Report

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P223 EM Modelling Projects

ELECTROMAGNETIC MODELLING GROUP

CSIRO Exploration & Mining

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Developing the Modelling & Inversion Environment

In this report, resistivity and conductivity are used interchangeably depending on context and common idiom. There is no hidden subtlety in this regard. In what follows, the use of the term, ground system, implies receivers and transmitters on or below surface and to some extent, magnetotellurics.

The Domains of Time & Frequency

All programs can be operated in time or frequency domain. In frequency domain, the user can specify the amplitude at each frequency.

Time domain computations are based on a spectrum of frequency-domain computations. This removes the need for the quasi-static assumption and allows the use of frequency-dependent complex conductivities. It also allows us to solve for multiple source locations simultaneously for all programs except the Loki class. The default spectrum for airborne is from 1 Hz to 10 Hz at 3 ppd (points per decade) and 6 ppd from 10 Hz to 100 KHz. For ground systems the default spectrum runs from 0.1 Hz to 10 KHz at 3 ppd and from 10 Hz to 100 KHz at 6 ppd. All the 2.5 and 3D programs have a control file option to change the limits and density of the spectrum.

Once the responses are computed for all frequencies, the response for each receiver is extrapolated back to DC, splined and transformed to time-domain using a custom-designed Hankel filter and the fast-flow Hankel technique (Raiche, 1999). The raw time-domain response is computed out to five pulse lengths to account for slow decays for highly conducting hosts or targets. This is then folded back to a one-pulse response and convolved with the input waveform before being integrated over the receiver windows (Raiche, 1998). For airborne systems, the receiver response time (delay time) is referenced to the beginning of the source waveform. For ground systems, the programs allow the user can set the origin anywhere; eg, at the top or base of the signal decay ramp.

Geoelectric Representation

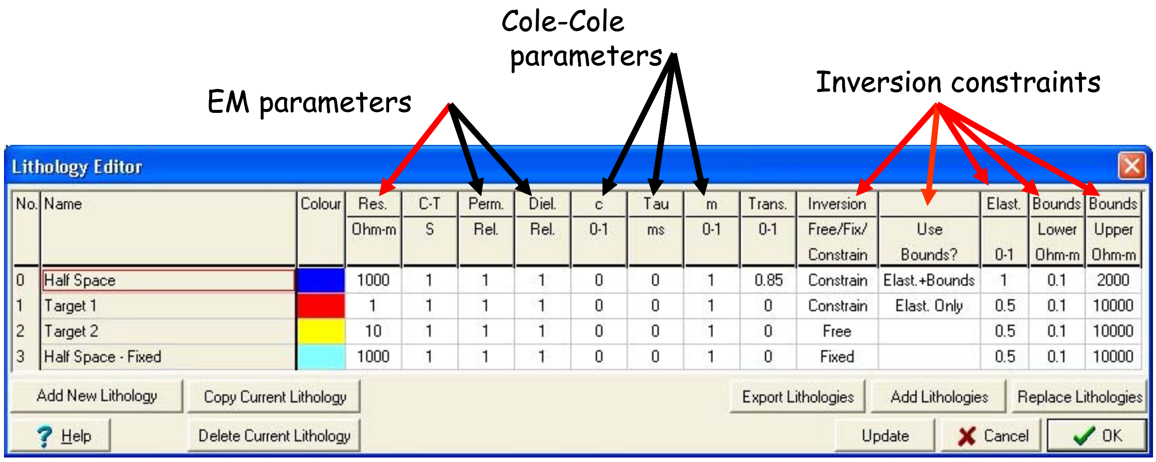
In all programs, the quasi-static approximation is eschewed in favour of the full wave representation. This is augmented with the Cole-Cole model to enable IP effects to be modelled. These Cole-Cole IP effects can be significant even for airborne EM modelling. In time-domain, they manifest as an elevated response at early times and a depressed response at late times.

The complex, frequency-dependent Cole-Cole conductivity (inverse complex resistivity) has the form:

$$\sigma = \sigma_0 \frac{1+(i\omega\tau)^C}{1+(1-m)(i\omega\tau)^C} + i\omega\varepsilon$$

,
σ_0 is the scalar DC conductivity, ε is the permittivity, and m , τ and C are the Cole-Cole chargeability, time and frequency constants, respectively.

In using P223F programs, one defines a number of seven-component lithologies as shown in the picture below. The components are DC resistivity, conductance (used in Leroi and LeroiAir only), relative magnetic permeability and permittivity and the three Cole-Cole parameters. These components are then assigned to the components of the model. Of the seven components, P223F inverts for DC resistivity only. These lithologies are then painted onto the model or assigned through a text editor.



No.	Name	Colour	Res. Ohm-m	C-T S	Perm. Rel.	Diel. Rel.	c 0-1	Tau ms	m 0-1	Trans. 0-1	Inversion Free/Fix/ Constrain	Use Bounds?	Elast. 0-1	Bounds Lower Ohm-m	Bounds Upper Ohm-m
0	Half Space		1000	1	1	1	0	0	1	0.85	Constrain	Elast.+Bounds	1	0.1	2000
1	Target 1		1	1	1	1	0	0	1	0	Constrain	Elast. Only	0.5	0.1	10000
2	Target 2		10	1	1	1	0	0	1	0	Free		0.5	0.1	10000
3	Half Space - Fixed		1000	1	1	1	0	0	1	0	Fixed		0.5	0.1	10000

An example of the lithology editor in Maxwell.

