.

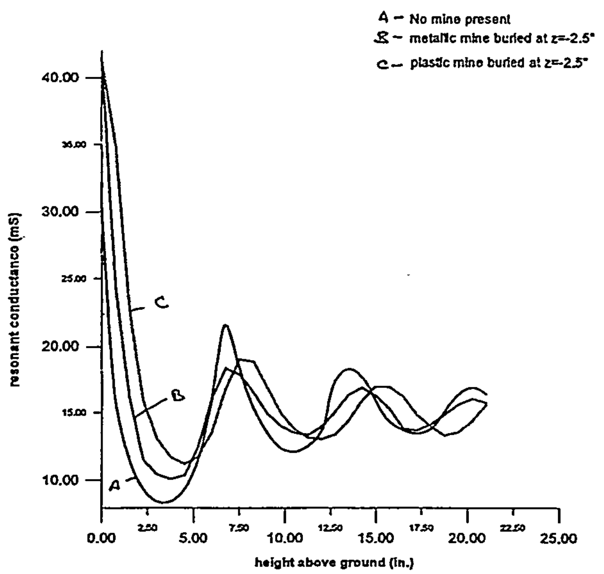

Figure 11 Resonant conductance in milisiemens versus stand-off height in inches measured over nonmetallic antipersonnel land mine and metal land mine.

These graphs compare the measured resonant conductance data acquired over undisturbed soil with RMPA sensor conductance values measured over nonmetallic and metallic land mines. The sensitivity reaches maximum value when the RMPA sensor is near the soil interface and at half wavelength intervals. At a stand-off height of one inch, the resonant conductance changes from 15 ms to 35 ms, a change of 133%. Because the detection sensitivity reaches a minimum value near a stand-off height of one-quarter wave length, a multi frequency system would ensure that the maximum response is achieved at each measurement location.

3.2 MEASURED RMPA CONDUCTANCE VERSUS ANTIPERSONNEL LAND MINE BURIAL DEPTH

The sensitivity of detection versus burial depth was determined by burying antipersonnel mines at depths of 0, 1, 2, 3, and 4 inches. Resonant conductance was measured as the RMPA sensor was swept along survey lines over the survey area.

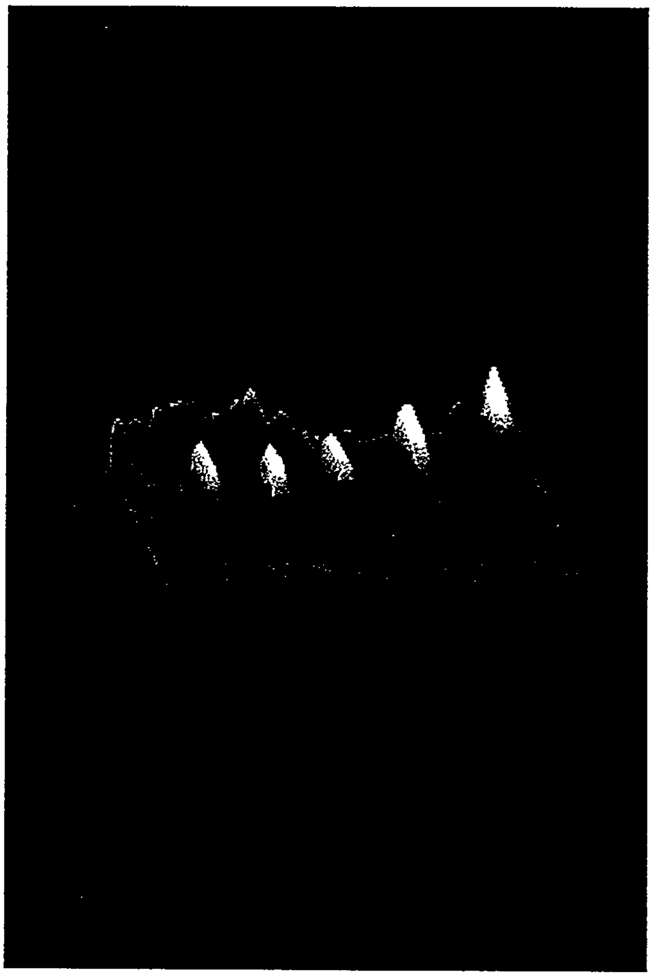

Figure 12 Three dimensional image of antipersonnel land mines buried at 0, 1, 2, 3, and 4 inches (left to right).

Conductance data was acquired by sweeping the RMPA along parallel survey lines spaced two inches apart over the survey area. Resonant conductance was measured at two inch intervals along each survey line. The image was formed by taking the absolute value of the difference between measured resonant conductance value and the average measured conductance value. Silhouettes of the antipersonnel land mines appear in the image.

3.3 MEASURED RMPA RESPONSE OVER BURIED CLUTTER OBJECTS

The next series of tests was conducted in a clay soil covering a variety of clutter objects.

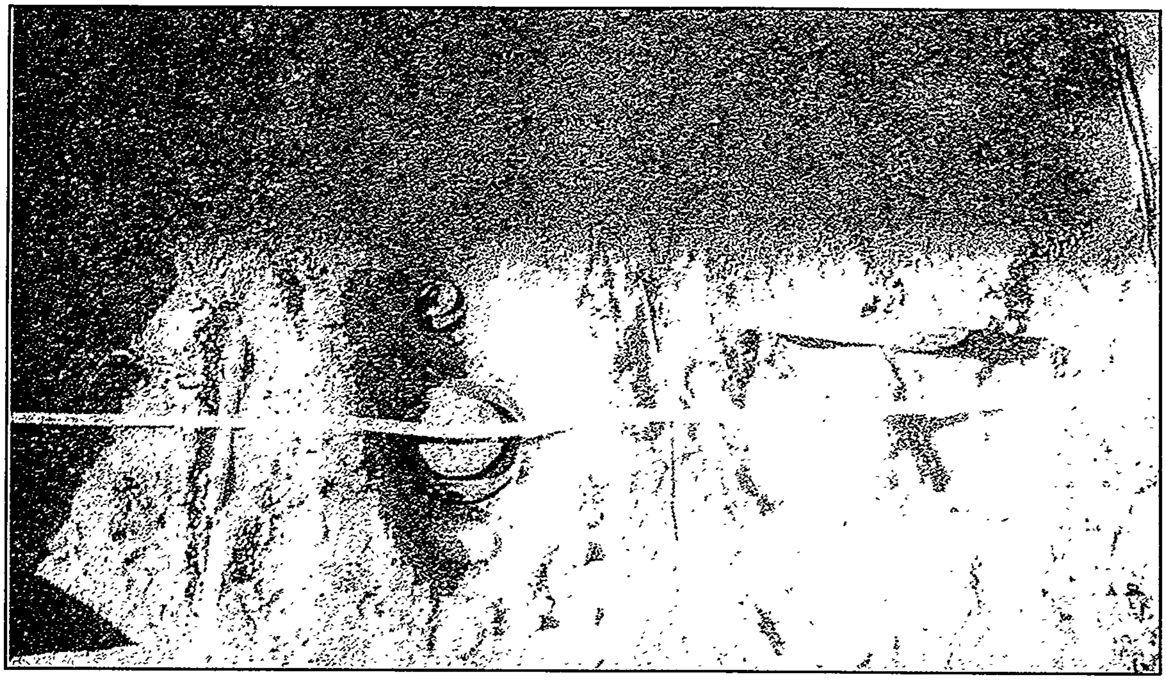

Figure 13 Photograph of clutter objects, antipersonnel, and antivehicular land mines prior to burial.

Starting on the left side of the photograph and proceeding to the right, a 3/4 x 8 inch electrical conduit pipe, nonmetallic antivehicular and antipersonnel land mines, river rock, 16 gauge electrical wire, a 2 x 4 x 6 inch pine board, and a 2-inch diameter by 6- inch long aluminum beverage can are shown in the photograph.

Images of the buried objects were formed directly from the measured conductance values.

