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Interpreting marine controlled source electromagnetic field behaviour with streamlines

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ABSTRACT

Streamlines represent particle motion within a vector field as a single line structure and have been used in many areas of geophysics. We extend the concept of streamlines to interactive three dimensional representations of the coupled vector fields generated during marine controlled source electromagnetic surveys. These vector fields have measurable amplitudes throughout many hundreds of cubic kilometres. Electromagnetic streamline representation makes electromagnetic interactions within complex geo-electrical setting comprehensible. We develop an interface to rapidly compute and interactively visualise the electric and magnetic fields as streamlines for 3D marine controlled source electromagnetic surveys. Several examples highlighting how interactive use has value in marine controlled source electromagnetic survey design, interpretation and teaching are provided. The first videos of electric, magnetic and Poynting vector field streamlines are provided along with the first published example of the airwave represented as streamlines. We demonstrate that the electric field airwave is a circulating vortex moving down and out from the air–water interface towards the ocean floor. The use of interactive streamlines is not limited to marine controlled source electromagnetic methods. Streamlines provides a high level visualisation tool for interpreting the electric and magnetic field behaviour generated by a wide range of electromagnetic survey configurations for complex 3D geo-electrical settings.

1. Introduction

The Marine Controlled Source Electromagnetic Method (MCSEM) is one tool used for offshore hydrocarbon exploration and development (Hesthammer et al., 2010). MCSEM utilises an electrical bipole source to generate time varying coupled electric and magnetic fields. For a typical survey, ocean bottom receivers record the electric and magnetic fields generated by the EM transmitter. These electromagnetic fields may be represented by a number of methods. Typical representations include profiles (Key, 2009), two-dimensional grids (Zhdanov et al., 2010) and electromagnetic vectors (Pethick, 2008). Less common visualisation techniques include polarisation ellipses (Key and Lockwood, 2010) and isosurfaces (Pethick, 2008). Streamlines represent the path of a particle through a vector field at a particular time (Hansen and Johnson, 2004). Streamlines are commonly applied in physical modeling of fluid flow (Zehner et al., 2010) and mantle flow (Billen et al., 2008). They have also been used in electromagnetic studies to express the electric field point charge (Bakshi and Bakshi, 2009), 3D coronal magnetic fields (Regnier et al., 2002) and electrical current flow (Sachse and Taccardi, 2004). We believe that the application of streamlines in applied geophysics can be particularly valuable for understanding complex sub-sea electromagnetic field interactions such as the airwave. The purpose of this paper is not to present a new streamline visualisation method, but rather the application of streamline to the interpretation of MCSEM electromagnetic field behaviour. Full expression of the coupled electric and magnetic vector fields as interactive streamlines can facilitate new ideas about how to configure and deploy resources (i.e. transmitting and receiving antenna) for deep ocean MCSEM surveys.

2. Streamline generation

2D streamline generation begins with simulating the electromagnetic field generated from a MCSEM survey throughout a 2D region. This includes populating a 2D grid with three component electromagnetic receivers then forward computing the EM fields at each receiver position. Secondly seed positions are populated through the 2D section. Lastly at each of the streamline seed positions second order vector interpolation is used to step the streamline through the electromagnetic vector fields. The streamline colour represents the total vector amplitude and is computed

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at each interpolation step by bi-cubic interpolation of the vector field.

The EM fields generated during MCSEM survey propagate at exceedingly low frequencies (e.g. much less than 10 Hz) and electromagnetic receivers are spread throughout large volumes (i.e. hundreds of cubic kilometres). The fields in the immediate vicinity of the transmitter vary rapidly over small distances. For practical applications, interpretation of this near field (i.e. within 10 m of the transmitter) is not required. In this case we use a constant step length, since the path of the streamline in space is dictated by the direction of the field and not the amplitude of the vector field.

The first step of our method is to compute a 2D grid of the electromagnetic fields generated by the horizontal electric bipole transmitting antenna just above the sea floor. A structured receiver grid was used to speed up subsequent interpolation methods. Our example MCSEM surveys are completed in the frequency domain. These streamlines represent the EM fields at an instant in time so that they can be utilised to visualise the EM field behaviour resulting from any transmitter waveform (e.g. a 50% or 100% duty cycle square waveform).

Electromagnetic fields are composed of coupled time varying electric and magnetic fields. Amplitude and phase are computed for each vector components of the electric and magnetic fields (i.e. E_x, E_y, E_z, H_x, H_y and H_z) and these are used to describe the complete time harmonic oscillation via Eq. (1). That is, Eq. (1) describes the full behaviour of each of the electric and magnetic vector field components for each location on the grid. The two resulting vector field grids are the electric and magnetic fields.

$$A(t) = A\ \sin(2\pi f t + \phi) \tag{1}$$

where

$A(t)$	Amplitude at time t
A	Total amplitude ($A = \sqrt{Re^2 + Im^2}$)
f	Frequency (Hz)
ϕ	Phase ($\phi = a\ \tan 2[Im/Re]$)

The second step requires seed positions to be populated throughout the data area. The seed positions can be placed in either (i) the grid, (ii) the ocean bottom or (iii) placed interactively. The streamline density is important. If the streamline density is low the EM field behaviour is not fully represented. Equally, a very high density of streamlines can obscure information and complicate interpretation. The most suitable streamline density is situation dependent and should be user controlled.