AEM Framework

All of the P223F AEM programs have a common framework, differing only by the actual core computation algorithms. This can be seen from the control file description. For each program the top part of the control file is used to define the task: the choice between time or frequency domain for modelling, inversion, or simply display. The next part contains either the frequencies and amplitudes for frequency-domain tasks or the waveform and receiver channel placement and widths for time domain. The next part describes the aircraft setup, either fixed wing or helicopter, followed by the survey description. The next part defines the lithologies to be used.

Up until this point, the control files for the different programs are identical. For modelling, the last block is followed by the model description: layered earth, plates, or 2,5D or 3D meshes. This is followed by the controls for inversion, including the constraints.

Data to be inverted is stored in a separate file to be accessed by the program. This file is **program independent** and consists of the data preceded by the controls describing its format. This structure allows one to try inverting to different model types without the need to modify the data file.

The AEM program framework reads the data, checks it for inconsistencies or absurdities, sets up the system, survey and model property arrays and sends these off to feed the core modelling subroutines.

For modelling, the programs use this data to compute the frequency-domain response for all receivers in Cartesian components for all the frequencies either from frequency-domain input or from the core frequencies for time-domain. If the latter, these results are converted to time domain response as per the section above. The resulting program output array is then sent back to the general framework for arrangement into the required component form (including normalisation requirements).   For the Leroi and Samaya class, they are combined with the layered earth fields to produce the complete field. They are then converted to the specified output units and written out to prog.out and prog.mf1. prog is the name of the program; eg, Leroi.out and Leroi.mf1

For inversion, the control file data is read in and checked as above and that plus the data to be inverted and the inversion controls are sent off to NLSQ (or NLSQ2) to start inversion.

NLSQ2 sets up the iterations and calls either RESJAC, or FORJAC to compute model results. These programs set up the model parameters and then call the core modelling routines to produce model data for the inversion process.

All AEM programs are based on one type of survey, a single magnetic dipole receiver travelling at constant offset to a magnetic dipole transmitter in air (hopefully).

Ground Systems

A separate framework was set up for ground systems, pretty much along the lines of what is described above. However the survey options for ground systems are a lot more complex if the programs are to base the inversion on lines. It took a long time to develop this system and design the arrays to convert from this to what was expected by the core modelling programs. It is for this reason that the inversion for Samaya and Loki are non-functional because we ran out of time before the links could be designed and written.

Survey options

The ground framework has six survey options. The first is a fixed, open or closed loop, each of whose lines are defined a single receiver array, each array defining a line.. New lines are defined when the previously fixed loop becomes unfixed and moved to another location. The receivers in each array must all be of the same type.

The second survey type consists of one or more magnetic dipole receivers moving at fixed offset with respect to a moving rectangular loop transmitter. The path of each receiver defines a separate line. In this sense, the lines are nested since the moving loop itself moves in defined lines.

The third survey option is similar to the second except that the transmitter is a magnetic dipole rather than a flat loop**.**

The fourth option is a coincident loop.

Option five is a borehole system with magnetic dipole transmitter and single receiver moving down a borehole at fixed offset.

Option six is magnetotellurics.

Transmitter options

For survey option 1, three transmitter types are allowed. They can be closed or open loops or magnetic dipoles. The closed loops can have any number of vertices with a minimum of three. The open loops are essentially grounded wires. They can have any number of vertices with a minimum of two. The loops can be on the surface or at any depth but they mist be flat; ie all vertices must be at the same depth. Closed loops can be in the air but open loops cannot because of the fact that they must be grounded. Magnetic dipole transmitters can be at any altitude or depth with any orientation.

Survey option 1 is the only one allowing different transmitter types but the type cannot vary during the survey simulation or inversion..

Receiver options

For survey option 1, receivers can be magnetic dipoles, electric dipoles (measuring voltage) or point electric (measuring electric field at a point). The electric dipoles must be on or below the surface and flat; ie, the two vertices must be at the same depth. None-flat electric dipoles can be simulated by using the point electric option and integrating the response between electrodes. Magnetic dipoles can be at any altitude or depth.

Magnetotellurics

This option has been implemented in Leroi version 7.1.0 but has been removed from version 8.0.0 in order to simplify the array structures required for multi-layer plate structures. It has also been implemented in Samaya. It also has been implemented in Loki but disconnected because of the galvanic response problem discussed elsewhere in this report. It has not been implemented in Beowulf because he only liked controlled source methods.

This option makes use of magnetic dipole receivers and electric point receivers; because electric field rather than voltage is used to calculate the impedances. The user specifies two separate arrays, one for multi-component magnetic receivers and one for two component electric fields. As per practice where the same magnetic receiver is used to normalise the electric field at more than

one location, the user must specify which magnetic field position is used to normalise the response at
each electric field receiver point.

Special Systems

Sampo is the Finnish frequency-domain moving loop system whose output consists of the ratio of the vertical to the radial magnetic field. A special option was designed for this. When I tested it for inversion, I got quite a surprise. It was able to recover models generated from perfect data much better than any other system.

