ADVANCED EMI MODELING AND PROCESSING APPROACHES FOR UXO DISCRIMINATION

F. Shubitidze(1), B. Barrowes, K. O'Neill(1,2), …
(1) Thayer School of Engineering, Dartmouth College, Hanover NH, 03755 , USA
Email: Fridon.Shubitidze@dartmouth.edu

(2) USA ERDC Cold Regions Research and Engineering Laboratory,
72 Lyme Road, Hanover NH, 03755, USA

Abstract –This paper presents a new, advanced non-traditional physics based inverse-scattering approach for determining a buried object's location and orientation. The approach combines an advanced electromagnetic induction (EMI) forward model called the normalized surface magnetic charge model (NSMC) with the pole series expansions technique. First, the NSMC is used to generate bi-static EMI data from actual measured mono-static data, and then the pole series expansion approach is employed to localize scattered field singularities, i. e. to find object's location and orientation. Once the object's location and orientations are found, then the total NSMC, which is characteristic of the object, is calculated and used as a discriminant. The algorithm is tested against actual EM-63 time domain EMI data collected at the ERDC test-stand site for an actual UXO. Several numerical results are presented to demonstrate the applicability of the proposed method for UXO discrimination.

I. Introduction

The detection and remediation of UXO on military ranges still continues to be the number one military environmental problem. As the result of past military and weapons testing activities, UXO are present at formerly used defense sites and other closed ranges. In the United State alone, more than 900 sites (about 11 million aces of land) are potentially contaminated with UXO. The UXO detection and discrimination activities conducted at DoD and DoE sites using current state-of-the-art technologies often yield unsatisfactory results due mainly to the inability to discriminate between UXO and non-hazardous items. Therefore, innovative discrimination techniques that can reliably distinguish between hazardous UXO and non-hazardous metallic items are required.

Recently, magnetic and electromagnetic sensing have been identified as promising technologies for both detection and discrimination of subsurface metallic objects, such as UXO. Both types of data are sensitive to the location, orientation, dimensions and material properties (conductivity and susceptibility) of subsurface metallic objects. Methods to discriminate between UXO and other non-hazardous items typically proceed by first recovering a set of parameters that specify a physics-based model of the object being interrogated. There are a wide range of different inverse scattering methodologies (single and double dipole models [1] –[4], the standardized excitation approach (SEA) [5],[6], the NSMC model [7], etc) currently being used or developed for discriminating UXO from non-UXO items. In order to utilize these approaches, the buried object's location and orientation have to be inverted from the data. Inverting these parameters is a time consuming and difficult task, particularly when two or more objects are simultaneously present in the sensor's field of view, which usually is the case in real field conditions. However, the secondary magnetic field that is measured by the receiver must have origins/sources, i.e. they are produced by a certain type of source e.g induced eddy currents or dipoles. These sources are distributed non-uniformly inside the scatterer. There are some particular points, named "scattered field singularities" (SFS), were most sources are located. One of the simplest examples of the SFS is an image source in electrostatics. Recently, researchers have applied the SFS theory to the method of auxiliary sources (MAS) [8], [9], to find the optimal location for the auxiliary sources (AS) using a complex pole distribution [9] coupled with the properties of a left handed medium [10]. The idea is to replace the entire scatterer with several AS. The mathematical and physical properties of SFS is very well documented and studied, and it is known in the literature as "*Catastrophe Theory*" [11], [12], [13].