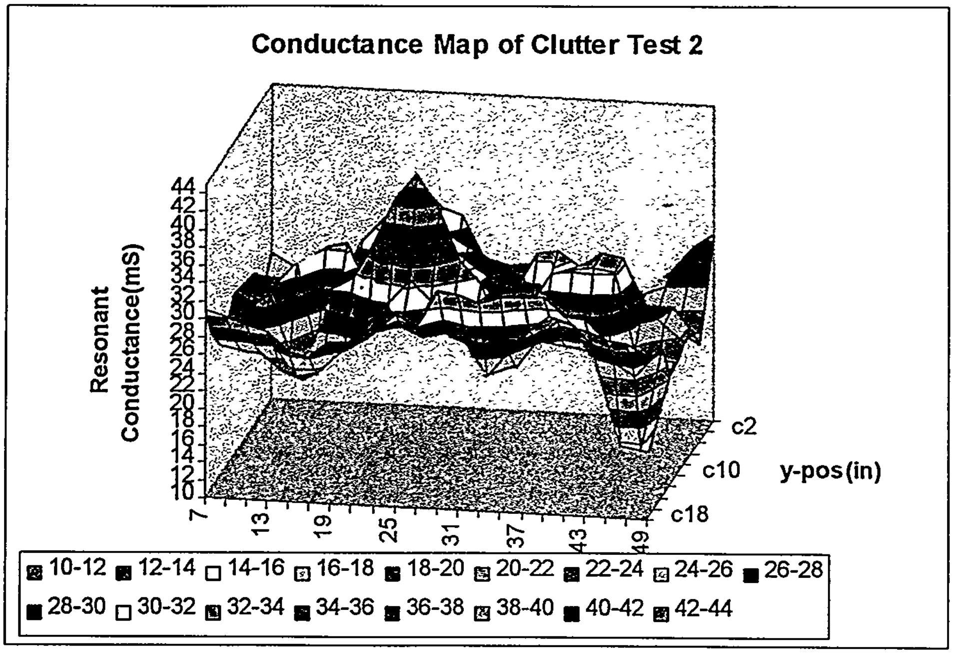

Figure 14 Sweep area map of conductance over the buried objects. Measured RMPA conductance values are in milisiemens.

The significant feature in the measured conductance data is that over the metal pipe and beverage can, the conductance values reached minimum values. The conductance values reach maximum over nonmetallic antipersonnel and antivehicular land mines. If significant, this difference may be useful in identifying metal and nonmetal objects. The electrical wire, river rock and 2 x 4 inch board are difficult or impossible to detect in the image. A plan view of the measured data is illustrated in Figure 15.

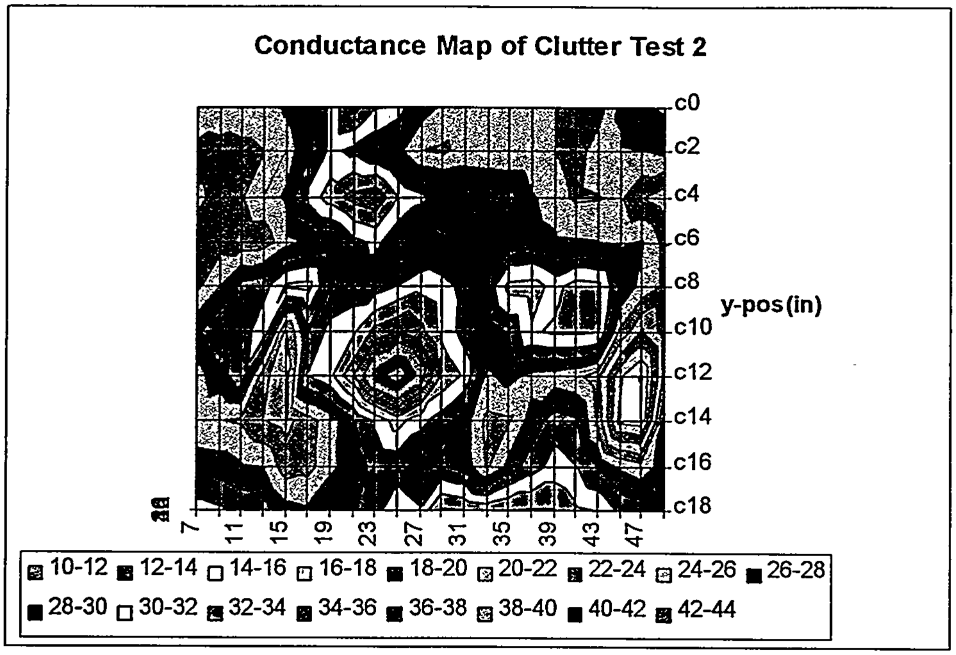

Figure 15 Plan view of measured conductance over the sweep area.

The silhouette of the conduit pipe appears to be near 8 inches long. The diameter of the antivehicular mine is near 6 inches. The antipersonnel mine is near 2 inches (it should be 3 inches). The silhouette of the metal can is rectangular with a diameter of 2 inches.

The measured conductance values shown in Figure 15 were processed by taking the absolute value of the difference between the measured data and the average value of conductance value in the image plane. The image is illustrated in Figure 16.

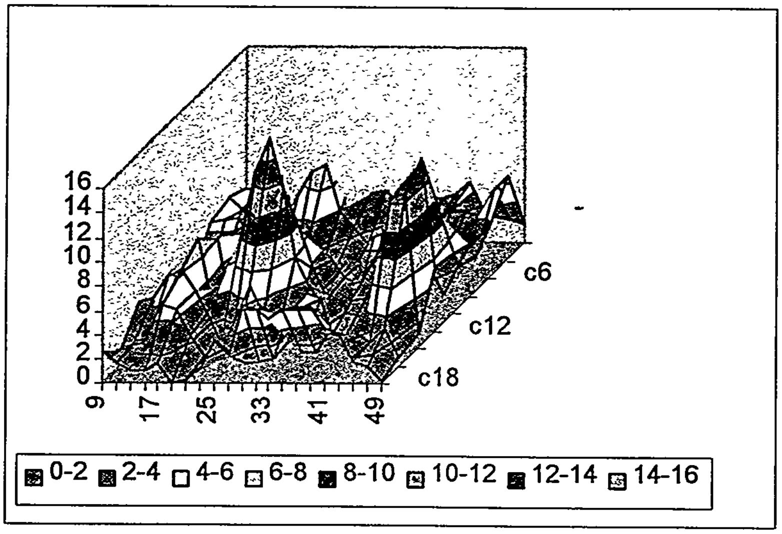

Figure 16 Three-dimensional representation of the absolute value of the difference between the measured and average conductance values acquired over the sweep area.

The image of the metal pipe, antipersonnel land mine, and, metal beverage can appear in the formed image. In this image the absolute value processing causes all of the silhouettes to increase in value. Figure 17 shows the plan view of the absolute value of the data.

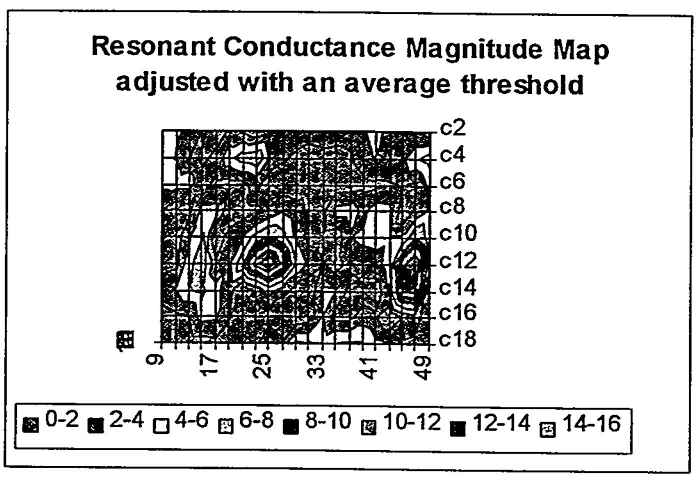

Figure 17 Plan view of the absolute value data.

A potential false positive detection is seen near the upper right corner of the image, near C4. The data illustrated in Figure 4 show that a minimum conductance value occurs at this location, which indicates that the false positive is not a nonmetallic antivehicular or antipersonnel mine. Our investigation of the false positive indicated that a soil surface depression occurred at this location. The data presented in Figure 1 confirms the possibility that a sensor stand-off height increase would decrease the measured conductance. This finding suggests that the RMPA instrument design must include a means of measuring sensor stand-off height.

3.4 MEASUREMENT OF RESONANT CONDUCTANCE OVER AP LAND MINES BURIED AT VARIOUS DEPTHS.

Nonmetallic antipersonnel land mines were buried at depths of 0, 1, 2, 3 and 4 inches. The map of conductance swept over nonmetallic land mines buried at various depths is illustrated in Figure 18.