Thee must be something in the Canadian water but I did set up special options for UTEM. This included the reverse time order and quaint normalisation. It also included expressing borehole system results using the SNW system. It all makes perfectly good sense when (and if) you get used to it

Visualisation & User Environment

At the start of the project, thee was a great deal of talk from both Encom and CSIRO about developing GUIs for P223F inversion software. In Encom's case, this would be incorporated into Profile Analyst. In CSIRO's case, there were plans amongst their Computational Geoscience group in Perth that P223F software would be part of joint inversion. Sadly none of the people who touted this had the slightest inkling of the issues involved. They did tend to get annoyed when I pointed this out. I also let them loose at a sponsors meeting to talk about web-based inversion but the sponsors got bored and fell asleep. Fortunately, only one person snored.

Spin is one thing and substance is another. EMIT offered to keep extending Maxwell capability to provide GUI support to whatever we would develop. Moreover, they would provide free support for one seat until 2009 for each sponsor for a cost to the project of $1000 per year. This was paid for out of project funds rather than being an additional sponsor cost. EMIT did a pretty good job for inductive modelling and inversion but exhibited a distinct lack of interest for galvanic and MT options.

Structured Programming

One of the most important things we had to learn was the discipline of writing structured software. Almost without exception, academic EM software is written in spaghetti fashion with little attention paid to the basic rules of information flow, modularisation and eliminating side effects. Indeed, it often contains non-standard language features that make it impossible to run reliably on machines with different operating systems. In a series of articles written in the late 1970's, Les Hatton showed that programs created in this way tended to have around 100 times the number of errors compared with software written in structured style. Moreover, the poor structure made it much harder to find errors and even correct them once they were found.

A lot of P223 software had its genesis on the ideas contained in programs that researchers from around the world made available to us. Although the concepts upon which the programs were based were valuable, the software realisation was not. Our usual mode of operation was to restructure the initial program to understand the concepts. Once this was done, we were able to use our own algorithms to recast the core modules and combine these with our existing software framework to produce what we naively hoped would be the final version. During the initial restructuring phase, we usually found many errors that were previously hidden by the original tangled structure. Typically the restructuring increased the speed, often by a factor of 10 and in one case, by a factor of 100, simply by revising the structure.

Over the years, our programs underwent many revisions. Sometimes it was because we devised faster or more accurate internal algorithms. Other times it was to incorporate new capabilities or to eliminate errors that appeared when the programs were used by industry. The benefits of structured programming become fairly obvious. The modularisation, and strict design of information flow, cut revision time by an order of magnitude. It yielded one other important benefit. By maintaining a common modular structure across all program classes as much as possible, it was easy to port improvements in one program class to others

During my working career, when I was invited to give lectures at universities with active research interests in electromagnetic geophysics, there was always interest in our mathematical approaches to EM modelling. However, any efforts to introduce concepts of structured programming in these talks were invariably met with complete disinterest. Imagine what would happen if cars were designed with no thought give to assembly procedures or maintainability.

We chose to write our programs in ansii-standard FORTRAN. We started with Fortran IV and as the language evolved to Fortran 95, we changed with it. By purchasing software capable of checking for non-standard or obsolete features, we were able to ensure that our programs could run on any operating system for which ansii-standard compilers existed. We chose FORTRAN because for numerical applied mathematics computations, it produces more efficient executables than is the case with other languages. Fortran has never become obsolete because it keeps changing.

The Programs

Final versions of P223 programs, Marco and MarcoAir were really P223D programs but I include them in the table below.

Program	version number	Version date	Model description	Inversion?	Topography
Airbeo	4.7.0	2007-03-16	layered earth	yes	Flat earth
Beowulf	1.0.3	2007-11-07	layered earth	yes	Flat earth
LeroiAir	5.44	2006-10-23	Thin plates in layered host	yes	Flat earth
Leroi	8.0.0	2008-01-16	Thin plates in layered host	yes	Flat earth
ArjunAir	7.0.5	2007-09-26	2D mesh 3D source	yes	Full domain
Arjuna	2.1.0	2004-01-29	2D mesh 3D source	no	Full domain
SamAir	2.2.5	2007-09-22	Compact 3D in uniform host	yes	Limited
Samaya	2.0.0	2007-10-30	Compact 3D in uniform host	virtual	Limited
LokiAir	4.0.4	2007-09-24	3D full domain	yes	Full domain
Loki	3.0.0	2007-10-30	3D full domain	virtual	Full domain
MarcoAir	2.8.4	2007-09-24	prisms in layered host	no	Flat earth
Marco	4.4.0	2003-06-10	prisms in layered host	no	Flat earth

The deeper technical aspects of the programs are covered in the pdf's that accompany this report. In what follows, I cover a few of the salient points of some of the more complex programs.

