*Paper 31*

# Developments in Geophysical Inversion in the Last Decade

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**ABSTRACT**

*Inversion of all types of geophysical data has become common place in the past decade. This is a result of suitable software and hardware becoming widely available as well as an industry which has learned the value of undertaking value added processing to obtain the maximum useful geological signal. Future developments will likely see the addition of some for of artificial intelligence to help guide the inversion processes.*

## INTRODUCTION

The business of Geophysics is and always has been inversion. To find an orebody that is not visible from the surface, one must make surface observations and use them to deduce information about the sub-surface distribution of the property of interest and from this make a decision about the likelihood of the presence and location of mineralization.

A quick search in Geophysics yields 340 papers and abstracts related to inversion in magnetics, gravity, EM and IP published in the last ten years while a search for the decade 1985 to 1995 yielded 180. Clearly the topic is one of considerable ongoing active interest to the industry. The aim of this talk is to distill the progress that has been made in the last decade into some coherent picture of what has been achieved.

### A brief review of geophysical inversion

Before proceeding too far along this line, let us first define just what inversion is. Quoting Wikipedia:

An inverse problem is the task that often occurs in many branches of science and mathematics where the values of some model parameter(s) must be obtained from the observed data

The problem is called inverse because it is the reverse of the forward problem:

The forward problem is the task of calculating the response at some set of observed data locations for a specified distribution of model parameters.

In a geophysical context, the model parameters are physical rock properties such as density, susceptibility or resistivity, the observed data are values such as Bouguer gravity, total magnetic intensity or apparent resistivity and the observation points can be surface stations, airborne bird positions or depths down a drillhole.

While not always trivial, the forward problem is much easier to solve than the inverse problem. You simply feed in a set of parameter values (density, susceptibility, resistivity etc) into the algorithm derived for solving the forward problem and calculate the response at the desired locations.

The availability of an algorithm for solving the forward model problem (often developed at some time after the successful use of the geophysical method), allows a practitioner to solve the inverse problem by manually adjusting a set of model parameters to obtain a match between the observed and modeled data. In the early days of geohysics, this process often used a graphical aid (or nomogram) to convert observations into physical parameters, but the rapid progress of first calculators and then computers allowed the forward calculation to be used interactively in fitting the observed data. Further increases in computer power permitted the forward problem to be embedded into a variety of optimization and parameter estimation methods to iteratively solve the inverse problem. The proliferation and power of computers and graphics in more recent times has seen the complexity of codes for forward and inverse problems increase to such a degree that large complex models can now be handled routinely.

But in spite of the growth in complexity of the problems that are being solved, inversion still has exactly the same inherent problems as the original simple models containing just a few parameters. For example an appropriately shaped anomaly on a magnetic profile can be fitted using a thin-sheet model by varying the depth, thickness dip and susceptibility parameters. Anyone who has undertaken such a task will immediately recognize that such a process does not yield a unique solution as the values calculated in the forward model depend on the product of the sheet thickness and susceptibility. So even if it is known that the observed data is the response of a thin magnetic sheet, the profile data alone is not enough to uniquely determine the physical properties of interest.

Similarly, when fitting observed magnetic data over a two-dimensional survey area using a 3D volume broken up into

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rectangular prisms, the observed data can be fitted to any desired accuracy using susceptibilities clustered near the surface and having no real depth extent.

So this is the first problem with inversion: there is no unique solution to the inverse problem. For a given set of model parameters, the forward problem has a unique solution, but for a given set of observed data, the inverse problem can have an infinite number of possible solutions. Changing the number of parameters or observations or type of measurement does not solve this problem.

The next problem with inversion is related to the first one. Since the forward model has to simplify the real world using a finite set of parameters, the inverse problem is necessarily ill-posed. For the forward model, small changes in the model parameters result in small changes in the calculated values. For the inverse problem, small changes in the observed data can result in arbitrarily large changes in the model parameters.

The final problem is that simplifying assumptions have to be made in solving the forward problem. Consequently, observations which result from physical properties which are not encompassed within the simplifications must result in distortions in the inversion. For example, the effects of remanence and demagnetization are not generally included as parameters in the inversion process, so any data containing either or both of these effects when inverted using a method which does not incorporate them cannot possibly generate a correct solution. Sometimes the distortion is minor and can be ignored eg the greater apparent depth of an off line 3D source in a 2D inversion. Sometimes the unaccounted for properties result in distortions of the model which can be corrected for eg migration of CDI images where 1D inversions can be corrected to more accurately define 2 and 3D source geometries.

This latter point is of extreme importance in the sense that whatever the formulation used for solving an inverse problem, it will always (if correctly implemented and applied) generate a feasible model. This is a simple consequence of the inversion process being an iterative method wrapped around a forward problem in which the forward model is successively modified until it fits the observed data to the desired degree of accuracy. However, just because the model is feasible, it does not mean that it is either realistic or useful. Unfortunately, these two aspects are the most important ones when judging the usefulness of an inversion, but they are also the hardest to achieve (Boschetti et al., 1999).

## Progress in the last decade

The advances that have occurred in the last decade are to some degree incremental changes based on the progress from the previous decade. Faster computers and better forward models mean that larger problems can be tackled. But there has also been a range of developments over and above the incremental progress which has allowed more difficult problems to be tackled.