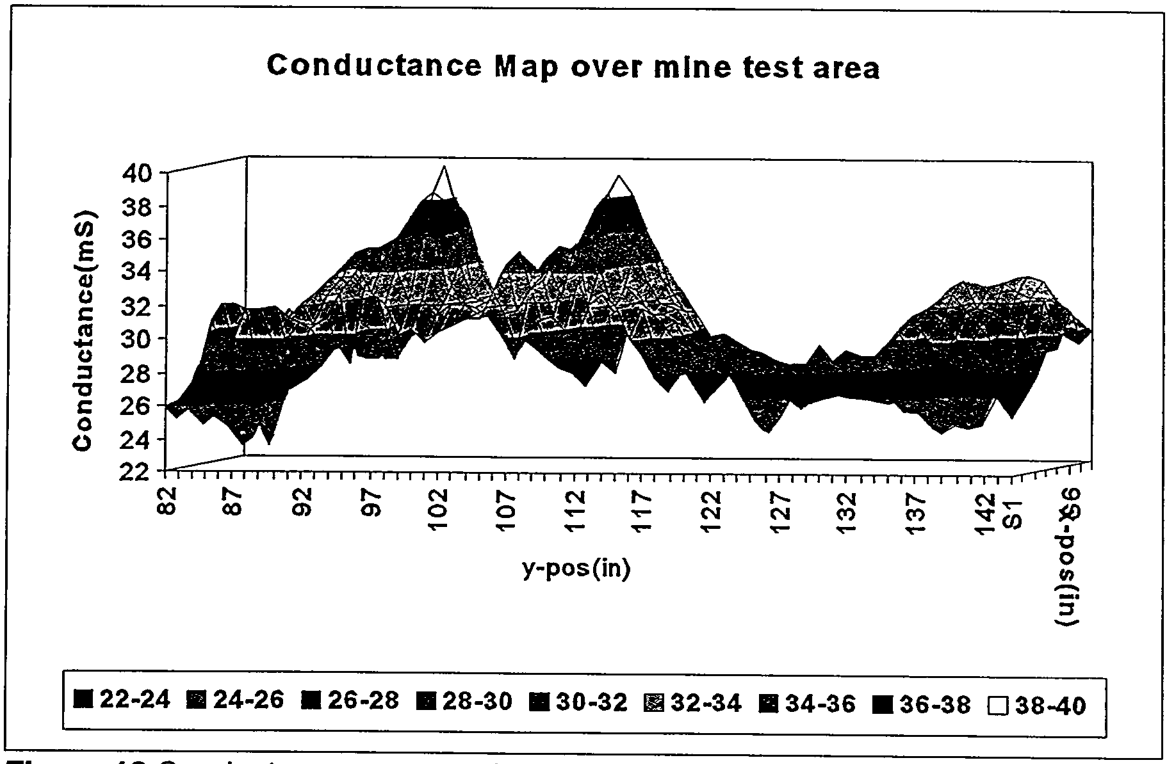

Figure 18 Conductance measured over nonmetallic land mines buried at 0, 1, 2, 3, and 4 inches in clay soil.

The first antipersonnel mine is buried at the 86-inch X direction location (burial depth of 0 inches). The conductance value reaches a minimum value at this burial depth and exhibits a double peak. The antipersonnel mine at the 99-inch (burial depth of 1 inch) and the 111-inch locations (burial depth of two inches) exhibit peak measured conductance values of 39 mS. This is a change of approximately 36% over the average value. The AP mine produces a minimum conductance value at a burial depth of three inches. This mine is located at an X location of 122 inches. The AP mine at a burial depth of 4 inches exhibits a maximum value at the X location of 134 inches.

The measured data shown in Figure 18 was processed by subtracting the average measured conductance value (28 mS) from each measured conductance value. The absolute value of the difference is shown in Figure 19.

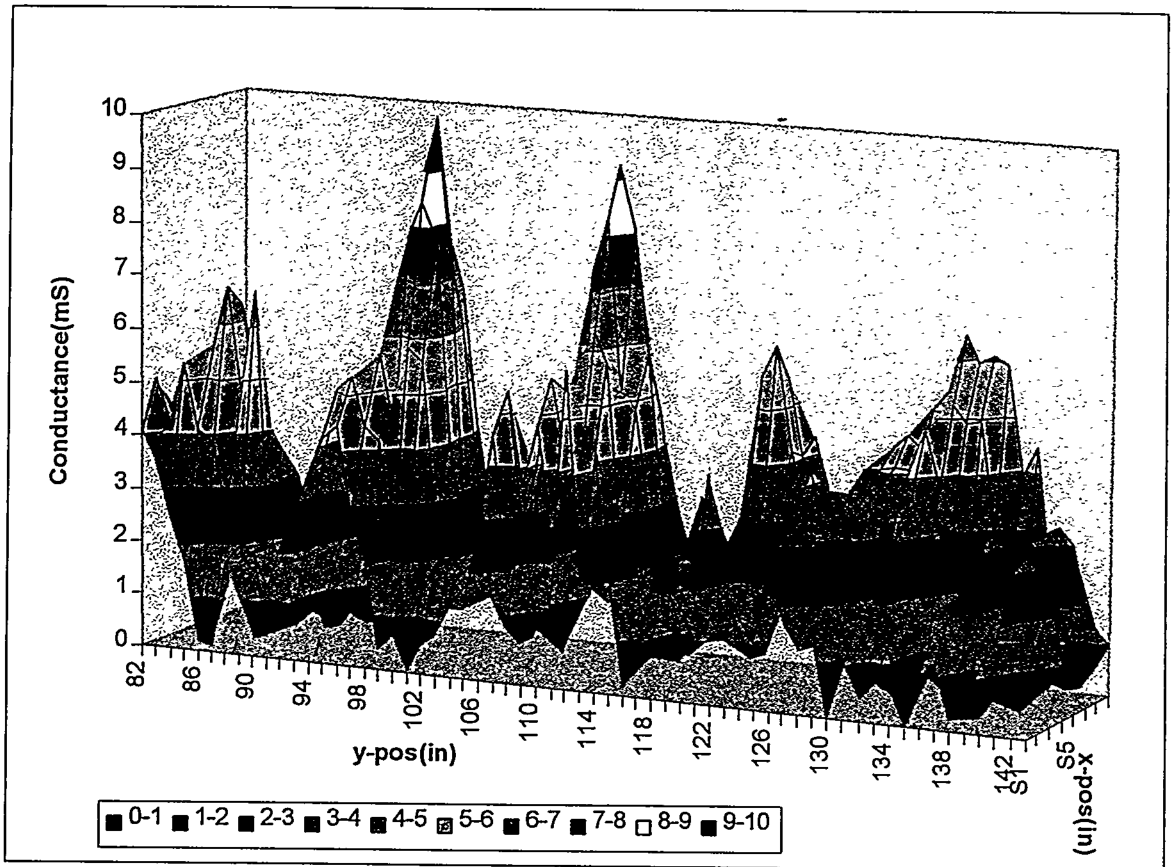

Figure 19 Absolute value of the difference in measured conductance and average conductance over the survey area.

The first antipersonnel mine buried at the ½ inch depth exhibits a double peak. Peak values occur at burial depths of one and 2 inches. Conductance peaks also occur for three and 4 inch burial depths.

The figure 20 illustrates the measured conductance values on the plan view of the image plane.

The AP land mine buried at a depth of ½ inch at the 86-inch X-direction location exhibits a double peak.

3.5 CLUTTER TEST DATA

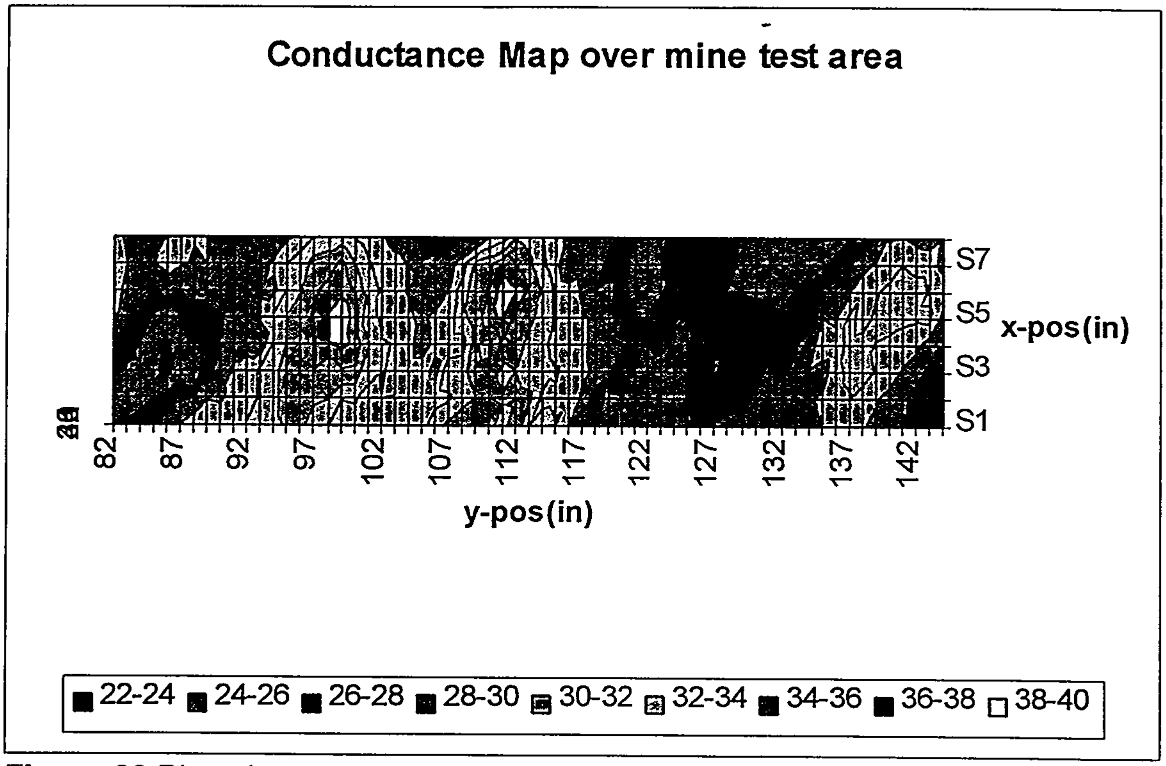

Figure 20 Plan view of the absolute value of the difference in measured and average value.