Leroi and LeroiAir - Modelling and Inversion

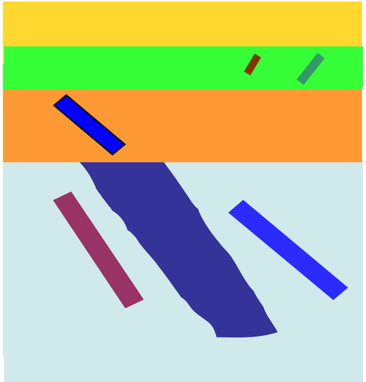
Leroi and LeroiAir are programs designed to model and invert the electromagnetic response of one or more thin plates in a horizontally layered host. Leroi is for ground systems by which is included surface and downhole transmitters and receivers. LeroiAir is specialised for AEM systems. At the start of AMIRA project P223F, the thin sheet core computations of the two programs were pretty similar. That is no longer the case.

At the start of P223F, the Leroi and LeroiAir model consisted of one or more thin plates in a basement overlain by a single overburden layer. Each plate was described by a conductance; the north, east and depth of the plate reference point; dip and strike angle of the plate; and the length and down dip width of the plate. During the course of the framework development, I extended the LeroiAir model to allow multiple layers over basement whilst still confining the plates to the basement. The strike angle, that the length of the plate made with north, was replaced by dip azimuth, the angle that the plate normal made with north.

When the inversion for LeroiAir was finished, I began development of a new ground framework, capable of dealing with the many different types of arrays. Before developing an inversion for Leroi, I decide to extend the model capability to include plunge. This turned out to be a major redevelopment task due to the fact that so much of the P223E version depended on symmetry shortcuts requiring the plate rows to be strictly horizontal. The new version required the development of a rapid 2D interpolation scheme amongst other things and new ways of addressing points for integrating the mutual responses of the various plates. I thought it would be slower but it turned out that it was faster and more accurate since the new 2D interpolation routine was more stable numerically than was the previous direct value extraction.

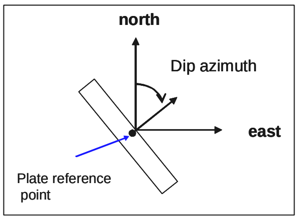
It is important to realise that the Leroi plates are infinitesimally thin; ie zero edge surface area. Amongst other things, it means that current can flow into the plate only through its broad surface. No current can flow into the plate through its edges. This when one plate edge touches that of another plate or a conductive layer above, there can be no galvanic boost to the response. It might be thought that the galvanic boost from a conductive overburden could be simulated by allowing the plate to intrude into the layer above. Not so, due to the physics of the situation. Since the model required the plates to have a uniform conductance, the electric field along the plate must be continuous. At the boundary of two layers, the vertical electric field must be discontinuous by the ratio of the conductivities of the two layers. The fact that the plate has no thickness but is merely a superposed conductance leads to an irreconcilable contradiction. In other words, the thin plates cannot be allowed to cross layer boundaries.

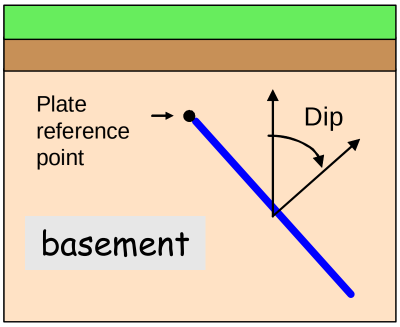
During the last three months of the project, I tried to develop a kludge to get around this problem with a few different ideas. All yielded different answers, none of which were believable. There was a benefit to this futile effort however. One of the initial hurdles to overcome was that the previous restriction that confined plates to basement allowed flagrant optimisation of many Leroi subroutines. A major redevelopment of the underlying Green's tensor computations was required and completed to allow plate response from different layers.

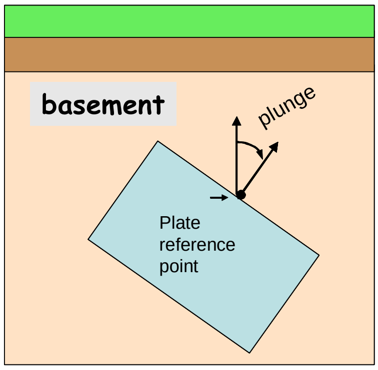


Having accomplished this revision was like being dressed for a ball only to find out that there was no way to get there. Well, there's always somewhere else to go. In this case, I redeveloped Leroi (not LeroiAir) to allow any plate to be in any layer. If any plate is in a layer above basement, all plates must have zero plunge, and to repeat the above, no plate can cross a layer. Because of the limited time available for this work, it was necessary to simplify the arrays before making the changes necessary to allow the plates to escape from basement. Therefore, the magnetotellurics option was eliminated from Leroi 8.0.0. Those who want this option should use version 7.1.0.

The above figure shows a four-layered host with plates in three of the layers. It's a bit over the top really but it does show what Leroi allows. Note that for LeroiAir, plates are still confined to basement.





