March, 2026

New 3D EM/IP Complete and Exact Simulation Algorithm Capabilities

Gustav Mie (1908, Annalen Der Physik, 330) first presented the complete and exact solution for EM scattering from a sphere due to a plane wave in terms of an infinite series of spherical harmonics. In this instance, "Complete" implies allowing any variations in conductivity, susceptibility and permittivity and location of scattered fields. As well, his solution is not limited to a specific frequency range nor limits the size of the sphere.

Peter Debye's work (1909) contributed to the understanding of Mie's solution and introduced the Debye series which utilizes the Debye potentials. This reformulation enabled interpretation of the solution in terms of physical processes. In this manner, the solution was utilized in many areas of physics prior to computational solutions. These works followed the introductory work of Ludvig Lorenz and thus the solutions are often referred to as the Lorenz-Mie-Debye (LMD) theory. The work was virtually ignored until the 1950's and not until the 1970's was it well known. Later work by numerous authors expanded the theoretical solution to dipole sources following the idea of Mie-type expansions and was used extensively throughout many areas of physics and engineering. For small spheres, the problem simplifies and in geophysics early approximate forms of the solution for "small" spheres were provided by James Wait (1951, 1960, and 1969). Of course, this work had limited practical uses until the advent of the computer. Other partial series approximations have also been presented by various authors in geophysics. However, the series is not monotonically convergent which means that the first term or even the first few terms may not correctly estimate the complete solution. While exploring a strong scattering extension to the Born and Rytov approximations for EM scattering, R. Groom and T. Habashy studied how to provide a precise computational solution to dipole excitation for a conducting sphere in the frequency domain. A method was devised to solve the LMD series for a magnetic dipole source up to 200 harmonics and to determine when and if the solution had converged. This solution was adapted for both electric and magnetic dipole sources and for electric and magnetic fields. The method of solution was found to be generally convergent at frequencies below several megahertz. The solution was subsequently in conjunction with a number of other accurate specialized algorithms to study the accuracy of the Localized Nonlinear Approximation (LN) solution and push forward the initial development of this algorithm. This sphere solution has since been used extensively to expand the capabilities of the initial LN solution and its subsequent extensions.
(https://www.eikontechnologies.ca/resources/technical.php).

The approach that was taken in the 1990's was a generalization to a uniform sphere of contrasting conductivity, permeability and permittivity to a homogenous background for either a magnetic or electric dipole source. The spherical series expansion which follows Mie's techniques for a uniform field but using Debye potentials is not a monotonically convergent series and thus a simple addition of the initial terms does not generally produce a sufficiently accurate solution except in cases of a "small" sphere. It was discovered that the series can be solved for a converged limit by utilizing the starting and ending terms like a rope tied at both ends. Introduced into the solution was examination of convergence and thus the implemented algorithm will not provide a solution in output if the calculated series does not converge for a particular scattering scenario. Comparisons of this Mie approach to scattering by a sphere to the Born, Rytov and the Nonlinear approximations can be found in Habashy, Groom and Spies (1993, JGR, Vol 98). This solution for scattering by a sphere due to a dipole source has been used for 30 years by ourselves and other researchers to study different numerical solution approaches and the nature of EM scattering in general. In particular, it has been used to study the accuracy of quite a few simulation algorithms. As well, it has been used for crosshole RIM studies, crosshole low frequency IP surveys, crosshole FEM studies with small downhole sources, airborne VLF and other experimental geophysical methods. Several papers on this technique may be found at link provided above.

In recent years, we have encountered numerous EM data sets, particularly in exploration airborne and ground TDEM but also ground-based CSEM where responses are clearly due to both conductive and magnetic materials within anomalies. An further long term request from clients was the ability to simulate weakly conducting volume targets as opposed to the response of the surfaces from stronger conductive targets. Thus, extending this SPHERE solution to loop sources became a necessity for interpretation of clients' data. Additionally, several researchers have been interested to use the algorithm for their studies but extended to common sources such as loops and grounded current dipoles. The effects on EM data due to magnetic material whether electric or magnetic fields and for both low frequency (*e.g.* IP) or moderate frequencies (TDEM, FDEM) and higher frequencies such as for VLF and RIM are threefold. There can be a magnetostatic effect, an effect on induction as well as an effect on the galvanic response (current channelling). The size of the different contributions depends upon the nature of the scattering problem. And, of course, there are the internal interactions between these effects. One study on these issues is available on our website in the technical papers section (Studies on the Effects of Magnetism on the Scattered Responses of Conductors to Inductive Sources, R.W. Groom).

By implementing discretization into multiple magnetic or electric dipoles, we have expanded the capabilities of this algorithm using various numerical approaches to include the use of:

1. <u>Loop Sources</u>: These loop sources need not be at a constant elevation. Loops with a non-constant elevation as for example vertical loops or loops laid upon sloping surfaces are all allowed. This extends the capabilities to simulate vertical loops inside underground mine workings and also for ground EM surveys in areas of significant terrain. While working with loops which are not of constant elevation is a simple simulation for freespace modeling of a thin sheet, the inclusion of a background response is not so simple. Up to this point, all of our simulation algorithms which allowed a background layered response required a flat loop. This capability, we have also extended to our FSPlate algorithm which does provide a background response to be included with the response of the spheres. There is automatic discretization of the loop sources but the user may also take over control of this process.

2. <u>Grounded Current Sources:</u> The new capabilities also allows for such a current source which varies in elevation. This capability can be used to simulate 3D volume conductive and magnetic targets for land based CSEM, CSAMT and gradient IP. But, it also allows for dipole-dipole and pole-dipole IP responses on sloping surfaces. Again, there is an automatic discretization of the source into electric dipoles but the user may take control if desired.

3. <u>Moving and Fixed source configurations</u>: As examples; airborne TDEM, fixed loop or moving loop ground TDEM, borehole TDEM are all supported as well as fixed grounded current dipole sources and moving current dipole sources. Surface grounded sources to borehole electric field and magnetic measurements is also allowed for arbitrarily low frequency. Simulation of VLF with a controlled vertical source is also provided for ground or airborne configurations.

4. <u>Parameters</u>: Arbitrary variations in conductivity, susceptibility and permittivity to the background are allowed. The background may be a whole space, halfspace or layered model. Small and large spheres as well as sources and measurements close to the sphere are allowed. Internal measurements to the

sphere are not provided in this version. Using the Cole-Cole frequency model for polarization effects, IP responses may also be calculated as well IP effects in other EM data.

5. Frequency and Time Domain Responses: Frequency ranges from extremely low frequency to frequencies into the low MHz range are generally allowed. If a particular response for a source-receiver-frequency combination does not reach convergence then a no data value is stored to the database for that particular measurement station and frequency. Time domain responses are obtained through our normal Fourier frequency to time domain transform.

6. Licensing: The algorithm with appropriate functionality is included with any suitable license. The algorithm is not sold separately although the source code may be licensed.

LIMITATIONS: It should be noted several limitations that exist in the present implementation. At present, simulation of the fields within the spheres cannot be done in the present implementation. Also, at present, there are no interactions between the individual spheres in a model. Both of these limitations in our implementation will be addressed in future. Another issue which is presently being addressed is the joint simulation of models which contain multiple primitives (i.e. plates, prisms, polyhedra, spheres). For example, at present one cannot jointly simulate a model consisting of spheres and thin sheets. You can, of course, run a model consisting of spheres and a second model consisting of plates and then add the secondary response of the two models as this functionality is provided in EMIGMA. This is a bookkeeping issue and so for fluidity and convenience, we are presently working on this aspect to allow the mixing of primitives and the simulation of the mixed primitive models.