The resonant conductance was measured along the survey lines over the buried objects shown in Figures 1 and 13.

Resonant Conductance vs position for Clutter Test

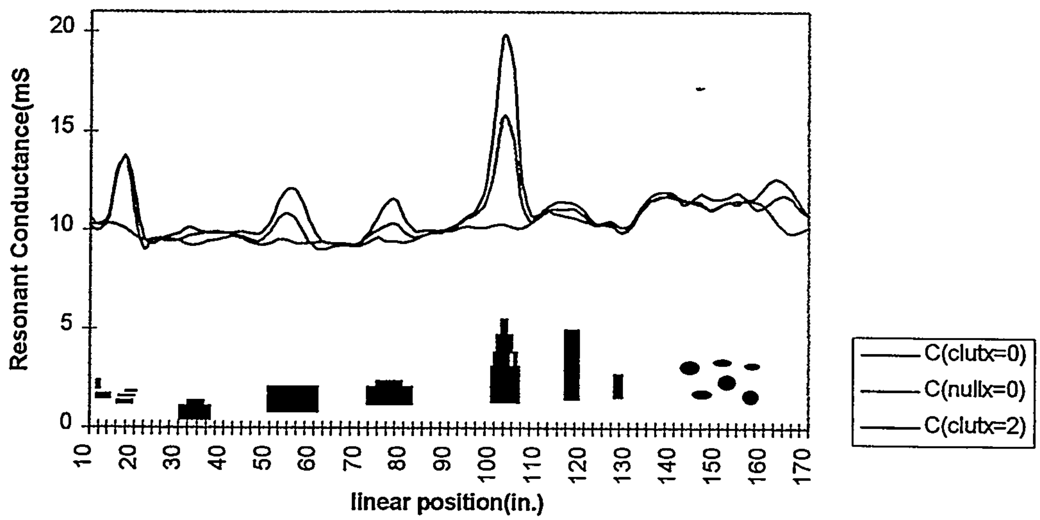

Figure 21 Measured conductance along the X = 0 and X = 2 survey lines.

The RMPA sensor feed-point conductance was measured prior to burial of the clutter objects and land mines (null X = 0 curve). The buried clutter and land mine data measured along the same survey line is illustrated on the CLUT X = 0 curve. The clutter data measured along the two-inch off set survey line is illustrated on curve CLUT x = 2.

The 3 x 4 inch metal plate at the X = 10 location produced a significant response. The air filled maple syrup bottle, at the X = 96 inch location, produced the greatest false positive response. The nonmetallic antipersonnel mine at the X = 24 inch location produced a very small response because it was buried at a depth of ½ inch. The RMPA stand-off height was approximately 3.5 inches: the minimum RMPA response stand-off. The dielectric cylinder and the antivehicular land mine produced significant responses. The dielectric pipe, shell casing, and river rock produced small responses.

The plan view, rotational view, side view, and oblique views of the measured data show silhouettes of the buried objects.

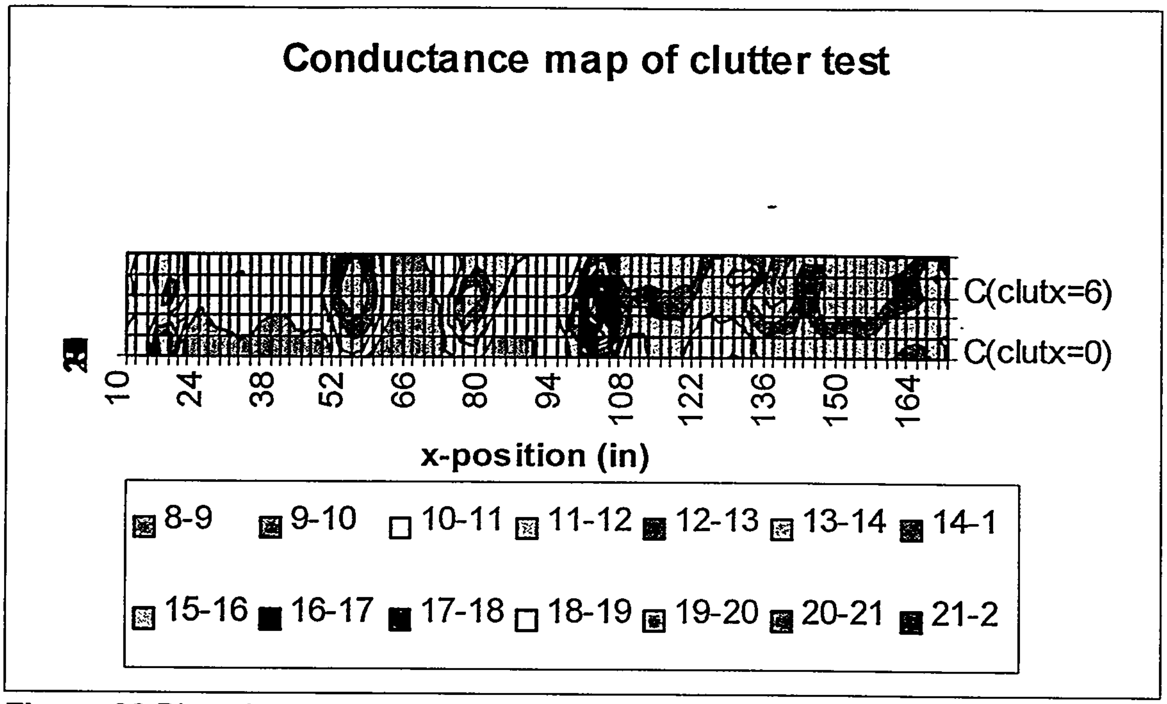

Figure 22 Plan view of conductance values measured over survey area.

The plan view illustrates the silhouettes of the buried objects. The bottle appears to have an oblong silhouette that is different from a land mine. The dielectric cylinder and the antivehicular land mine exhibit round silhouettes and appear to be land mines.

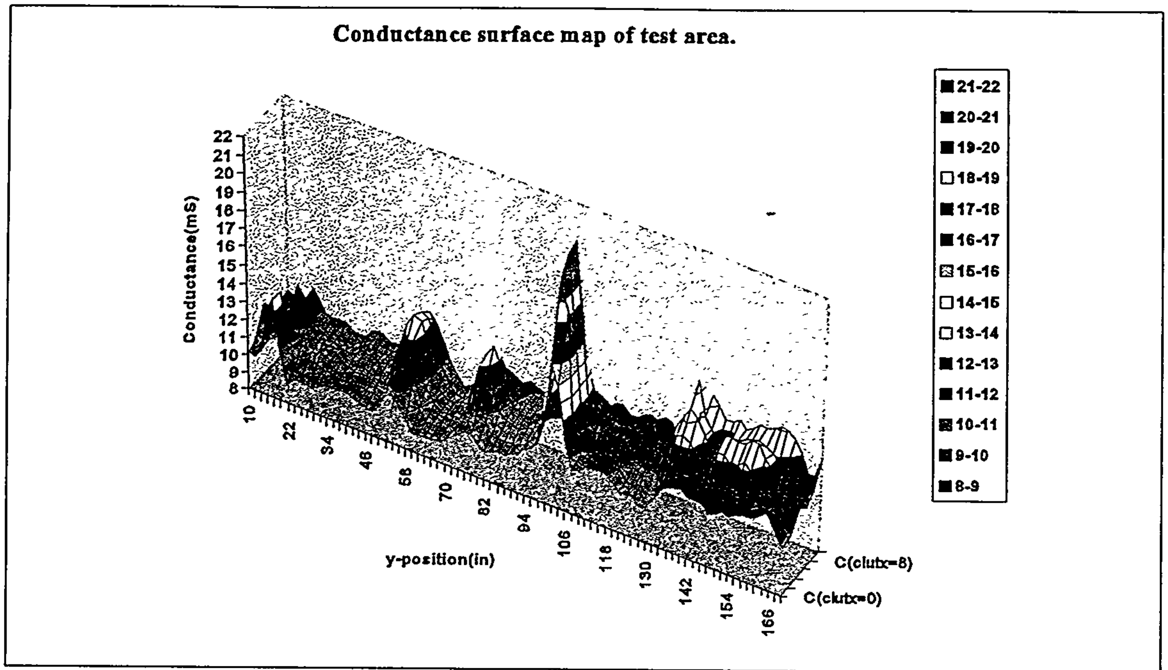

Figure 23 Rotational and oblique view of conductance values measured over the survey area.