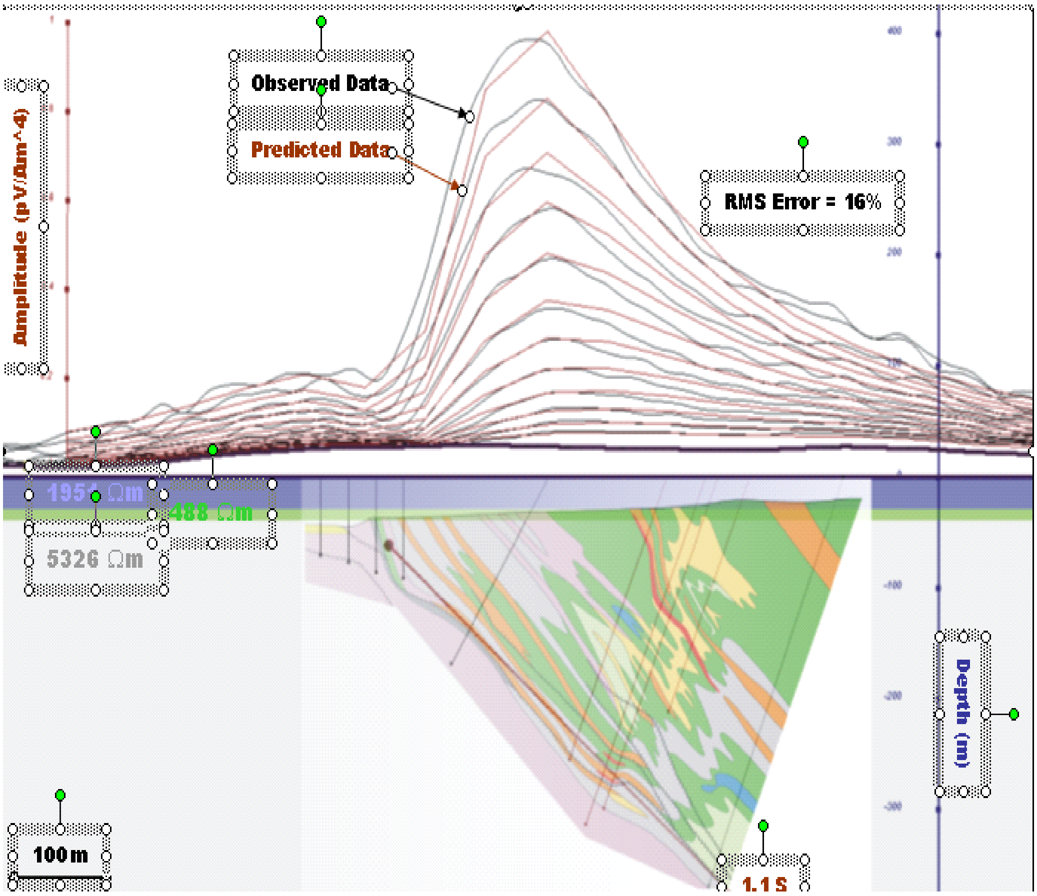


The three figures above illustrate the plate orientation convention. These are based on rotations about the PRP (plate reference point). For a plate with non-zero dip, the PRP is the midpoint of the top edge. Suppose, however that we start with a flat rectangular plate oriented squarely with the

X-Y Cartesian axis with x pointing north and y pointing east. The PRP is the midpoint of the southern edge. All rotations are performed about axes passing through this point. The order of the rotations is important. The first is the dip azimuth (**ϕ**) rotation about the vertical axis. **($0 \leqslant \phi \leqslant \pi$).**

The second is the dip (**θ**) about the top edge of the plate. **($0 \leqslant \theta \leqslant \pi$)**. The third is the plunge (**χ**) about an axis normal to the plate surface, passing through the PRP**)** is positive clockwise about the vertical axis. **($-\pi/2 \leqslant \chi \leqslant \pi/2$).**

Just in case that sounds too simple, let me tell you how Leroi actually orients the plates. The plunge rotation is performed first about the vertical axis. The dip is performed about the east-west axis followed by the dip azimuth rotation about the vertical axis. These two are equivalent but the second way is easier to implement.

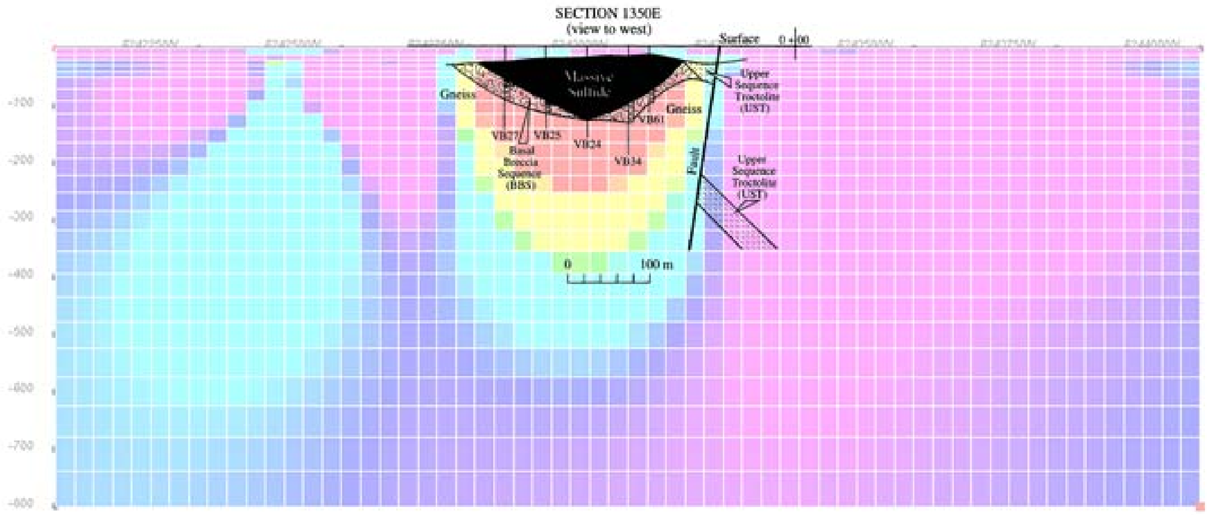


Inversion capability was developed for both LeroiAir and Leroi for all applicable systems. As an example, the above figure shows a LeroiAir model recovered from the inversion of VTEM data over the O2 deposit, Athabasca Basin, with the geological section of the line above (from Cristall and Brisbin,2006).

