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Magnetotelluric Modeling Using a Parallel Computational Scheme: Code Development and Preliminary Results

Wenchien Chou [1], Fumiko Tajima [2], Ryoji Matsumoto [3]

[1] RIST, [2] U C Berkeley Seismo. Lab., [3] Dept. Physics, Fac. Sci., Chiba Univ.

A new parallel code has been developed to carry out simulational experiments of magnetotelluric investigation in Cartesian coordinates by solving the electromagnetic induction equation in the time domain. In this paper we present several preliminary tests that demonstrate the performance of this code. The results show accuracy of the computations in several aspects including the effect of skin depth, and the phase shift and magnitude of the induced field relative to the external electric field.

Over the past decade seismology has made significant progress in using tomographic techniques for 3-D imaging of the elastic properties of the crust and mantle and the topography of the core-mantle boundary. While seismic waves provide information on elastic properties, measurements of electrical conductivity can be effectively used to constrain the spatial variation of temperature as well as to characterize chemical composition and degree of partial melt within the Earth. The naturally occurring powerful, low-frequency electromagnetic (EM) fields whose primary sources are located in the magnetosphere and ionsphere have long been considered to be promising for studies of the Earth's interior. However, they have not been utilized to their full advantage due to several limitations such as the spotty geographical and temporal distribution of observation sites, and the difficulty to distinguish or isolate the external EM sources. We believe that computational experiments are effective to assess the feasibility of the magnetotelluric (MT) method to image the mantle structure and shed light on what information we can obtain from the limited observational data. There are several groups of researchers who attempt to carry out this kind of computer simulations. To our best knowledge, however, these simulations are carried out in the frequency domain, and more importantly none of these efforts have successfully parallelized the calculation or fully utilized the power of the modern computer technology. This paper presents a newly developed parallel code to solve the EM induction equation in the time domain.

If we assume that there is no static electric field and ignore the displacement current, the Maxwell equations can be reduced to a diffusion equation of the vector potential A,
\begin{equation} \displaystyle\frac{4\pi\sigma}{c^2}
\displaystyle\frac{\partial {\bf A}}{\partial t}
-\nabla^2{\bf A}=0, \label{diffusion}\end{equation}
with a Coulomb gauge $ \nabla \cdot {\bf A}=0,$ and
${\bf B}=\nabla \times {\bf A}$,
${\bf E}=-\partial {\bf A}/(c\partial t)$, where σ and c
are the electric conductivity and the speed of light, respectively.
Adopting Crank-Nicholson scheme and Cartesian coordinates, the diffusion equation can be re-written as a finite difference equation, organized in a (symmetric) matrix form, and solved by using the

Incomplete Cholesky conjugate gradient (ICCG) scheme.
In our code the conductivity σ and the boundary condition can be given as any function of space and time. At present, however, we choose only some simple cases for which the analytical solutions are known.
We assume periodic boundary conditions at four sides ($\pm x,\pm y$), and $A=0$ at the bottom ($z=-z_{max}$) boundary which corresponds to the core-mantle boundary. At $z=0$ we assume a sinusoidal dependency on time, $A_x(z=0)=\sin \omega t, A_y=A_z=0$, which corresponds to applying an electric field $E_x=-\omega \cos(\omega t)/c$ on the surface of the earth.

First we tested the skin depths effect by applying a sinusoidal electric field E_x with a period of 10000s on the surface.
The theoretical skin depths for a uniform conductivity of 0.01 S/m, 0.1S/m and 1S/m are 505km, 160km, and 51km, respectively.
Our simulation results agree with these values.
In the second test we assumed four layers of different conductivity in the vertical direction.
The boundaries of these four layers were chosen at depth of seismic velocity discontinuity, i.e., approximately 50km, 410km, and 660km.
We demonstrate that the effects of different conductivity in the second or third layer appeared in the difference in the ratio of the surface magnetic field to the electric field and the difference in their phases. We also tested a case in which the conductivity is a function of all three coordinates.
We found that a non-zero component of the induced field B_z is generated.
The theory expects this induction from the term $\partial A_x/\partial y$.