The glass bottle stands out in the oblique view. The metal plate appears to be a wide object. The dielectric cylinder and the antivehicular mine are apparent in the image. The river rocks produce a response; however, the stand-off height merges to within an inch of the soil surface. The stand-off height is approximately 3.5 inches from 10 to 34 inches. This accounts for the low antipersonnel mine detection sensitivity.

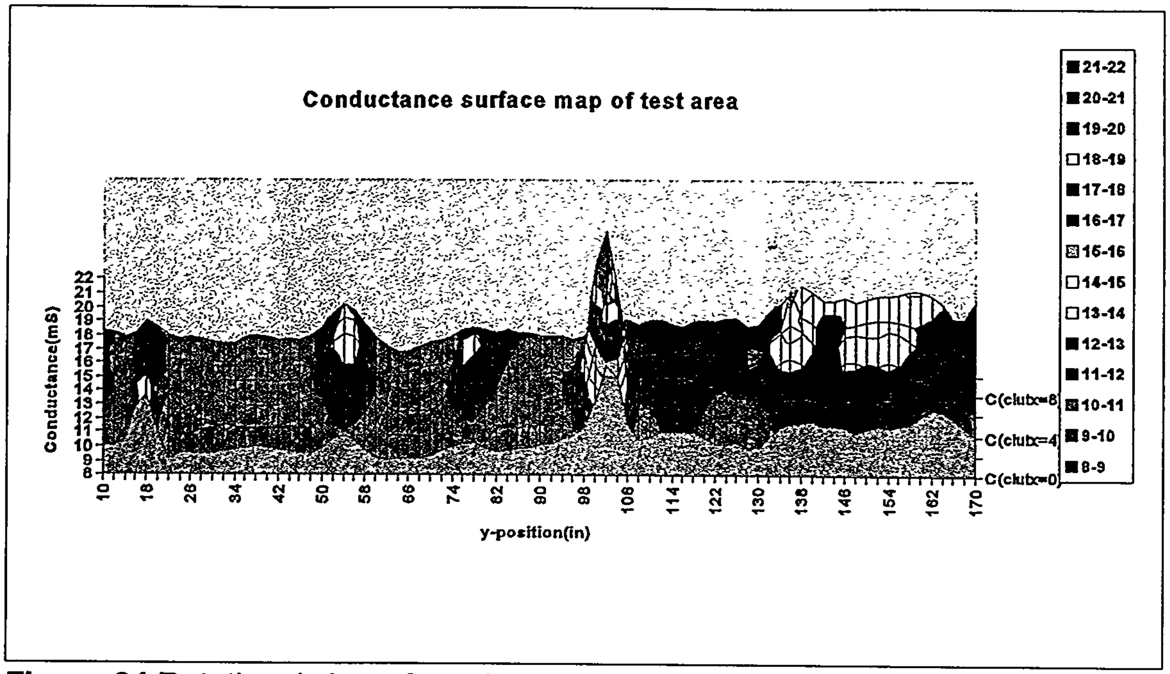

Figure 24 Rotational view of conductance values measured over the survey area.

This particular presentation of the data seems to be the best from an object identification point of view. The antivehicular mine clearly stands out in the image.

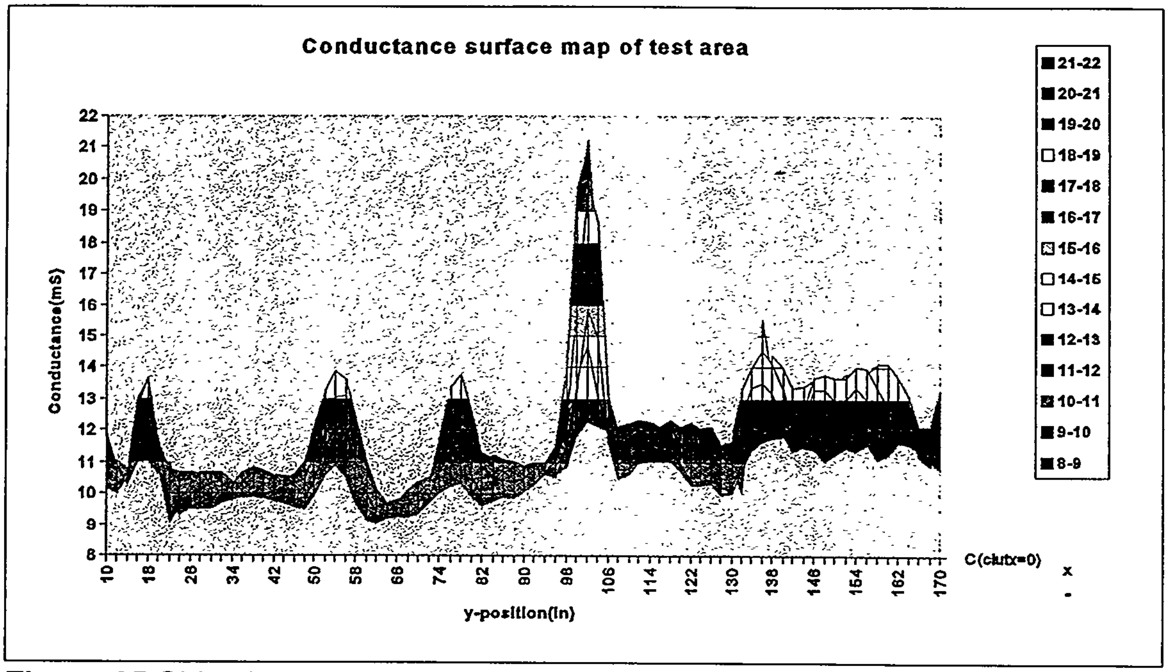

Figure 25 Side view of conductance values measured over the survey area.

The contour lines form a silhouette image of the empty bottle. The bottle appears to be six inches long and features a silhouette that is oblong. The images clearly show the dielectric cylinder and the antivehicular land mine. The metal plate does not exhibit a silhouette similar to a land mine. The AP mine is not apparent in the image. This is due to the fact that the sensor stand-off height is approximately 3.5 inches. The detection sensitivity is minimum at this stand-off height.

The RMPA stand-off height was not controlled during this clutter test. The stand-off height was measured at the end of the test and the data is presented in Figure 26.

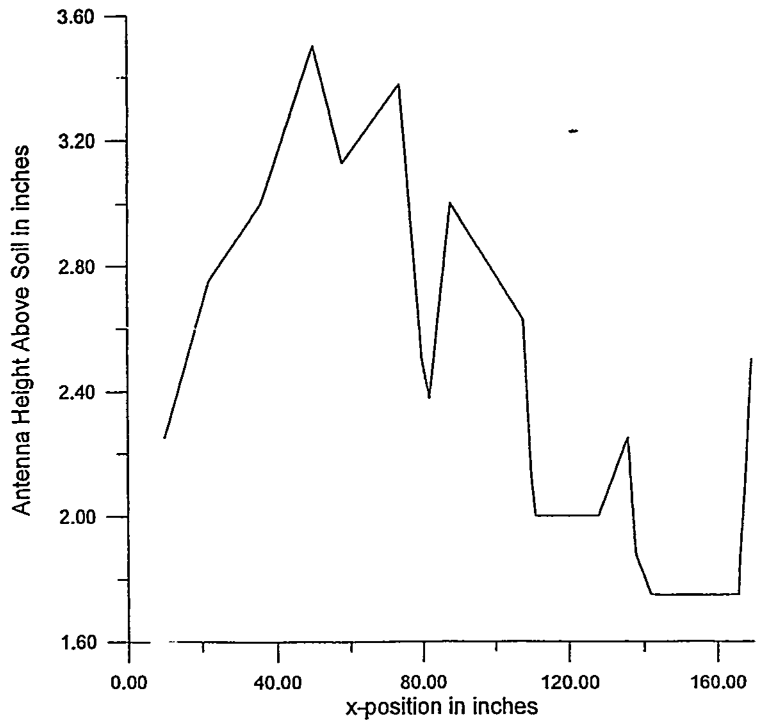

Figure 26 Measured antenna height above the soil for the clutter test. (Note: This implies a general trend only because these data were taken at various antenna offset positions and over the course of all clutter tests.)

3.6 MEASUREMENT OF RESONANT CONDUCTANCE OF THE RMPA SENSOR WHEN SWEPT OVER ANTIPERSONNEL MINE

The shallowly buried antipersonnel land mine detection problem was investigated by making a series of resonant conductance measurements.

In the first tests, the RMPA response was measured at different heights above the soil surface.

