Investigation of EMI response for magnetically susceptible rough surfaces

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Abstract ---Magnetic and electromagnetic induction (EMI) sensing have been identified as two of most promising technologies for the detection and discrimination of subsurface metallic objects, particularly unexploded ordnances (UXO). In magnetic sensing, the principle of detection is that the sensor measures a distortion of the Earth's magnetic field caused by ferrous objects/ordnance. Similarly, in EMI, the sensors are detecting signals that are produced by induced and permanent magnetic polarizations. While these sensors can detect ferrous objects, they also find many other magnetic anomalies in the close vicinity. Soils, which contain small magnetic particles, called magnetically susceptible soils, can produce EMI responses, and therefore they can mask or modify the object's EMI response. These soils are a major source of false positives when searching for UXO using magnetic or EMI sensors. Studies show that in adverse areas up to 30% of identified electromagnetic (EM) anomalies are attributed to geology. Therefore, to enhance UXO detection as well as discrimination in geological environments the effects of the magnetic soils on the magnetic and EMI signal demands studies in detail. In this paper, the method of auxiliary sources (MAS) is applied to investigate the EMI response from magnetically susceptible rough surfaces. Several important physical phenomena such as the interaction between surface irregularities, modeled as multi hemitoroidal objects, surface roughness and antenna elevation effects are studied and documented. The numerical results are checked against available measurement data.

Keywords: susceptible, rough surface, magnetic, EMI, Polarization, UXO, detection.

1. INTRODUCTION

Unexploded ordnance (UXO) detection and neutralization are emerging environmental issues around the world. In the USA alone there are as many as 11 million acres of land and about one million acres of underwater environments that are potentially contaminated with UXO. UXO items include artillery shells, bullets, mortars, bombs and are relatively large metallic objects. While metal detectors can find UXO, they also find everything else metal in the vicinity. This is particularly a problem in highly contaminated UXO cleanup sites, where multiple subsurface objects appear within the field of view of the electromagnetic induction (EMI) sensor simultaneously. The task of discriminating UXO from non-UXO items is much more complicated when sensor data is contaminated with geological noise originating from magnetic soils.

Magnetic soils are a major source of false positives when searching for landmines or UXO with electromagnetic induction sensors. Recent studies [1] -[10] showed that, magnetically susceptible soils can produce electromagnetic anomalies of the same magnitude as buried metallic targets. In adverse areas up to 30% of identified electromagnetic (EM) anomalies are attributed to geology [1]. Several studies have been conducted to understand the interaction between the object and host magnetic soil [7], [8], and to distinguish between anomalies originating from UXO and geology. In parallel several discrimination techniques that generally include a combination of (a) spatial filtering of the data and (b) comparing the EM response of the soil to a soil model have been developed [4], [6]. Some UXO discrimination studies have showed how important it is to include magnetic soil models into inversion algorithms when the response of the soil closely matches the response of a target [2]-[6], [9]-[13].

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In those studies, it is assumed that the spatial distribution of magnetic anomalies are constant, similar to a half space, and that this response can be subtracted from measured data. This process is only partially effective, yet even in areas of very flat smooth magnetic soil and under controlled conditions, variations in sensor height and orientation, as well as small variations in the surface topography, can produce anomalies similar to those from UXO [5]. Due to the difficulties in spatially distinguishing between soil and metal anomalies, it is important to study in detail the EMI response from magnetically susceptible soils with a rough surface profile.

The main objective of this paper is to study EMI response from magnetically susceptible soils with a rough surface, and to understand how spatially distributed anomalies/roughness affects on EMI responses from a UXO detection and discrimination perspective. To do so, the full EM problem is solved using a numerical approach called the method of auxiliary sources (MAS) [14]-[17]. For the low frequencies of interest here, induced conduction currents are much stronger than the displacement currents inside the UXO, so the latter can be neglected. Electric fields are typically negligible in EMI frequency range. Thus, given the low frequency range characteristic of EMI sensing (10's of Hz to perhaps 100 kHz), the dielectric properties of the surrounding media are relatively unimportant for EMI identification of buried targets such as UXO. It also implies that magnetic fields are irrotational, and can thus be represented efficiently using a simple scalar potential.

In the MAS, boundary value problems are solved numerically by representing the electromagnetic fields in each domain of the structure under investigation by a finite linear combination of analytical solutions of the relevant field equations, corresponding to sources situated at some distance away from the boundaries of each domain. The "auxiliary sources" producing these analytical solutions are chosen to be elementary dipoles/charges located on fictitious auxiliary surface(s), usually conforming to but offset slightly from the actual surface(s) of the structure. Enforcement of standard electromagnetic boundary conditions at an array of points over the object's actual surface allows us to solve for the auxiliary sources, from which we can immediately express all EM fields in the problem.