In both programs the user can invert for the parameters of the layered earth model, the size and location of the plates and their dip azimuth and dip. In addition, Leroi can invert for plunge but inversion is permitted only when all plates are in the basement. This restriction was imposed strictly because of the need to meet project deadlines.

ArjunAir – Modelling and Inversion

ArjunAir 2.5D full-domain inversion was developed initially as a prototype for 3D inversion but later proved to be useful in its own right. A conductivity structure that could vary with depth and across strike turned out to be a practical alternative to 3D full-domain modelling. ArjunAir can model topography and irregular subsurface structures but the structure along strike is presumed to be constant for a geoelectric distance greater than the 3D source footprint. In other words, although the computation is based on the response of a 2D model to a 3D source, the Arjuna class can be applied to 3D structures whose conductivity precludes the spread of the source wave beyond the 2D region during the time range of the data.



This point is illustrated with an ArjunAir model recovered from the inversion of DIGHEM^V data from line L604900 over the Ovoid deposit, Voisey's Bay, with the geological section of line 1350E overlain to scale (from Wilson *et al*. 2006). Note that ArjunAir can invert for the resisitivities of the structure but not the structure itself. That remains constant after being defined by the control file.

The solution is obtained via the transformation the along strike component into the Fourier domain where Maxwell's equations reduce to two coupled partial differential equations for the along strike components of the secondary electric and magnetic fields. A conventional finite-element formulation with quadratic basis and test functions and homogeneous Dirichlet boundary conditions is solved for 21 spatial transform values logarithmically spaced from 10^{-5} m^{-1} to 0.1 m^{-1} using the frontal solution method (Irons, 1970). The frequency-domain fields are initially computed at appropriate nodes in the Fourier domain from shape function interpolation and/or differentiation of the along strike field components. These are then splined and transformed back into the 3D Cartesian domain. The implicit continuity of the along strike components ensures numerical stability and accuracy when modelling problems with resistivity contrasts up to 10^6:1 (Sugeng *et al.*, 1993).

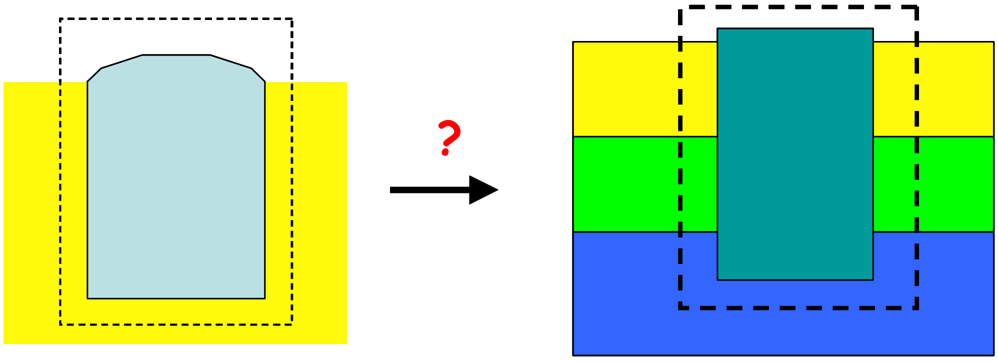
As described in the inversion section, the ArjunAir mesh is "painted with a seven-component lithology. However the inversion is for DC cell resistivity only. The other lithology components and the structure itself remain constant during the inversion.

The lithology concept is useful for applying any of the P223F constraint styles. A lithology constraint applies to the resistivities of the cells only in that part of the mesh that was painted with that lithology. One could start with a mesh described by lithologies that differed only by the constraints attached to them. In that way, one could do an inversion such that the resistivities in selected regions were fixed or could vary little whereas those in other parts of the model were free to vary widely.

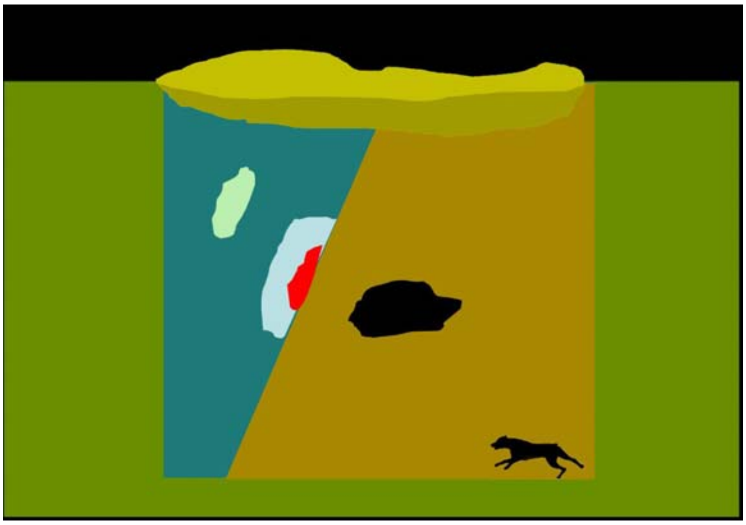
We note in passing that the sensitivities for ArjunAir are computed using the reciprocity method (McGillivray et al, 1994). The modelling and inversion methods underlying ArjunAir are discussed in the accompanying documentation on ArjunAir and inversion.