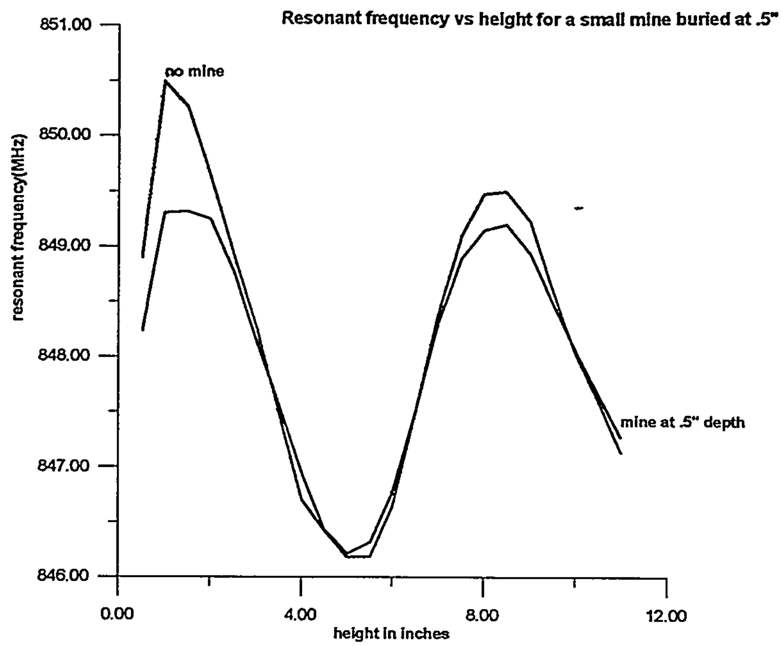

Figure 27 Frequency change versus RMPA sensor height above soil surface for undisturbed soil and the antipersonnel mine buried at ½ inch.

The resonant frequency appears to decrease when the AP mine is present. The Maximum decrease (sensitivity) occurs when RMPA is near the earth's surface and periodically at the ½ wavelength (6.8 inch) period. The near field resonant conductance is illustrated in Figure 28.

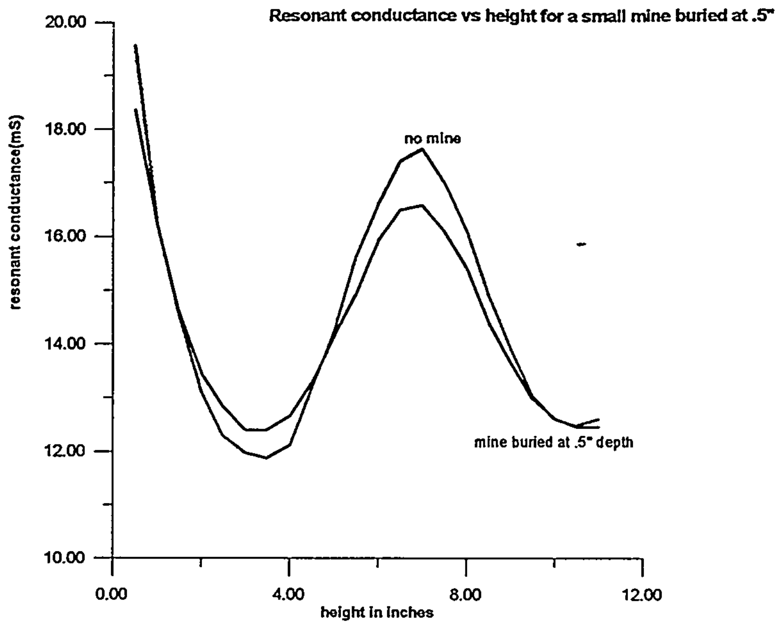

Figure 28 Measured resonant conductance versus RMPA height above the earth.

When RMPA is very near the soil surface, the measured resonant conductance decreases from the undisturbed soil condition. The same measurement phenomenon occurs when the RMPA sensor height is increased by ½ wavelength. The change in resonant conductance is 6.2% at 850 MHz.

In the next test, RMPA was swept over a shallow buried (0.25 inch) AP land mine and the resonant conductance was measured at 1 inch intervals. The measured data is shown for operating frequency of 850 MHz in Figures 29 and 30.

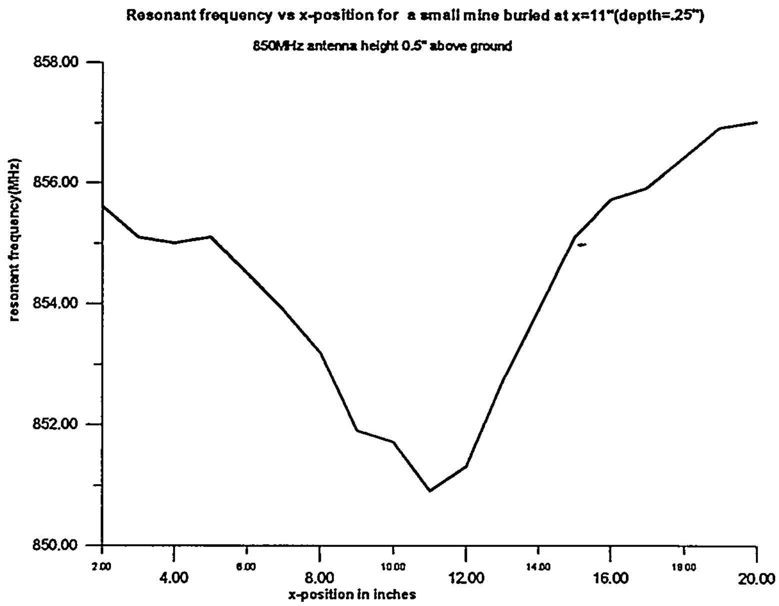

Figure 29 Measured resonant frequency versus X position swept over antipersonnel land mine at 850 MHz.

The conductance values reach maximum values on each side of the AP land mine. The maximums are located approximately 1.96 cm (5 inches) from the center of the AP land mine.

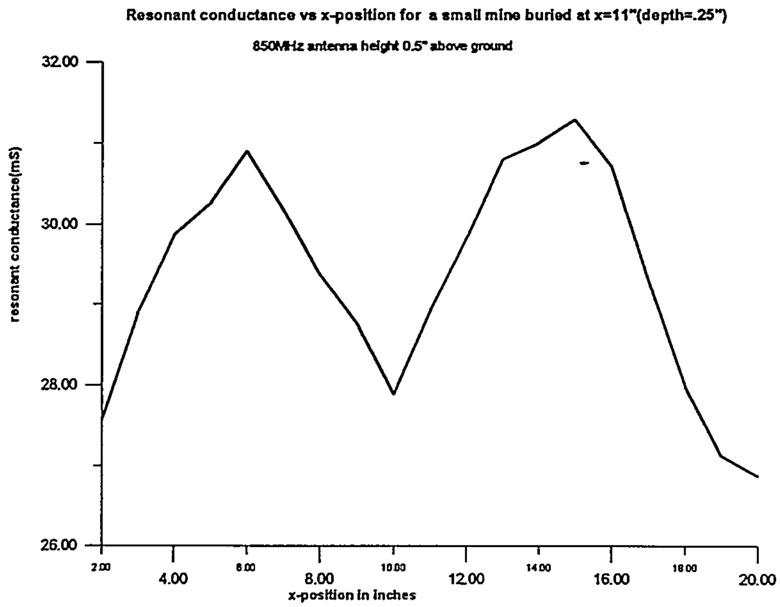

Figure 30 Measured resonant conductance versus X position swept over an antipersonnel mine at 850 MHz.

The double peaks are observable in the graphical display of the data acquired when sweeping the RMPA sensor over AP land mines buried at various depths. The reason for the double peaks follows from the illustration of the TM_{11} mode fields shown in Figure 9. When the RMPA sensor approaches the edge of the land mine the circular patch sensor fringing fields are closer to the land mine. This causes a significant change in the RMPA internal cavity fields along with a change in RMPA response.

3.7 CLUMP OF GRASS

The sensitivity of the RMPA to a clump of grass was determined by comparing the measured conductance values over undisturbed spoil and a clump of grama grass at the same location. The measured data is illustrated in Figure 31.

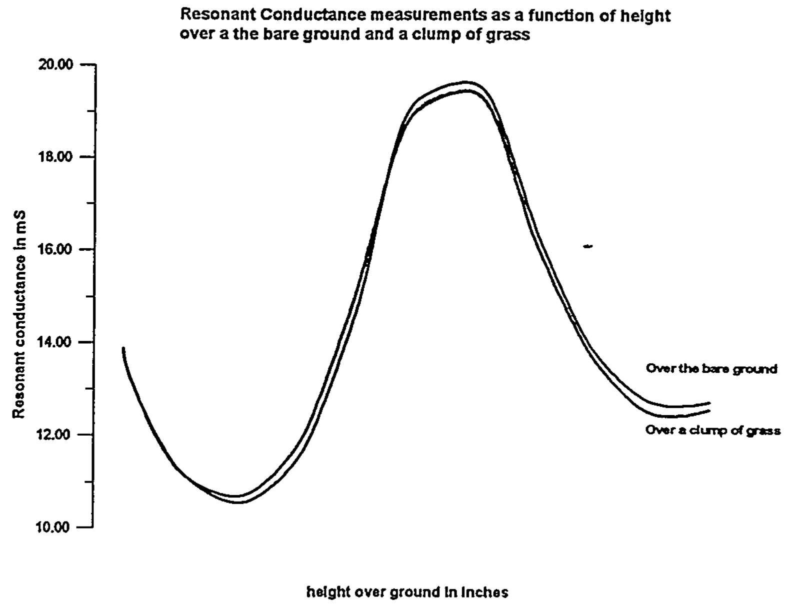

Figure 31 Measured resonant conductance versus RMPA height over undisturbed soil and a clump of grass.