The paper is organized as follows: In section II, the problem is discussed, Section III describes the data acquisition and results for a magnetically susceptible half space and a steel sphere and finally, in Section IV several experimental and numerical results are presented which show the EMI response from magnetically susceptible soils with rough surfaces. The near and far field effects are shown and analyzed.

2. PROBLEM

The magnetic properties of soils are mainly due to the presence of iron and iron-titanium-oxides [18]. Hydrated iron oxides such as muscovite, dolomite, lepidocrocite, and geothite are weakly paramagnetic, and play a minor role in determining the magnetic character of the soil. Ferromagnetic minerals such as maghaemite and magnetite primarily determine the magnetic character of the soil. Maghaemite is considered the most important of the minerals within archaeological remote sensing circles [19]. Magnetite is the most magnetic of the iron oxides, and is the most important mineral when considering the effects of magnetic soils on total-field magnetic and EM measurements [2]. Given the presence of these magnetic minerals, the strength of the magnetic susceptibility primarily depends upon the mass fraction of these dominant magnetic minerals. The static magnetic sensors are sensitive to the presence of magnetic minerals because the earth's magnetic field creates an induced magnetization in them. This anomalous magnetic field produced by the soil magnetization will be superimposed on the magnetic anomalies produced by UXO's and other metallic objects and will therefore introduce adverse effects into the discrimination problem. There are three magnetic effects that impact the magnetic and electromagnetic characteristics of the subsurface: (1) induced magnetization, (2) viscous remanent magnetization (VRM); and (3) permanent/remanent magnetization.

The magnetization that arises in the presence of an external magnetic field is referred to as the induced magnetization. For an object with susceptibility χ in an external magnetic field, the induced magnetization is

$$\mathbf{M} = \chi\left(\mathbf{H}^{\mathrm{pr}} + \mathbf{H}^{\mathrm{sc}}\right) \qquad (1)$$

where $\mathbf{H}^{\mathrm{pr}}$ and $\mathbf{H}^{\mathrm{sc}}$ are the external primary field and the secondary induced magnetic field respectively.

Viscous remanent magnetization (VRM) [19] is a phenomena which is similar to relaxation in dielectrics, when changes in magnetization are delayed relative to the applied primary magnetic field. VRM occurs in ferrimagnetic materials that are arranged into individual magnetic domains with adjacent domains anti-parallel but of unequal magnitude so that a net-field can result. And finally the magnetization that exists in the absence of any external magnetic field is called permanent magnetization.

The total secondary magnetic field measured by a sensor is a distance-weighted summation of all the infinitesimal volumes of induced magnetization, VSM and permanent magnetization. The distribution and magnitude of the susceptibility, therefore, determines the spatial characteristics and magnitude of the induced secondary magnetic field as observed above the soil. The primary minerals responsible for the susceptibility are the ferro- and ferri-magnetic iron-titanium oxides which include magnetite and maghemite. Therefore, understanding the effect of geology on electromagnetic sensors lies in understanding: 1. how susceptible soil's surface roughness affects the sensor's performance, 2 is there any interaction between a highly conducting and permeable metallic object, such as UXO, and its magnetically susceptible host medium.

For magnetically susceptible ground in the present of a metallic object the field that is measured by the sensors contains two parts and it can be written as

$$\mathbf{H}^{\text{mes}} = \mathbf{H}^{\text{gr}} + \mathbf{H}^{\text{obj}} \tag{2}$$

where, $\mathbf{H}^{\text{gr}}$ and $\mathbf{H}^{\text{obj}}$ are magnetic fields produced by magnetically susceptible soil, and the object respectively. The $\mathbf{H}^{\text{obj}}$ field contains all interactions between the object and susceptible host medium. To determine the $\mathbf{H}^{\text{gr}}$ and $\mathbf{H}^{\text{obj}}$ contribution of each terms in measured field, a full EMI problem must be solved. In the EMI induction frequency range, the normal component of magnetic flux and the tangential components of magnetic field are continuous at each interface. Here, the MAS is used for solving this boundary value problem. Enforcing boundary conditions on each surface at selected points leads to a linear system of equations.

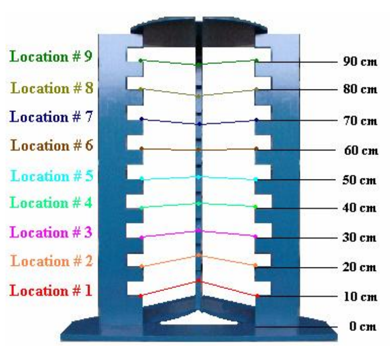


Fig. 1. An experimental setup.