Samaya (Modelling only) and SamAir (Modelling and Inversion)

In order to develop a practical EM inversion scheme able to run on a high end laptop and still accommodate irregular 3D structures, we resurrected and revised the compact finite-element method (CFEM). This replaces the homogeneous Dirichlet boundary conditions of the full-domain FEM with an integral equation boundary condition, thus reducing the finite-element region to a heterogeneous domain of arbitrary complexity embedded in a horizontally layered host.

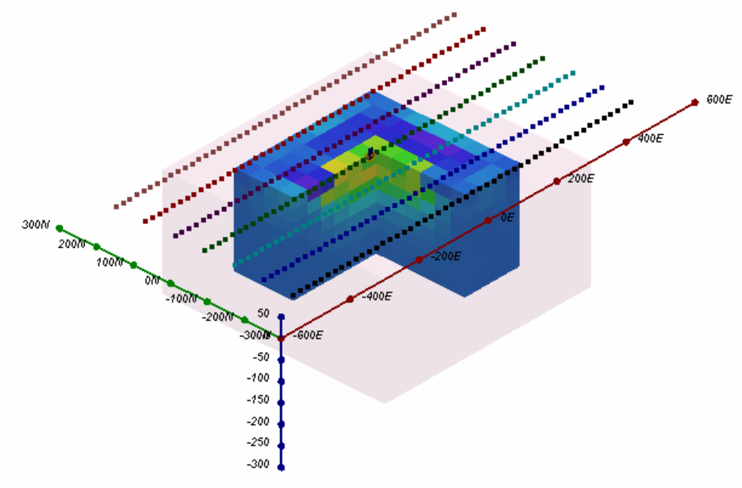


The figure above shows the schematic of the Samaya class. The figure on the left illustrates a heterogeneous region embedded in a uniform host. This is the current model. The figure on the right shows the heterogeneous region embedded in a three-layered host. This is what we were hoping to accomplish. Although the mathematics and algorithms for interacting with an N-layered host were completed, the actual tedious bookkeeping work to tie these layered earth, tensor Green's tensors to the heterogeneous, finite-element region was not completed. The figure below shows the sort of thing that can be accomplished with such a model.



The finite-element part of the model allows topography and unconformities to be taken into account within that limited domain. A unique feature of the CFEM is that it solves for the total electric field directly rather than as a sum of the layered earth field and the scattered field. This is particularly useful for maintaining accuracy when modelling highly conducting targets where the very small interior electric field is not represented as the sum of two large fields of opposite sign. This eliminates a major source of inaccuracy due to round-off error. The use of edge-elements obviates the electric field discontinuity problems that afflict conventional finite-element methods. In experiments to date, the CFEM has been shown to be stable and accurate for a broad conductivity contrast range of up to 10^5:1 (Sugeng and Raiche, 2006). In practice, we have limited model size to around 1000 cells because of the storage requirements and execution times of the direct matrix solver upon which Samaya and SamAir are based.

The sensitivities for SamAir are computed using the reciprocity method (McGillivray et al, 1994). The lithology concept for applying any of the P223F constraint styles, as described in the ArjunAir section, is also used in SamAir. An example of SamAir inversion from 350 stations of synthetic DIGHEM data (5 frequencies). is shown below using a 1000 element model. The target was a 100 Ω-m kimberlite beneath a 50 Ω-m clay cap in a 1000 Ω-m half-space (Raiche 2001). The starting model was a uniform 1000 Ω-m half-space. Initial misfit = 20%. Final misfit (10 iterations) = 2%. Time = 15 hours.

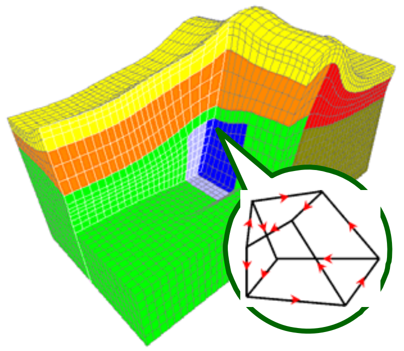


The modelling and inversion methods underlying SamAir are discussed in the accompanying documentation on SamAir and inversion. We are disappointed that time ran out before we could produce a working inversion capability for Samaya. In fact, subroutines NLSQ and RESJAC, based on the newly developed domain differentiation concept, are contained within the distributed version of Samaya but the software links to tie them to the rest of the program are incomplete.