Since the curves are substantially the same, grass appears to have minimal impact on RMPA measurements. The minimum sensitivity to grass may be due to the fact that the RMPA E-fields are orthogonal to the vertical grass. The E-Field is minimally coupled to the grass.

3.8 AP LAND MINE TILTED AT 45 DEGREES

The test was designed to determine the RMPA sensor detection sensitivity for land mines buried with a 45° tilt. The measured data is illustrated in Figure 32.

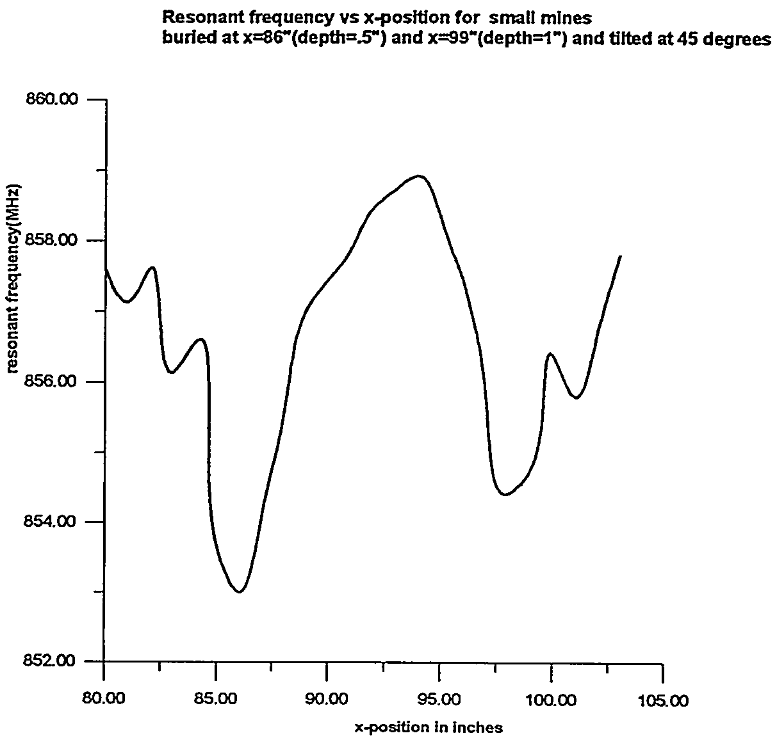

Figure 32 Measured resonant frequency in MHz versus X position sweep distance in inches.

The AP land mine is buried at a depth of 0.5 inches at X = 86 inch position. The second land mine is buried at a depth of one inch at the X = 99 inch position. This data shows that the resonant frequency changes by 5 to 6 MHz (approximately 0.6%) when RMPA is swept over the AP land mines. The measured conductance values are illustrated in Figure 33.

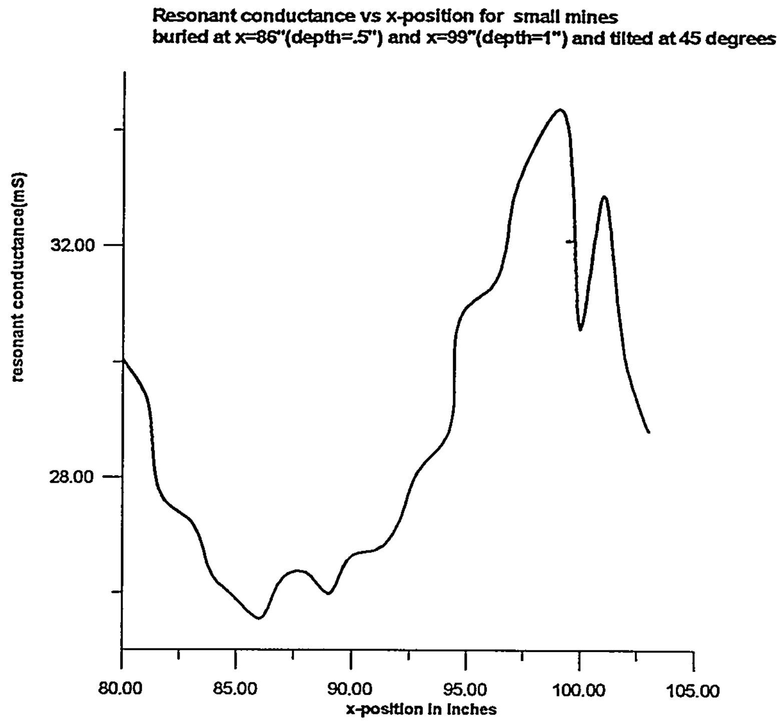

Figure 33 Measured resonant conductance in milisiemens versus X position swept distance in inches.

As the RMPA sensor is swept from left to right over these AP land mines, the conductance values reach a minimum value over the AP land mine at depth 0.5 inch and reaches a maximum value over the AP land mine buried at a depth of 1 inch.

The measured data for the 45° tilted AP land mine exhibits a change in conductivity of approximately 6 mS (22%). This is a change in conductivity of 38 percent.

3.9 RIVER ROCK

The photograph of the buried river rock is shown in Figure 3. The conductance presentation shown in the three-dimensional plot is shown in Figure 4. It is impossible to detect the river rock. This is partly due to the large response from the antivehicular land mine. In Figure 17, the test series 2 clutter tests show that the Measured conductivity increases over the river rock in this test. The RMPA sensor stand-off height was nearer to the soil interface which partially accounts for the increase in conductivity.

3.10 MEASUREMENT OF SOIL WATER SATURATION EFFECTS ON MEASURED CONDUCTIVITY

The RMPA sensor was swept over undisturbed soil and the conductance was measured along the survey line. The RMPA sensor stand-off height was 3.5 inches, near the quarter-wave minimum sensitivity stand-off height. Measurements were repeated for two conditions of soil moisture: normal and saturated. The data is shown in Figure 34.

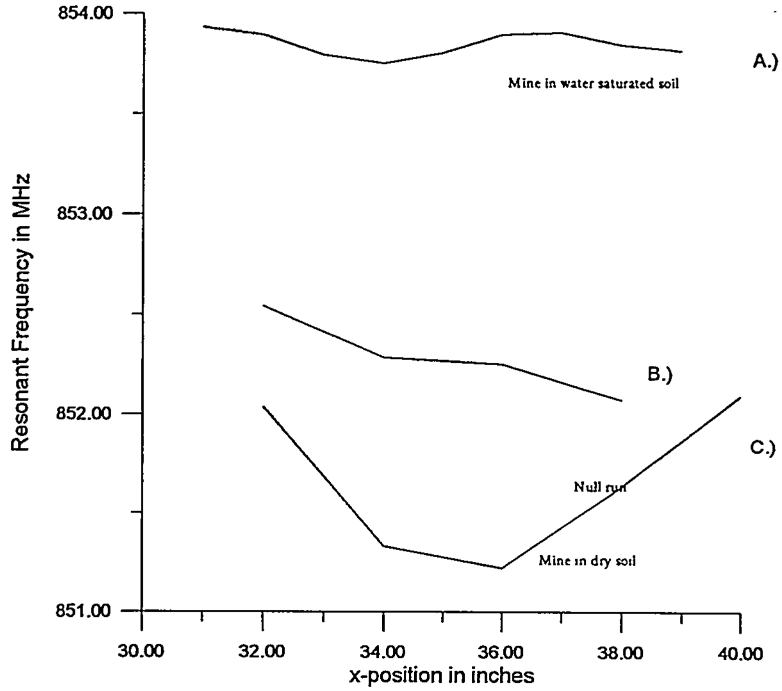

Figure 34 Measured RMPA frequency values in MHz versus distance along survey line.

a) undisturbed soil
b) normal soil
c) saturated soil

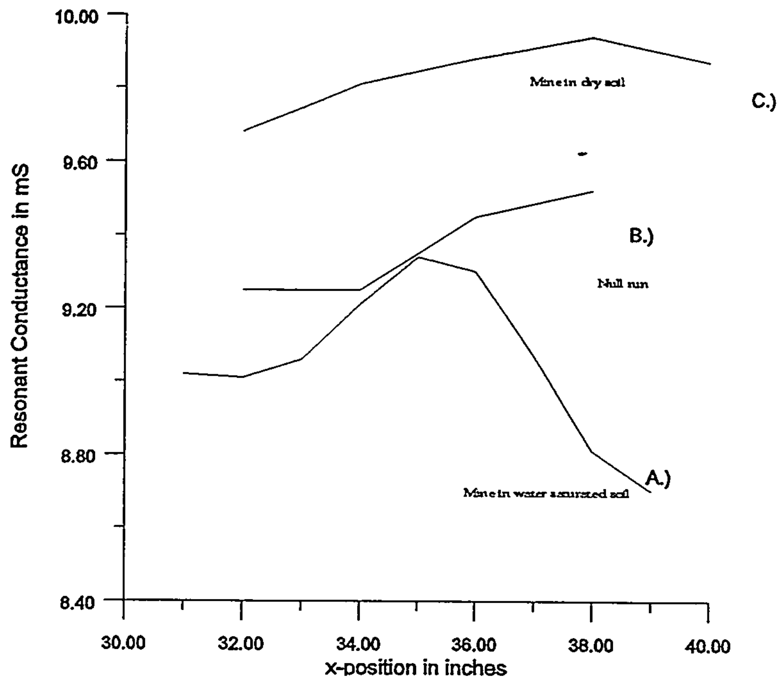

Figure 35 Measured RMPA conductance values in milisiemens versus distance along survey line.

a) undisturbed soil

b) normal soil

c) saturated soil.