In this work a pole series expansion algorithm is combined with the NSMC for (1) determining buried objects' location and orientation without solving ill-posed inverse problems, and (2) discriminating UXO from non-UXO items by using the total NSMC. The NSMC technique is a simple and accurate numerical approach for reproducing EMI signals from highly conducting and permeable metallic objects in the EMI frequency band, including all complexities of geometry and material properties [Error! Reference source not found.**]-[7].** In the NSMC model, the scattered magnetic field is produced by a set of magnetic charges placed on a fictitious surface. The fictitious surface is divided into small sub-surfaces (see Figure 1). At each subsurface the impinging (excitation) magnetic field is determined, and the amplitudes of magnetic charges are scaled by the actual primary magnetic field. The amplitudes of the NSMC are determined by matching the modeled magnetic field to the measured field at a selected set of the measurement grid points. Once the amplitude of this source set is found for each object, it can be stored for subsequent use in a discrimination algorithm. In addition, the frequency or time responses of the characteristic interior sources are unique for a given object. Therefore the total NSMC is used as discrimination parameters for distinguishing suspicious objects from innocuous items.

II. Physical problem

In the electromagnetic induction method, a time varying magnetic field illuminates a target. The primary magnetic field penetrates inside a highly conducting and permeable metallic object and induces eddy currents with in it. The induced eddy currents produce a secondary field that is measured at the surface of the ground. The electromagnetic data are then inverted using different forward models. Thus, the classification of UXO from non-UXO items reduces to an inverse problem for finding the objects location, orientation and the object's parameters, such as the polarization tensor parameters [1]-[4], or the total NSMC [7]. This procedure is carried out by determining an objective function as a goodness of fit measure between the forward model and measurement data. Routinely, the least squares (LS) approach is taken to recover the object parameter vector $\mathbf{v}$, which contains the information about the object, its location and orientation. Formally, if $\mathbf{d}^{\mathbf{obs}}$ is the vector of the measured scatter field and $\mathbf{F}(\mathbf{v})$ the forward problem solution, the least squares approach assumes the criterion

$$\text{minimize } \phi(\mathbf{v}) = \left\| \mathbf{d}^{\mathbf{obs}} - \mathbf{F}(\mathbf{v}) \right\|^2 . \tag{1}$$

One of the simple ways to determine model vector $\mathbf{v}$ is to use the Gauss-Newton method, that updates the current model $\mathbf{v}_k$ iteratively i.e.

$$\mathbf{v}_{k+1} = \mathbf{v}_k + \mathbf{s}_k \tag{2}$$

where k denotes the iteration number and $\mathbf{s}$ is the the perturbation direction. We solve for the $\mathbf{s}_k$ that minimizes ϕ. This approach is computationally intensive because it requires massive repetition of the forward problem solution. Particularly, the convergence of non-linear parts of F(v)*********, such as the objects' location and orientation, are the most time consuming and not straight forward. To solve the ill-posed inverse problem, different approaches that are based on regularization have been proposed and tested recently. However, the results totally depend on the regularization parameters. To overcome these difficulties, a new physics based inverse approach named the pole series expansion is employed and tested here from the UXO detection and discrimination point of view.

III. Pole series expansion

Two of the most frequently used domains for formulating and solving EM problems, and for many other physical phenomena as well, are the time domain and frequency domain, for which generic descriptions are given by exponential and pole series, respectively. More generally, it should be noted that the same transform relationship exists between other observable pairs that are also described by exponential and pole series, as listed in Table I [14]. Here, we will focus mostly on the pole series, to determine the position of a source along line of measurements as suggested in [14]. The series of complex poles for a source position can be expressed as [14]:

$$G(z) = G_S(z) + G_{NS}(z) = \sum \frac{R_\alpha}{z - s_\alpha} + G_{NS}(z)\,. \qquad (3)$$

For α=1,2,…, N, N is number of expansion terms $G_S(z)$ and $G_{NS}(z)$ are polynomials representing the singular and non-singular part respectively for the scattered magnetic field (here the z component of the scattered magnetic field), $j = \sqrt{-1}$, $s_\alpha = jz_{o,\alpha}$ are complex scattered field singular points [14], and R_α are the modal amplitudes.