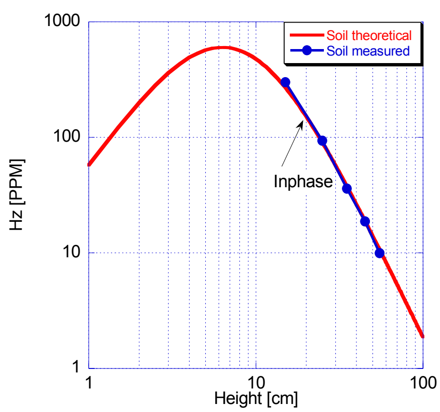


Fig. 2. EMI response for a soil versus height.

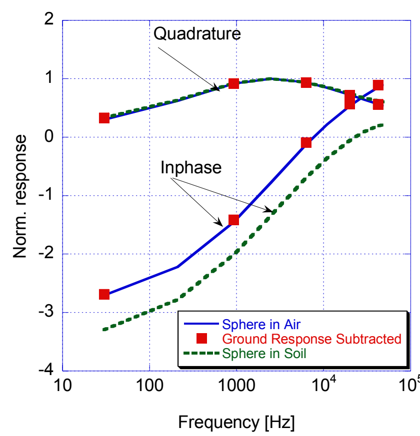


Fig 3. EMI response for a steel sphere.

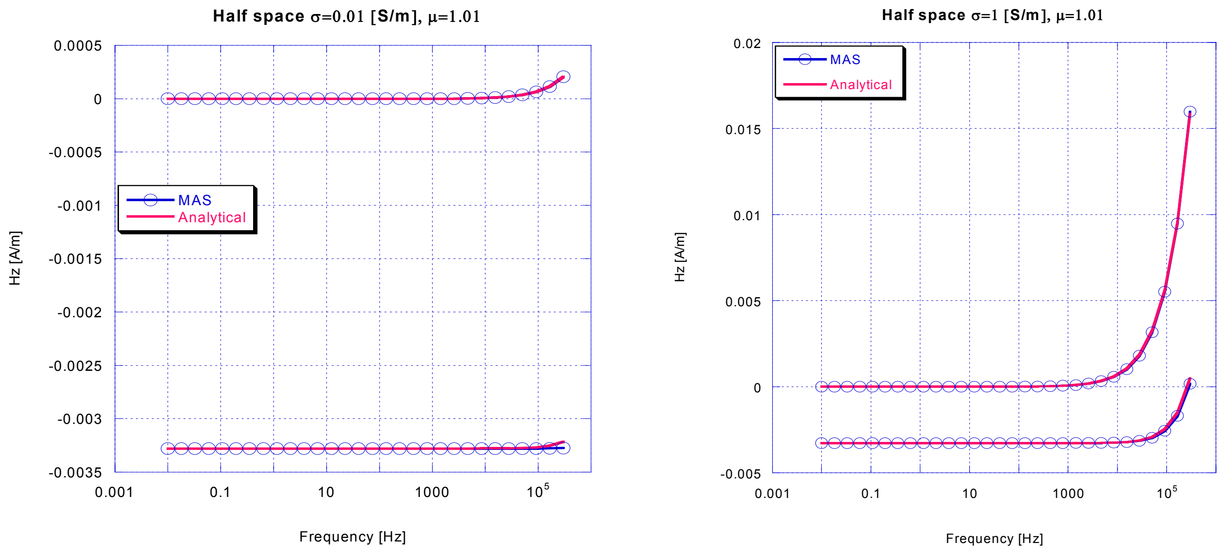
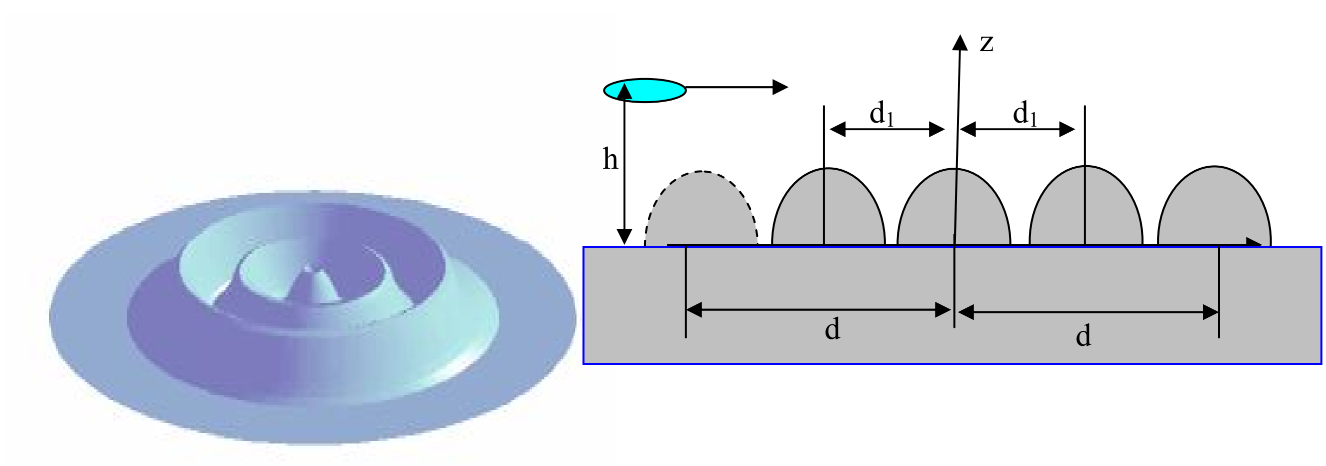