### Data collection

There has been a general improvement in the quality, density and variety of geophysical data collected. Airborne surveys now usually use GPS navigation and the improved positional accuracy has helped to reduce the contribution of survey inaccuracies to the measurements and so results in cleaner data. (Nabighian et al., 2005; Jia et al., 2004) Improvements in data acquisition devices also mean that data measurements are more accurate and more closely spaced (Irvine et al. (2006), Ritchie and Sheard (1999), Paine and Copeland (2003)).

Developments of new sensor types such as the gravity gradiometer (van Leeuven (2000)) mean that new types of surveys are possible and inversion of the data yield improved understanding of the geological structures in the survey area. Another such advance has been in the progress made with squid based B-field sensors for collecting magnetic and EM data (Schmidt et al. (2004), Dransfield et al. (2003), Lee et al. (2002), (Nabighian et al. (2005)).

### Data processing

Improvements in data collection and increased data density have been accompanied by improved processing techniques for improving data quality (Nabighian et al. (2005), Markham and Morris (2002)). This is especially the case for helicopter EM systems where bird pitch and roll are now being measured and used either to correct the measured data or in the inversion process itself (Yin and Fraser (2004)). Better understanding of the impact of data processing has also helped ensure that the inversion process is more consistent with the data collected (Lee et al. (2005), Davis et al. (1999).

### Computer hardware

Processor speed, available memory and storage space have all increased significantly in the last ten years. These increases on their own have allowed much larger inversion tasks to be undertaken. These advances have been augmented with the growth in parallel processing possibilities opened up by multi-core processors, clustered processors and grid processing. The latter possibilities have become practical as networking speeds have improved (Kowalczyk et al. (2002), Yoshioka and Zhdanov (2005)).

### Computer software

These have been less significant than other factors, but computer languages have evolved in sophistication and have aided in the development of robust efficient solution of forward models and also allowed more rapid deployment on distributed computing environments eg MPI (A Message-Passing Interface Standard, http://www-unix.mcs.anl.gov/mpi/mpi-standard/mpi-report-1.1/mpi-report.htm).

### Forward models

There have been many developments in forward models to incorporate more realistic real-world physics in the model and to more accurately model the real-world response. For example, improvements in EM forward modeling have allowed the use of larger conductivity contrast models and greater accuracy over a larger time range (Zhdanov et al. (2006), Farquharson et al. (2006)). Similarly the inclusion of more complex conductive plates allows modeling codes to handle geometries closer to that which exist in the real world (Walker and Lamontagne (2006)).

Inversion methods

Improvements in computers and modeling software have permitted a vast increase in the size of problems which can be handled. But as always, this has fuelled a greater desire to model even larger problems. The main advances in the last decade have been focused on providing methods for doing this.

The introduction of practical voxel based 3d mag, gravity and IP inversion programs which use regularization techniques to generate geologically reasonable models (Li and Oldenburg (1996, 1998, 2000), Dahlin et al. (2002)).

The ability to include topography in 2D and 3D inversion has greatly improved the usefulness of inversions (Li and Oldenburg (1996, 1998, 2000), Dahlin et al. (2002), Katayama and Zhdanov (2004).

The use of compression techniques to improve the computational efficiency of the inversion algorithms (Li and Oldenburg (2003).

Improvements in models have allowed users to perform 3D inversions of IP data and progress has been made in doing the same for EM data (Napier et al. (2006), Loke (2000), Li and Oldenburg (2000), Dahlin et al. (2002), Katayama and Zhdanov (2004).

The capacity to include drilling and geological knowledge to constrain the inversion has fuelled a desire to include such information in the inversion process (Fullagar et al. (2004), Li and Oldenburg (1996, 2000), Guillen et al. (2004), 10, (Fullagar et al. (2006)).

New types of geophysical data being collected have led to the development of corresponding forward model and inversion codes. This has led to gravity gradient and B-field now being collected and inverted (Zhdanov et al. (2004), Nabighian and Macnae (2005).

The growing use of down hole data collection surveys has also led to the development of forward modeling and inversion codes to accommodate such data ( Li and Oldenburg (2000)).

Progress has been made in including remanance and demagnetization effects into mag inversions (Li et al. (2004), Paine et al. (2001)).

The growing use of inversion has driven the use of non-standard data collection geometries designed for maximizing the sensitivity of the readings rather than for ease of use in manual interpretation eg offset pole-dipole IP surveys (White et al. (2001)).

The standard inversion process is generally based on least-squares, but other methods are being developed and used. These range from “blocky” L1 methods to genetic and Monte Carlo type methods and techniques such as SOM (Loke et al. (2003), Guillen et al. (2004), 10, Wijns and Kowalczyk (2003), Wijns et al. (2003), Farquharson (2006). Artificial intelligence has been making progress in helping cluster Euler deconvolution solutions (Mikhailov et al. (2003)) and neural networks are bringing together multiple datasets and helping to target ore deposits (Reford et al. (2004).

## Where to next?

There has been significant progress in the last ten years in the theory and implementation of inversion in geophysics. But more importantly, these developments have been enthusiastically adopted in the exploration industry and their use has become widespread. This growth in the utilization of inversion will continue and hopefully will support continued research and development in the next decade. The direction for this research will partly be driven by continuing improvements in hardware. So the use of parallelization and distributed computing will become more widespread and will be used to solve a wider variety of larger problems than is currently possible. These advances will be accompanied by the development of techniques that will be make it easier for users to explore the range of feasible solutions in order to better judge the reliability of inverted models. These developments will partly be interface oriented ie better data management, 3d graphics, model databasing, and partly by improved algorithms for exploring model parameter space. This algorithmic development will most likely include some form of artificial intelligence.

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