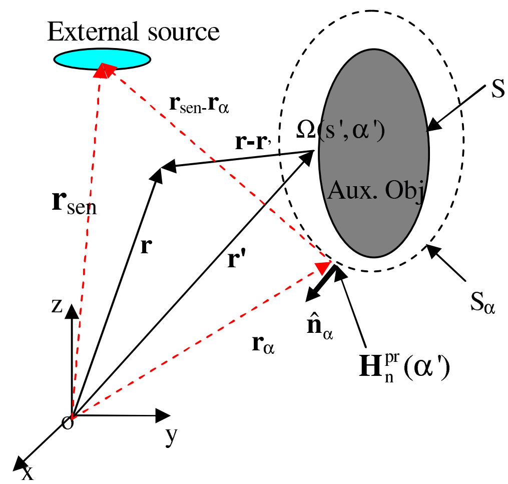

Fig. 1. NSMC diagram.

The singular part that actually corresponds to the SFS of the response in (3) can be developed into a particular rational function, where the denominator order is greater than or equal to that of the numerator by one. Expanding the non-singular part in terms of the distance z and combining it with the singular part, the equation (3) leads to a representation of the complete response by the pole expansion rational fitting model:

$$G(z) = \frac{N(z)}{D(z)}\ , \qquad (4)$$

where

$$N(z) = \sum_{i=0}^{n} N_i z^i \ \text{ and } \mathrm{D}(z) = \sum_{i=0}^{d} D_i z^i \qquad (5)$$

Coefficients $\{N_i\}_{i=o}^{n}$ and $\{D_i\}_{i=o}^{d}$ are unknowns. To obtain these coefficients, bi-static data for a set of z_k points are required. There are two ways to obtain the required data by using: 1. a bi-static EMI sensor, or 2. actual mono-static data measured at a given elevation and extend the radiated field above the measurement surface via numerical techniques. Since most, if not all, current state-of-the-art sensors (EM-63, EM-61, GEM-3, Nano-TEM and others) are mono-static, in this work the second approach, in this case based on the NSMC model, is used.

IV. SIMPLE MAGNETIC CHARGE MODEL

Let us assume that a highly conducting and permeable, arbitrarily shaped, heterogeneous metallic object is replaced with an auxiliary object (here a spheroid with surface S), and it is placed in a medium with the electromagnetic properties of free space (Fig. 1). The auxiliary object is surrounded with a fictitious surface, here again a spheroid (a major and b minor semi-axes). In the magneto quasi-static regime, both the primary and secondary magnetic fields are irrotational. After applying the irrotational condition into Maxwell's equations, it is easy to show that both the primary $\mathbf{H}^{pr}$ and secondary magnetic fields $\mathbf{H}^{sec}$ and their corresponding scalar potentials ψ^{pr} and ψ^{sec} satisfy Poison's equations:

$$\nabla^2\psi^{\gamma} = -\rho_{\gamma}(\mathbf{r}_{\gamma})\delta(\mathbf{r}-\mathbf{r}_{\gamma}) \tag{6}$$

and

$$\nabla^2\mathbf{H}^{\gamma} = \nabla\rho_{\gamma}(\mathbf{r}'_{\gamma})\delta(\mathbf{r}-\mathbf{r}''_{\gamma}), \tag{7}$$

where $\gamma = \{\mathrm{pr, or\ sec}\}$, and ρ_{γ} is volume magnetic charge density, δ is Dirac's delta function. Since a magnetic field flux is divergence free, the relations between the $\mathbf{H}^{\gamma}$ magnetic field and the scalar potential ψ^{γ}, and the volume magnetic charge density ρ_{γ} are as follows:

$$\nabla\cdot\mathbf{H}^{\gamma} = \rho_{\gamma}, \tag{8}$$

$$\mathbf{H}^{\gamma} = -\nabla\psi^{\gamma}, \tag{9}$$

here $\rho_{\gamma}(\mathbf{r}') = -\nabla\cdot\mathbf{M}_{\gamma}(\mathbf{r}')$, $\mathbf{M}_{\gamma}(\mathbf{r}')$ is a scatterer's/source's total magnetization.