Fig. 4. EMI response for permeable and conductive half space versus frequency, μ=1.01,
a): $\sigma=10^{-2}$ [S/m], b): σ=1 [S/m],

3. DATA ACQUISITION

The frequency domain GEM-3 data considered here were acquired at The Cold Regions Research and Engineering Laboratory Facilities. Different types of magnetically susceptible soils were brought into facilities and several test plot sites were created. These sites are ideal for this study due to its well-controlled environment, e.g. having the ability to precisely measure the sensor's orientation and position. A series of tests were devised to investigate the



a) b)

Fig. 5. Semi-toroidal magnetically susceptible surfaces. A) 3D view, b) xoz cut profile.

relationship between a buried object and its host soil, the sensor's height effects, and the topography of the soil and its affect on EMI signals. A special frame was designed for controlling data collection at different elevations (Figure 1). The sensor height tests were performed above the most magnetically susceptible soil available. In all tests, the sensor's orientation was fixed. The instrument drift was accounted for by measuring the EMI response at highest elevation #9 (Figure 1) at the beginning and end of the survey, and the average of these two measurements subtracted from data taken at each of the other location #1-5. During the elevation test, data were collected from location #1 up to location #5 using the GEM-3 sensor. The soil is 5 cm below the 0 cm mark on the frame. The measurement results alongside numerical data are depicted in Figure 2. In this numerical calculation, the ground was assumed to be a half space, and the EMI response was calculated using the image theory [7], [20]. Figure 2 shows a $1/h^3$ dependency of magnitude of soil response when the height of the GEM-3 sensor is more then 15 cm. The numerical result, which agrees very well with actual data, reveals near field effects: as sensor approaches the flat ground, the soil's response decreases.

Similar tests were done for a ferrous sphere. First, the sphere was placed in air and the EMI response was measured using the GEM-3 sensor. The distance between the GEM-3 sensor and the center of the sphere was 15 cm. Then the same sphere was buried in the magnetically susceptible soil, and the EMI responses with and without the sphere present in the soil were measured. The normalized EMI responses are depicted in Figure 3. Normalized measurements for the steel sphere buried in soil show a shift in the inphase component relative to its response in air. Subtracting the flat soil response, measured independently at the same elevation, produces agreement with the measurements in air. The results reveal two facts (1) the response from a buried object can be approximated as a simple sum of the independent responses from the soil and the buried object and as a corollary (2) there is negligible interaction between the buried metallic object and its host medium. Numerical results for magnetic soil with realistic susceptibility values were similar [7].

Usually, most soils are conductive and susceptible. Therefore, a soil's EMI responses are produced by both induced eddy currents (conductive soils) and by magnetic polarization (susceptible soils). Recent studies showed that the EMI response from conductive soils are several orders of magnitude less than the EMI response from susceptibility soils [21]. To understand the shift in the inphase part for the buried sphere (Figure 3), we solved a detailed EMI problem for a conducting and permeable half space both numerically using MAS and analytically [21 and references there in]. The GEM-3 sensor illuminates the magnetic and conducting half space. The sensor is placed 10 cm above the half space. The secondary induced magnetic field is then calculated at the sensor's center. The comparisons between MAS and analytical solution are given in Figures 4a and 4b. The half space EM constitutive parameters are: magnetic susceptibility χ=0.01 and conductivity σ=0.01 [S/m] Figure 4a, and σ=1 [S/m] Figure 4b. The simulations are done for a broadband EMI frequency range from 0.001Hz up to up to 300 kHz. The results demonstrate that the EMI response for conducting and permeable soil is almost entirely associated with susceptibility. The influence of conductivity appears only at very high frequencies. Comparisons show excellent agreement between MAS and analytical data for entire EMI frequency spectrum.