3.11 ANTIPERSONNEL LAND MINE RESPONSE AT 1700 MHZ

The antipersonnel mine was buried at various depths in a grass lawn. The conductance was measured along survey lines directly over the antipersonnel land mine. The measured data is shown in the table below:

MEASURED DATA AT 1700 MHZ
Resistance values in Ohms

	Burial depth in inches				
Distance in inches	no mine	1	1.5	3	magnetite
4	25.8	24.8	26	28.5	32
7	26.4	20.6	20.4	21.5	21.5
9 (land mine)	26.5	18	15	18	19.2
11	22.5	24	19	27	21
14	19.5	22	24.9	26.9	27.4

When the soil covering the land mine was removed (buried at a depth of three inches) and replaced with magnetite, the measured conductance values were similar to the 5 inch burial depth values (see far right column of data). This difference in values is within experimental error. The measured data acquired over buried antipersonnel land mines shows that the 1700 MHz RMPA sensor conductance begins to decrease approximately two inches from the antipersonnel mine. The decrease is approximately 6 - milisiemens. This represents a 30 percent change.

3.12 MEASURED RMPA RESPONSE OVER RIVER ROCK

An antipersonnel land mine was buried at a depth of two inches. The survey area was covered with one inch diameter river rocks. The measured data is illustrated in Figure 36.

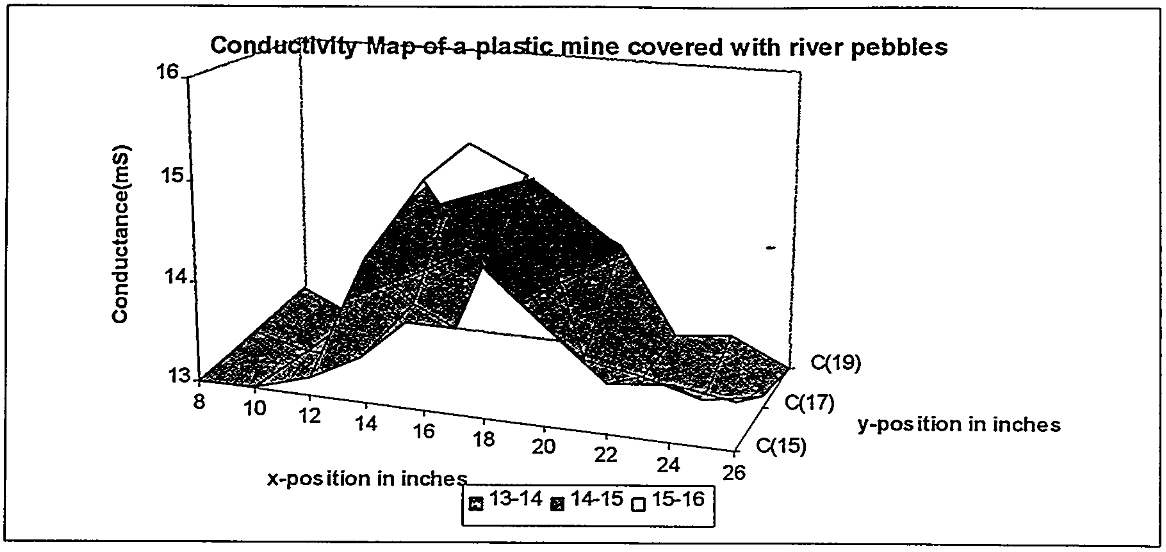

Figure 36 Measured RMPA conductances with antipersonnel land mine survey area covered with one inch diameter river rocks.

V CONCLUSION

5.1 SUMMARY AND RECOMMENDATIONS

We found that the RMPA sensor and associated microcomputer-controlled electronics can detect and form images of nonmetallic (and metallic) antipersonnel land mines and clutter objects. The RMPA sensor achieves maximum sensitivity when near the air-soil interface and at half wave intervals in stand-off distance. The RMPA sensor design will find application for close-in man carried mine detection.

We found that clumps of grass, roots of oak brush, 2 x 4 inch boards, 16 gauge electric wire, spent shell casings, and river rocks produced very small changes in resonance when RMPA was swept over the clutter test site.

Clutter objects such as 3/4 inch metal pipe, aluminum beverage cans, glass bottles and dielectric cylinders produced significant response. When the unprocessed measured conductance data was presented in two dimensional gray scale or color plots, silhouettes of the clutter objects were formed. Three-dimensional plots of the raw data indicated that metal objects caused local minimums while nonmetallic objects produced local maximums for a given antenna height. This feature may possibly be used as a signature in the identification problem. Since the local minimum or maximum response depends on the scattered wave from the buried object, the min/max response is expected to switch with changes in frequency. This suggests that a multi frequency system would improve both the P.D. and F.P.R. figure of merit.

When the measured data were processed by subtracting the average value and taking its absolute value, the min-max response was converted to a local maximum (peak) response over the buried objects. Three-dimensional graphical representations seem to be more idealistic and effective in the identification problem. With this type of imaging, we were able to determine that the 3/4 inch pipe, aluminum can, and glass bottles were not land mines.

Nonmetallic antipersonnel land mines were detected and the "absolute" value imaging presentation assisted in the identification of these mines. When the antipersonnel land mine was buried within one half inch of the surface, the RMPA sensor swept response exhibited a local maximum values on approach and departure from the antipersonnel mine. Directly over the antipersonnel mine, a local minimum appears in the data. To experimentally evaluate the phenomenon, the test frequency was changed from 850 to 1700 MHz. At 1700 MHz, only a minimum was found over the antipersonnel land mine. This experimental finding added to our conviction that a multi frequency system will improve identification of buried objects.

Other related tests found that when water was used to saturate the soil overlying the antipersonnel land mine, the detection sensitivity improved. This is due to the increased dielectric constant contrast between the saturated soil and the antipersonnel mine. Regional changes in soil moisture are expected to produce false positive responses. This is a common problem in scattered wave imaging. Imaging is an important factor in resolving this problem. Fusing the RMPA sensor with an IR sensor could resolve this problem. Magnetite in the overlying soil did not significantly change the RMPA sensor response to buried antipersonnel land mines. The orientation of the land mine did not significantly affect the resonance because of the scattering phenomenon. Electrical noise from power lines, internal combustion engines, and hand held radios had no effect on the response.

Changes in stand-off height caused by footprints, tire tracks, and local erosion will, have an impact on the measured conductance values. If a stand-off height sensor (acoustical sensor) were fused with this sensor, the effectiveness of RMPA would improve.

The RMPA sensor operates with high detection sensitivity at 850 MHz. A multi frequency design is recommended to overcome the strong detection sensitivity dependance on stand-off height and burial depth. The multi frequency system appears to enhance the identification and image forming aspects of the RMPA system. An image forming capability is required in the identification of land mines and clutter objects.

Clutter Object	Clutter Response/Comments
Roots	no effect
Grass	no effect
Rocks	small perturbation
Single rock covering mine	Mine detected with and without rock
Many small rocks covering mine	Small effect; improved detection with disturbed soil
8 rifle shell casings	Small but definite signal; enhanced in wet soil
chopped, disturbed soil	Minimal influence but
Magnetite covering mine	Mine still seen
Dr. Pepper can	Large response; imaged
Maple syrup bottle	Large response; imaged; less contrast when filled with water
Lucite cylinder (mine size)	Detected like a mine
coins	Same response as shell casings
Metal pipe ($\approx$ 3 cm diameter)	Definite response and image; enhanced ion wet soil
dielectric pipe	Nearly invisible
wood block	Small perturbation
metal strips/plates	Large response
cow pie	No effect
metal plate under mine	Slightly enhanced and broadened signal
metal plate over mine	Reversed the conductance change
metal plate over mine but on the surface	Increased the response; probably sensing more of the metal