Let us divide the spheroidal surfaces into ds' and $d\alpha'$ infinitely small surfaces. Then the primary magnetic field inside the spheroid can be expressed using surface equivalent magnetic charges σ^{pr} as

$$\mathbf{H}^{pr}(\mathbf{r}) = -\int_{S_\alpha}\sigma^{pr}(\alpha')\nabla\psi^{pr}(\mathbf{r},\mathbf{r}_{\alpha}')d\alpha', \tag{10}$$

where the free space Green's function $\psi^{pr}(\mathbf{r},\mathbf{r}_{\alpha}) = \dfrac{1}{4\pi\mu_o|\mathbf{r}-\mathbf{r}_{\alpha}|}$, $\mu_o = 4\pi\cdot10^{-7}\,\mathrm{H/m}$ is the magnetic permeability of free space, S_alpha********** is the spheroid's surface, $\mathbf{r}_{\alpha}\in S_{\alpha}$ is an integration point, and $\mathbf{r}$ is an observation point inside the fictitious spheroid. Because the electromagnetic properties inside and outside the fictitious spheroid are the same, (10) above implies that the surface charge is proportional to H_n^{pr} on either side of the interface. Because a set of sources such as σ^{pr} is completely sufficient for specifying the primary field, this means that the corresponding H_n^{pr} values over the surface are similarly sufficient. Thus the complete problem breaks down to solving a full EMI problem for each input $\sigma^{pr}(\alpha') = H_n^{pr}(\alpha')$. Just as the primary field can be replaced by a distribution of equivalent sources over a convenient surface, so can the scattered field. Thus, in effect we replace the actual scatterer by a simpler, equivalent, fictitious object (Figure 1). *********Fridon, this doesn't flow well. Will discuss on W.Perhaps a bulleted list???Finally the entire EMI problem can then be recast as follows: The equivalent surface primary magnetic charges ($\sigma^{pr}(\alpha') = H_n^{pr}(\alpha')$)

reproduce the total primary magnetic field inside the fictitious spheroidal surface (Figure 1). Any primary field can broken down into contributions from subsets or patches of $\sigma^{pr}(\alpha')$ or, equivalently, of $H_n^{pr}(\alpha')$ (see Figure 1). Thus we require the *responding* magnetic charge $\sigma(s',\alpha')$ values for each impinging patch of excitation. The amplitudes of responding magnetic charges $\sigma(s',\alpha')$ will be determined by solving a full EMI problem for the s' patch excitation; And finally, at any **r,** the scattered magnetic field corresponding to patch s' with $H_n^{pr}(\alpha')$ charge can be written mathematically as,

$$\mathbf{H}_s^{sc}(\mathbf{r},\alpha') = -\int_S \sigma\ (s',\alpha)\nabla\psi^{sec}(\mathbf{r},\mathbf{r}')\, ds' \tag{11}$$

We introduce the normalized magnetic charge as

$$\Omega(s',\alpha') = \frac{\sigma\ (s',\alpha')}{H_n^{pr}(\alpha')} \tag{12}$$

After combining equations (11) and (12), finally the total scattered magnetic field can be expressed as

$$\mathbf{H}^{sc}(\mathbf{r}) = -\int_S \nabla\psi^{sec}(\mathbf{r},\mathbf{r}')\, ds' \int_{S_\alpha} \Omega\ (s',\alpha')\ H_n^{pr}(\alpha')\, d\alpha'\ . \tag{13}$$

We can show that the second integral in (13) simplifies to ********* fewer equations?