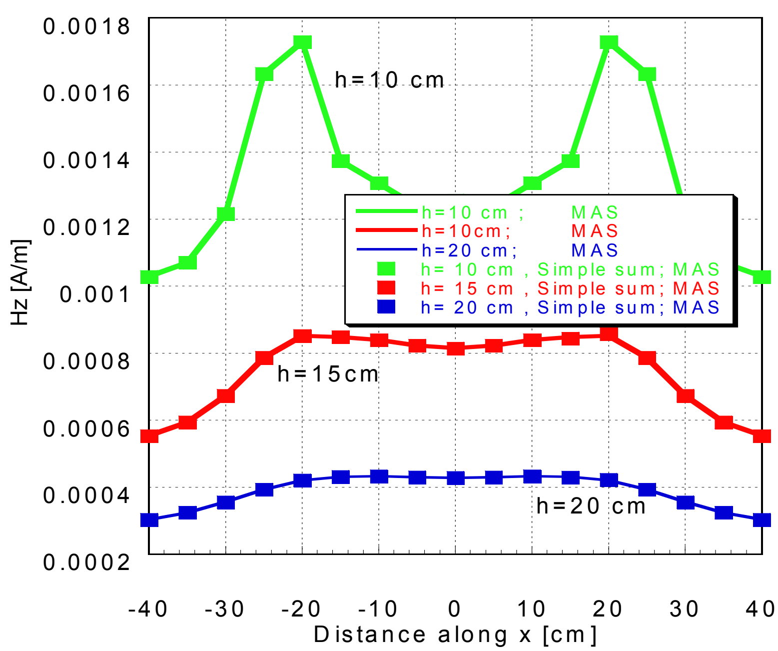


Fig.6. EMI response for the surface from Fig. 5 versus distance.

4. RESULTS

a) *Multiple bumps: interaction effects*

As a practical matter, soil surfaces are not smooth or flat. As it was reported in [5], small variations in the surface topography can produce anomalies similar to those from UXO. Therefore studying how the magnetic susceptibility of the soil affects an EMI response is very crucial for UXO clean up. In the section, a magnetostatic problem is solved for a magnetically susceptible rough surface. The surface irregularities are assumed to be hemispherical or hemitoroidal objects (Figure 5). The main objective of this study is to understand the interaction