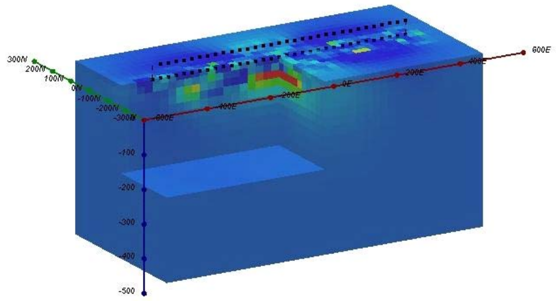
Loki (modelling only) and LokiAir (modelling and inversion)

The most general model is consists of a conformable 3D finite-element mesh which is able to account for topography and any irregular subsurface structure. Basically it should be able to represent any realisable geological structure at the scale appropriate to EM surveying. The use of edge-elements rather than the more conventional node-based elements precludes any conflict between continuous basis functions and discontinuous normal electric fields.

This formulation has been shown to be stable and accurate for a broad conductivity contrast range, up to 10^6:1 (Sugeng and Raiche, 2004). It can solve a 60,000 cell problem in around 90 seconds per frequency per source position on a high end, single-chip laptop. That is impressive for frequency domain surveys with only a few source positions. However, since as mentioned earlier, the execution time for Loki and LokiAir models is proportional N_FREQ * N-SOURCE, (the number of frequencies and sources respectively) to the product of the number of frequencies with the it also implies that a 50 position time-domain system would require more than a day if only a single Intel CPU was used. However, since the information contained in AEM survey data falls far short of being able to resolve all the cells individually of a 60,000 cell model, one can use a more approximate LokiAir model to invert a less refined model as illustrated in the above figure.



Example of a Loki class model with a cartoon of the edge-element topology.



LokiAir model (8,000 elements) recovered from the inversion of 33 stations of synthetic GTK data (2 frequencies). The target was a 1 Ω-m block in 1000 Ω-m half-space, with a uniform 1000 Ω-m half-space starting model. Initial misfit was 55%. Final misfit was 6 % after 4 iterations 4 hours, 40 minutes.

We actually had no intention of using Loki or LokiAir for inversion until sponsors informed us that they were interested in using parallel systems to make its use practical. This is discussed in the future possibilities section. Inversion has been implemented into LokiAir. Inversion is non-functional in Loki as per the discussion above for Samaya.

$$\mathbf{E} = -i\omega\mu\mathbf{F} + \boxed{\frac{1}{\sigma}\nabla\nabla\cdot\mathbf{F}}$$

The Loki code has provision for the full range of ground system options but those for galvanic receivers and, by implication, magnetotellurics, have been disconnected. This is because we use an incomplete Green's tensor operator to compute the scattered electric field **E** from the Schelkunoff potential **F** that is the basis of the Loki solution.

In Loki and LokiAir, we omit the term in the red box in order to avoid the instability of numerical derivatives. For all AEM and inductive ground surveys, this yields accurate results. This Is not the case for galvanic receivers. Developing a clever interpolation scheme or finding some other way to avoid the numerical double derivatives, with their burden of excessive discretisation, remains a worthy research topic.

Further details on the development of Loki and LokiAir are contained in the accompanying documentation on the Loki model class.

Airbeo and Beowulf

These are layered earth inversion for AEM and ground systems respectively. They differ from the other inversion programs because they invert data for one receiver position at a time. Beowulf inverts for all controlled source ground systems. Their speed has been optimised using the Green's tensor theory explained in the layered earth theory paper that accompanies this report and also in (Raiche, 1999), my final paper of the 2nd millennium CE.

Technical Transfer

Program Packages

Over the course of the project whenever a new version of a program was completed, a package was sent out to sponsors. The Fortran source code itself is thoroughly documented with the top one or two thousand lines containing instructions for constructing the control file and running the program. These instructions would be copied into a text file bearing the program name and version number. In addition, the program was internally documented at subroutine level, with comments describing the workings of the subroutine intermingled with the source code.

The general package consisted of a Windows exe (executable) file, the text file containing program instructions, a Read_Me.pdf describing package contents and any other relevant usage issues plus a large collection of sample control and output files germane to the program testing. To try to bypass IT security, this was sent as a password-protected zip file which seemed to get through to everyone except Cameco.

The source code was sent out separately to people designated by their companies to receive it. This was disguised as a text file to enable reception.

Finally a simple text email was sent out informing people that the program had been released so that those who were frozen out by their IT departments could possibly access it from the AMIRA website.

Sponsors Meetings and Company Private Workshops

During the course of the project we have had seven group workshops spread amongst Sydney, Perth, Toronto and Melbourne as part of AMIRA's quaint custom of semi-annual meetings between sponsors and researchers. In addition we have given one or more company private workshops in sites as diverse as Perth, Brisbane, Darwin, Johannesburg, Espoo (which comes from the old Swedish word *äspe*, meaning stand of aspen), Keyworth, Toronto, Sudbury, Saskatoon and Vancouver. We have also given private workshops to sponsors at our office in North Ryde. During this time we have talked to a lot of people – and that's the trouble. In several cases, we rarely see the same person twice from a given company. Whether that's because we have bad breath or have bored our company representative silly or that person has found a better job is immaterial, The problem is that the material we transmit is lost; ie, not retained; eg loss investment value for the sponsor.

This used to be of great concern to me but with advancing age and the concomitant loss of short term memory, I too will forget this material so I guess that makes us even.

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