$$\Omega^{total}(s') = -\int_{S_\alpha} \Omega\ (s',\alpha')\ H_n^{pr}(\alpha')\, d\alpha' = \int_{S_\alpha} \Omega\ (s',\alpha')\ \nabla_\alpha \psi^{pr}(\mathbf{r}_{sen,}\mathbf{r}_\alpha)\ \cdot \hat{\mathbf{n}}_\alpha d\alpha' \tag{14}$$

where $\hat{\mathbf{n}}_\alpha$ unit normal vector; ∇_α is derivative respect $\mathbf{r}_\alpha$. or

$$\Omega^{total}(s') = -\int_S \left\lfloor \left(\nabla'\ \nabla' \cdot \mathbf{H}^{sec}\right) \cdot \nabla'\ \psi^{pr}(\mathbf{r}_{sen,}\mathbf{r}'_s) \right\rfloor + \nabla' \cdot \mathbf{H}^{sec}\left(\hat{\mathbf{n}}' \cdot \nabla'\psi^{pr}(\mathbf{r}_{sen,}\mathbf{r}'_s)\ \right)\frac{1}{\xi_{s'}} ds'_s \tag{15}$$

and finally the secondary magnetic field is

$$\mathbf{H}^{sc}(\mathbf{r}) = \int_S \left\lfloor \nabla'\ \Omega_o(\mathbf{s}') \cdot \nabla'\ \psi^{pr}(\mathbf{r}_{sen,}\mathbf{r}'\ ) + \Omega_o(\mathbf{s}')H_n^{pr}(\mathbf{r}_{sen,}\mathbf{r}')\frac{1}{\xi_{s'}} \right\rfloor \nabla\psi^{sec}(\mathbf{r},\mathbf{r}')\, ds' \tag{16}$$

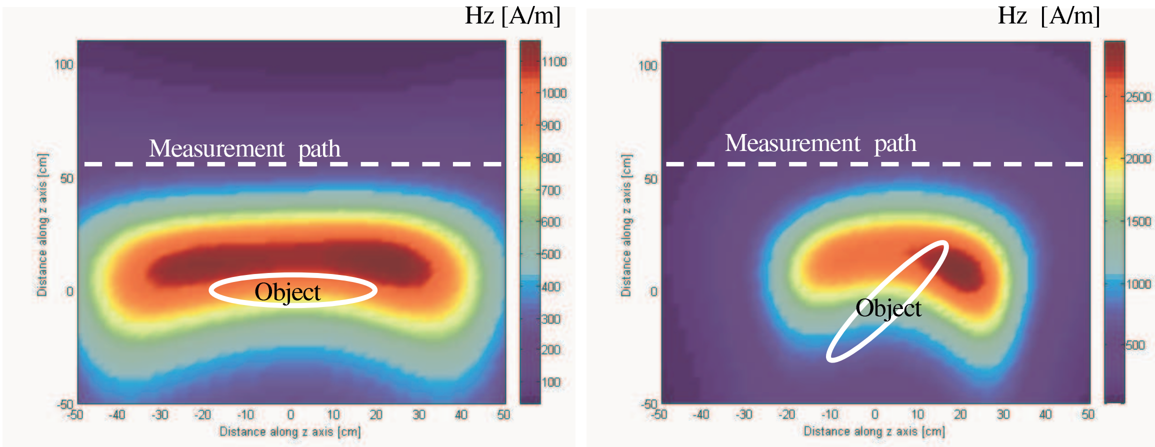

Figure 2. Distribution of the inverted magnetic field over xoz******** plane, for a 2.75 inch UXO is oriented: a) horizontally, and b) 45 degrees.