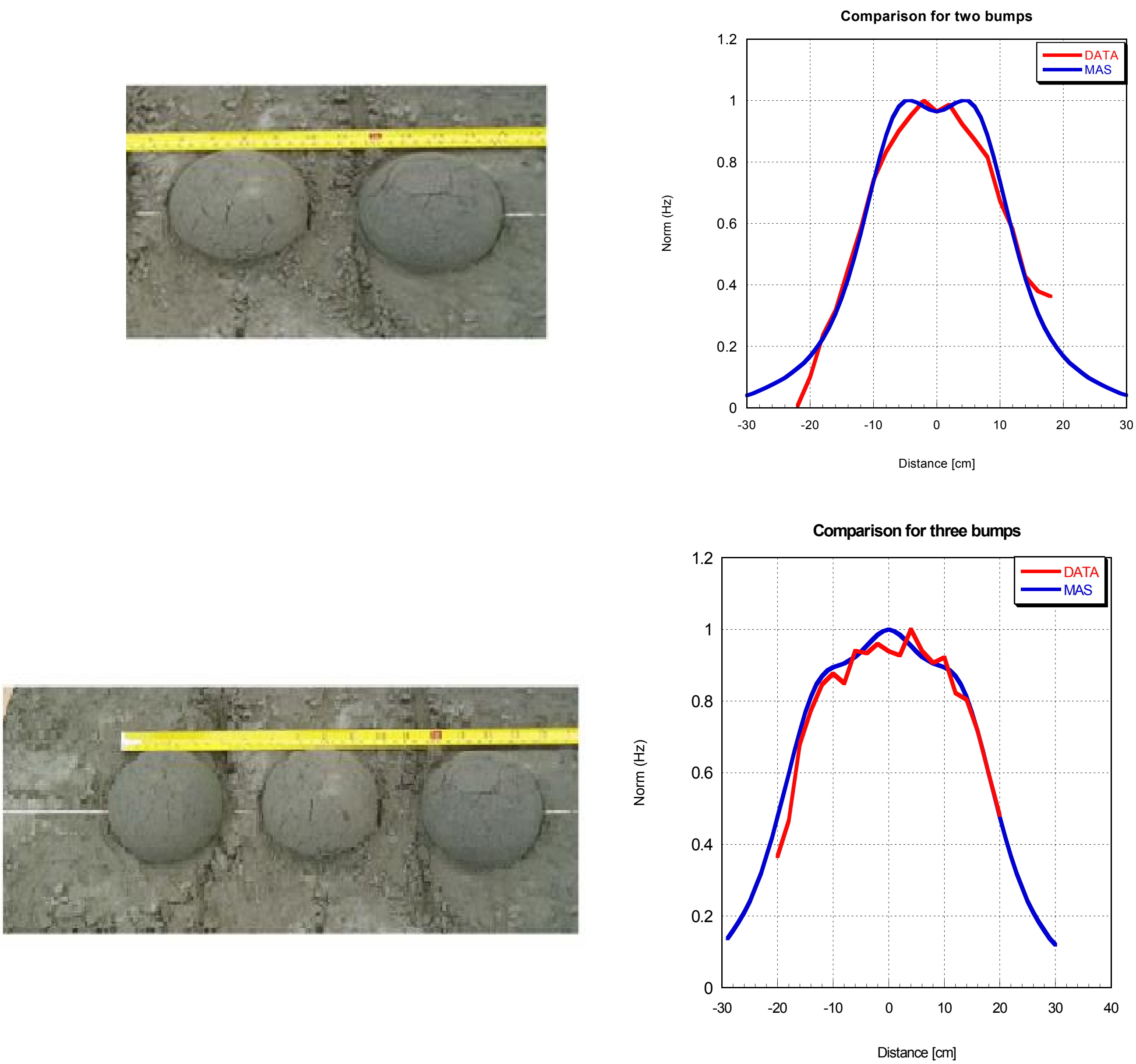


Fig.7. Normalized EMI responses for two (first raw) and three (second raw) semi spheres versus distances. Red lines actual data, blue lines numerical data.

phenomena between surface irregularities. To do so, we first solve the EMI problem for each of the irregularities (hemisphere, inner hemitoroid, outer hemitoroid) separately. Then the EMI problem is solved for entire structure in Figure 5 simultaneously. This includes all interactions between each part. The GEM-3 sensor is used as the excitation source. The sensor is placed at three elevations and swept from left to right Figure 5 b) at 5 cm step from -40 cm to 40 cm. The separation between centers of the surface irregularities are d=11 cm. The EMI response calculated as a summation of the individual responses from each irregularity are shown in Figure 6 as solid squares for three different sensors elevations. The EMI responses for the entire structure including all interaction between the protrusions at the same elevations are shown with solid lines. The comparisons show that the EMI response from entire structure with and without (simple sum) interactions are almost identical. Thus, there is negligible interaction between surface irregularities. Additionally, we conclude that the EMI response from a set of irregularities can be approximated as a simple sum (i.e. superposition) of the EMI responses from each irregularity independently. As a further test of this supposition, the following measurements were done: magnetically susceptible hemispheres (two and three) were placed on flat magnetically susceptible ground. The GEM-3 sensor was positioned 15cm above the ground and moved from right to left with 2 cm increments (Figure 7). For each hemisphere the full EMI problem was solved using the MAS and the total EMI response from the entire structure was generated as a simple summation of the responses from each individual hemisphere. The comparisons between the measured and modeled normalized EMI responses for two and three hemispheres placed on flat ground are depicted on the right column in Figure 7. The results show very good agreements between modeled and measured data. These results show two significant effects: (1) the EMI response strongly depends on the distance between the irregularities and the sensor, and (2) again, there is negligible interaction between the irregularities.

b) Rough surface:

To understand the behavior of a magnetically susceptible ground for a more realistic case, a rough surface (Figure 8, left) was created at CRREL facilities. The surface profile was measured using a profilometer and is depicted in Figure 8 (right). The geometrical size for each irregularity was estimated from the surface topography (Figure 8, right). GEM-3 measurements were taken along an ordered path at different elevations. Using MAS code, the full magneto quasi-static problem was solved for each of the irregularities. Again, the total EMI response at each point was calculated as a sum of responses from each individual irregularity. The comparisons between the measured and simulated normalized magnetic field data are depicted in figure 9. In this case, the GEM-3 sensor is at 15 cm elevation and moves from south to north along the center line (Figure 8, right black dashed line) designated points 1-51, at 2cm increments. Both data and simulation are in excellent agreement. Finally, near field distributions for the rough surface (Figure 8) on a surface at two elevations are shown in Figure 10. Figures 10 a) and c) are actual measured fields at h_1 and $h_2$elevations respectively. There corresponding simulation are depicted in Figures 10 b) and d). In all these figures the center (0,0 point) corresponds to the center of surface that is shown in Figure 8, right.