The third step requires the propagation and visualisation of the streamlines from the seed positions. Electromagnetic fields are continuous in nature. The computed electromagnetic fields, however, are discrete. Streamlines require the field to be computed at any position within the grid. Euler integration (Tricoche and Garth, 2006) and the Runge–Kutta method (Hansen and Johnson, 2004) can be used to approximate the streamline path in a discretely sampled dataset in time and space. Exceedingly low frequencies are used for the MCSEM method (e.g. 0.01–10 Hz). Under these circumstances it is highly reasonable to interpolate both the orientation and amplitude of the vector field between grid points. A small step size was chosen to avoid the possible errors associated with second order vector interpolation (i.e. one-tenth of the data spacing). Termination of the streamline occurs when either the maximum number of steps is reached or the streamline exits the data area. Fig. 1 provides an illustration of how MCSEM streamlines are constructed. Here the streamlines were created from 200, propagation steps (10 m per step) through an inline electric vector field at 0.1768 s. The transmitting antenna was an electric bipole operating with a time harmonic frequency of 1.5 Hz.

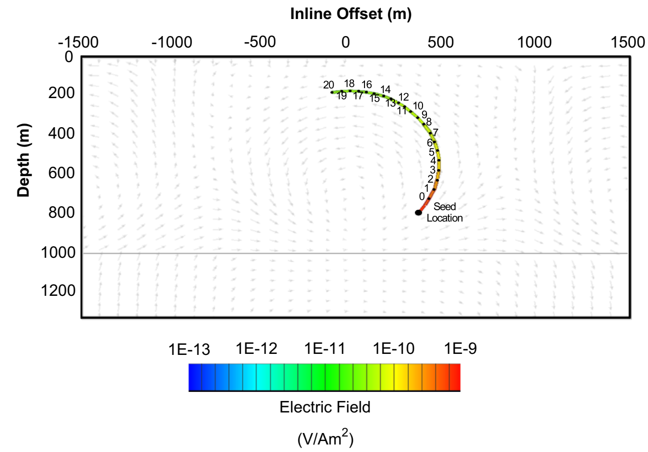

Fig. 1. Propagation of a streamline through a vector field from a single seed location. This Figure shows the first 200 steps of a single inline electric field streamline through the associated vector field (arrows show direction of the field) at a time 0.1768 s using a transmission frequency of 1.5 Hz. The numbers show every tenth integration step. The streamlines were generated using a second order vector interpolation. The electromagnetic fields generated by MCSEM are at such low frequencies for which a constant step length could be used. In this Figure a step length of 10 m was used.

3. Software development

We developed an interactive MCSEM software package including streamline modules written in the Java programming language. The software has been written to facilitate research and education in deep ocean electromagnetic methods. Multi-touch devices have allowed experimentation with computer–human interaction to provide an interactive and user-friendly experience. A number of interface features were implemented. These included, touch and drag axis, colour scales, time selector, large menu combo boxes and single touch streamline generation (see Fig. 2). The development of the software has been overviewed by Pethick and Harris (2012).

Several MCSEM forward modeling algorithms have been integrated into the software and can be used with our streamline generating algorithm. These include Dipole1D, which is a 1D MCSEM forward modeling algorithm developed by Key (2009) and Marco, which is a 3D integral equation forward modeler (Xiong, 1992). These were both chosen because they are open source, cross-platform and can quickly and accurately model electromagnetic fields that could be generated by a MCSEM survey.

Our approach to streamline generation is intended for representing synthetic data (i.e. forward modeled data), however if enough data is collected it should in principle be possible to represent field data as streamlines. For example, streamlines could be computed from records made from three component magnetic and electric field receivers distributed within the Ocean volume. Field data is typically sparse, but a structured grid of the recorded field can be obtained through Delaunay triangulation (Floater and Iske, 1996) to improve performance. Clearly, this would be limited by the spatial domain and sampling of receivers (i.e. the actual grid of receivers).

We have integrated the streamline algorithm of our software package. The package includes creation and display options. Streamline options include (i) seed mode, (ii) maximum integration steps, (iii) step length, (vi) interpolation in both forward and reverse directions, (v) selection of the number of seed positions in the x and y directions and (vi) associating the colour of the streamline with phase, amplitude at time or total amplitude. Seed mode defines the positions and consequently density of the streamlines. The seed position options include ocean bottom, grid and custom options (see Fig. 3). An interactive streamline placement