III. RESULTS

One of the advantages of the NSMC technique is that it could be used for generating both mono-static as well as bi-static data for any given sensor. Mono-static data plays a crucial part in determining object locations and orientations from the pole series expansion technique described here. It is known that in order to reconstruct the three-dimensional spatial distribution of the scattered magnetic field, data acquired at various observation angles must be used. *********wordingThis requires either that the changed relative positions of a given object be identifiable from the different reconstructions, or that simultaneous solutions of observations made from multiple viewing angles be obtained. Both requirements can be achieved readily by the NSMC. To illustrate the applicability of the NSMC – pole series expansions in these studies an actual UXO (2.75 inch projectile) were placed in the magnetic field of the EM-63 sensor. The data were collected at the UXO test-stand site over a set of grid point on xoy****** surface $x\in[-1.5\ \text{m}\ 1.5]$, $y\in[-1.5\ \text{m}\ 1.5]$, z=60 cm. The NSMC were distributed on a flat surface $x\in[-1.5\ \text{m}\ 1.5]$, $y\in[-1.5\ \text{m}\ 1.5]$, z=0 cm, that is conformal but do not coincide with the measurement surface. In this arrangement, the NSMC reconstructs the magnetic fields radiated by all metallic objects distributed in the $z<0$ space. The amplitudes of the NSMC were determined by solving a linear system of equations. Once the amplitudes of the NSMC source set were found, the scattered EMI field was extended above the measurement xoy******** surface, z=60 cm*********z?. The magnetic field predicted by the NSMC model, at time channel #, are depicted in Figure 2, for two orientations over the y=0, xoz********* plane. In this case, the scattered

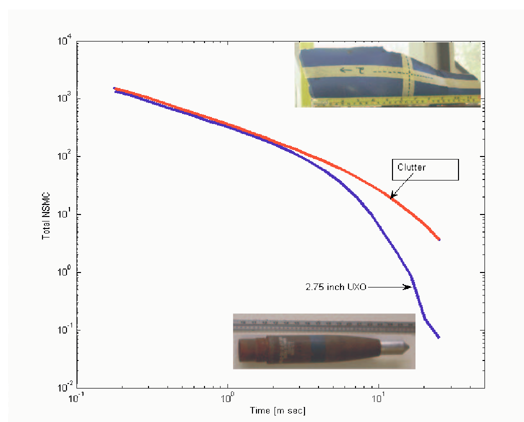

Fig. 3. Total normalized magnetic charge in time domain for 2.75 inch UXO and Clutter.

magnetic field was computed on the $x \in [-50 \text{ cm } 50 \text{ cm}]$ $z \in [-50 \text{ cm } 110 \text{ cm}]$ plane. For each fixed x using field values along z-axis, the pole expansion coefficients (*n*=6, *d*=6) were determined, and the magnetic field was reconstructed backwards. The field distribution is shown on figure 2. Note that the computation is straight-forward and very fast. We see that the field maximum or SFS is localized near the object for both cases. Results also demonstrate that the distance between the maxima of the reconstructed field is on the order of the object's size. Therefore, we can estimate the object's size using this technique.

Finally, to illustrate the applicability of the NSMC as a discriminant, time domain EM data were collected for two objects: 2.75 inch UXO and sizeable metallic clutter (see Fig. 3) on a grid points. The objects response was modeled with only 4 magnetic charges rings. The targets was oriented horizontally and illuminated by the EM-3 sensor from different positions. The sensor was placed at H_1=60cm above the object and swept along a plane parallel to the object's axis of symmetry. The total NSMC were calculated for both objects and are depicted in Figure 3. The comparisons between the calculated *total NSMC* for each object show that at early time (very high frequencies), the total NSMC for the both objects are similar because the size of both objects are similar. However at late time, the NSMC becomes different for the two targets, suggesting that we may be able to identify one object from other using the total NSMC as a discriminant.

IV. CONCLUSION

In this paper, a new, physics based model called the pole series expansion approach is combined with the normalized surface magnetic charge model to invert a buried object's location and orientation without solving the traditional ill-posed problem. The proposed technique is tested against real measured data for an actual UXO. First, the NSMC is used for extending the measured magnetic field in the computational space, and then the pole series expansion approach is applied for localizing scattered field singularities. Once a buried object's location and orientation are determined, the amplitude of the total NSMC is computed and is used for discriminating UXO from non UXO items.