The results show that if the GEM-3 sensor is close to the irregularities (Figure 10 a, b), then the response from each irregularity is strong. However, when the sensor moves to a higher elevation, the combined response from the irregularities smoothes out. Thus, by raising the senor above the rough surface the EMI response from that rough surface can be approximated by the response from a flat half space. Since, for magnetically susceptible soil with realistic χ between 10^{-3} or 10^{-2} [18], there is no mutual coupling between the buried object and its host magnetic medium, then, for sensors at higher elevations the total EMI response can be approximated as the sum of the separate responses from a half space and from the object.

5. CONCLUSION

In this paper, the EMI secondary response from a magnetically susceptible soil was investigated and analyzed. The method of auxiliary sources (MAS) was used to simulate the EMI response from a magnetically susceptible medium. The numerical results from the MAS have been tested against analytical solutions and field data and have been shown to be in excellent agreement. Both the numerical and experimental data show that the EM response from soil depends on the distance between the sensor and the surface irregularities. As the distance between the irregularities and the sensor increases, the response due to surface effects smoothes out, and the soil behaves like a half space. As it has been demonstrated in [7] for realistic soil magnetic susceptibilities on the order of about 10^{-3} or 10^{-2} [18], the soil's permeability does not significantly influence the object's EMI response. Therefore, the total EMI response can be approximated as a sum of the responses from the ground and the object. The results also show that interactions between soil surface irregularities are negligible, and they can be modeled separately with their respective solution superposed.

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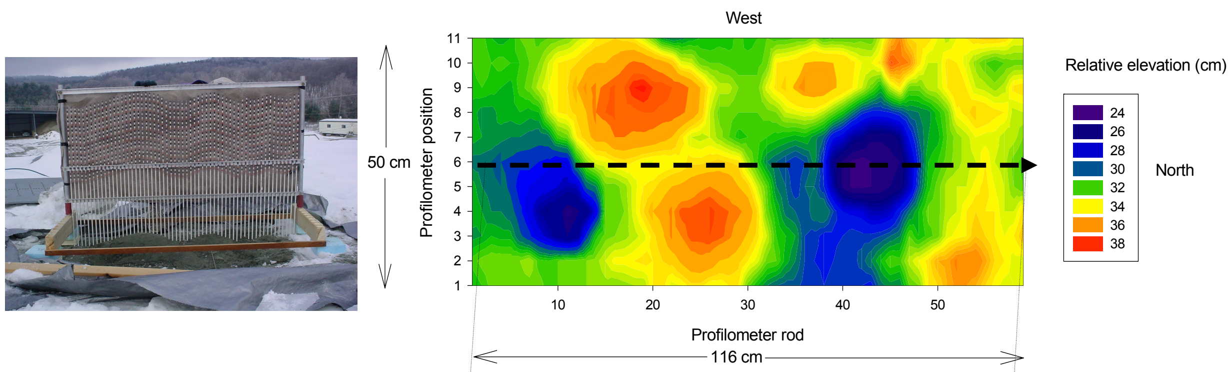

Fig. 8. Magnetically susceptible rough surface 3D view (left) and its surface profile (right).

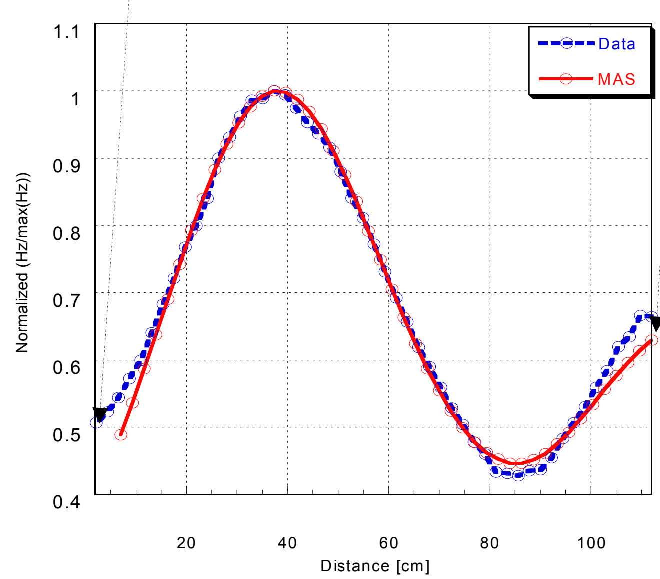

Fig. 9. Comparisons between actual and modeled EMI responses for the rough surface Fig.8 along measurement path (dashed black line Fig. 8 right) from South to North.

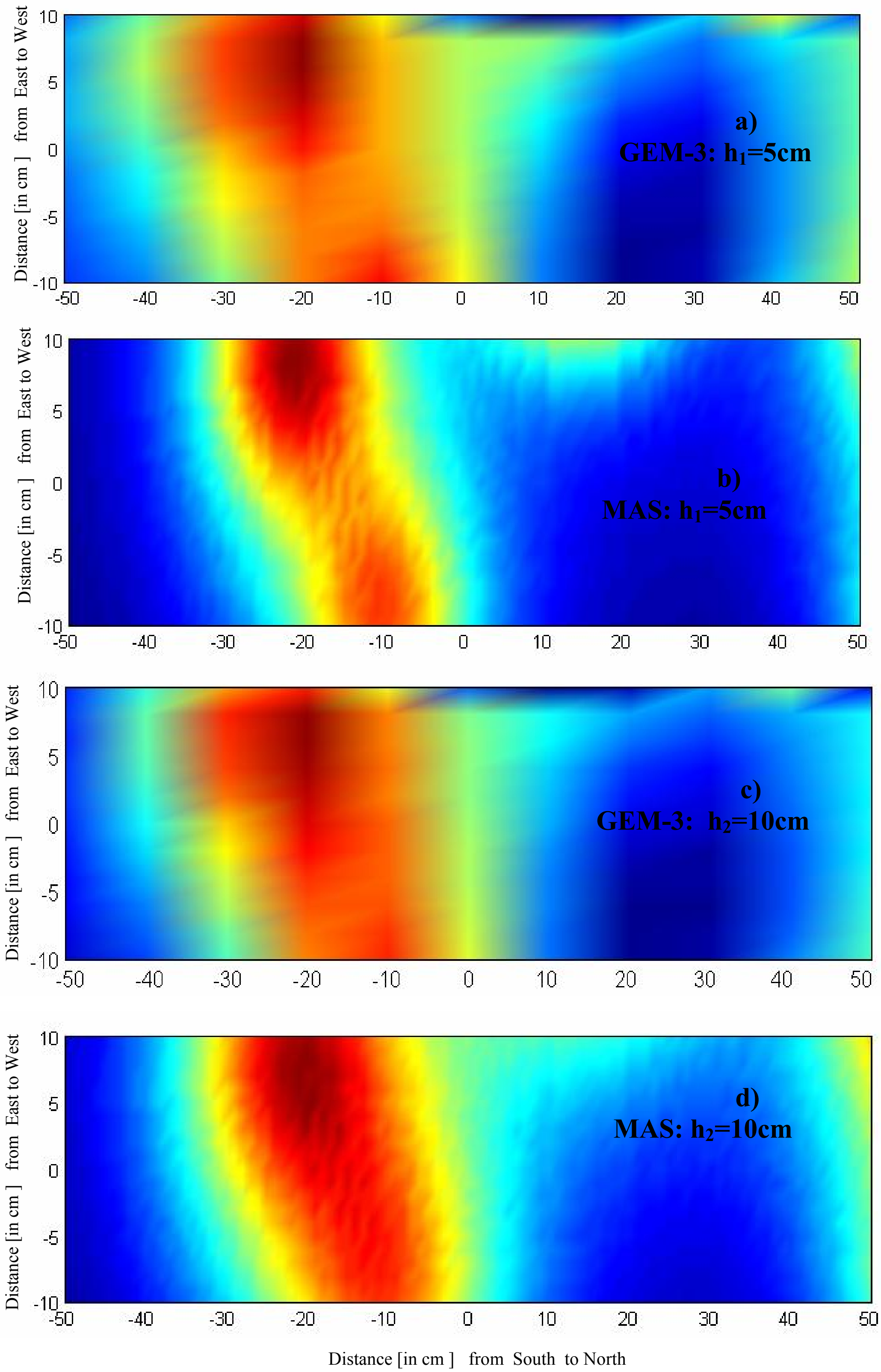

Fig. 10. Hz field distribution on a surface for the GEM-3 sensor at: a) and c) actual data, b) and d) MAS;

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