Acknowledgment. This work was supported by the US Army CoE ERDC BT25 program, with development and testing under the DoD SERDP, and code development under the US Army CoE ERDC AF25 program.

1. L. R. Pasion and D. W. Oldenburg, "A discrimination algorithm for UXO using time domain electromagnetics", *Journal of Engineering and Environmental Geophysics*, volume: 28, issue: 2, pages: 91-102, 2001.
2. T. H. Bell, B. J. Barrow, and J. T. Miller, "Subsurface discrimination using electromagnetic induction sensors", *IEEE Transactions on Geoscience and Remote Sensing*, volume: 39 , issue: 6, pages:1286 – 1293, June 2001.
3. L. Carin, H. Yu, Y. Dalichaouch, A. R. Perry, P. V. Czipott, and C. E. Baum, "On the Wideband EMI response of a rotationally symmetric permeable and conducting target", *IEEE Transactions on Geoscience and Remote Sensing*, volume: 39, issue: 6, pages: 1206-1213, June 2001.

4. Y. Zhang, L. Collins, H. Yu, C. E. Baum, and L. Carin, “Sensing of unexploded ordnance with magnetometer and induction data: theory and signal processing”, *IEEE Transactions on Geoscience and Remote Sensing*, volume: 41, issue: 5, pages: 1005-1015, 2003.
5. F. Shubitidze, K. O’Neill, K., I. Shamatava, K. Sun, K., and K.D. Paulsen, ” A Fast and Accurate Representation of Physically Complete EMI Response by a Heterogeneous Object to Enhance UXO Discrimination”, IEEE Transactions on Geoscience and Remote Sensing, Volume 43, Issue 8, page(s):1736 – 1750, August 2005.
6. K. Sun, K O’Neill, F. Shubitidze, I. Shamatava, K. D. Paulsen, “Fast data-derived fundamental excitation models and implementation in UXO discrimination,” *IEEE Transactions on Geoscience and Remote Sensing,* Volume 43, Issue 11, page(s):2573 – 2583, November 2005.
7. F. Shubitidze, K. O’Neill(, B. Barrows, J. P. Fernández, I. Shamatava, K. Sun, and K. D. Paulsen, “Application of the normalized surface magnetic charge model to UXO discrimination in cases with overlapping signals”, Journal of Applied Geophysics, *Submitted for publication (can be found on our web site: http://engineering.dartmouth.edu/other/uxo/).*
8. R. Zaridze, G. Bit-Babik, K. Tavzarashvili, D. P. Economou, M. K. Uzunoglu, N.K.; “Wave field singularity aspects in large-size scatterers and inverse problems”, *IEEE Transactions on Antennas and Propagation*, Volume 50, Issue 1,page(s):50 – 58, January 2002.
9. A. G. Kyurkchan, B, Y. Sternin, V. E. Shatalov, “Singularities of continuation of wave fields” Physics Uspekhi, Russian Academy of Science (translated in English) 39 (12) pages: 1221-1242 , 1996.
10. N. Bliznyuk, R. J. Pogorzelski, V. P. Cable,. “Localization of Scattered Field Singularities in Method of Auxiliary Sources”, in Proceedings of the 2005 IEEE AP-S/URSI Symposium.
11. V. I. Arnold, “*Catastrophe Theory*”. Second revized and expanded edition. Springer, Berlin, 1986, 108 pages.
12. Berry, M V, 1976, *Physics Bulletin,* March, 107-8, ‘Waves as catastrophes’.
13. Berry, M V, 1976, *Advances in Physics,* **25**, 1-26, ‘Waves and Thom's theorem’.
14. E.K. Miller, “Model Based Parameter Estimation in Electromagnetics: Part I. Background and Theoretical Development, ” IEEE Antennas and Propagation Magazine, vol.40, pp. 42-52, Feb. 1998.