SATELLITE INDUCTION STUDIES BASED ON SPATIOTEMPORAL ANALYSIS OF LOW-EARTH ORBIT MAGNETOMETER DATA

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ABSTRACT

An independent perspective is given of geomagnetic induction based on spatiotemporal analysis of low-Earth orbit satellite magnetometer data. The goal of geomagnetic induction is to map 3-D electrical conductivity of Earth's mantle. This is a primary objective of the *swarm* multi-satellite mission. The main challenges arise from the fact that the geological signal from induced currents exhibits length-scale dependent heterogeneity and is small in magnitude. Furthermore, the external Sq and Dst source geometries are poorly represented by the F10.7 and Dst indices. A 1-D inversion of storm-time CHAMP data reveals a jump in mantle electrical conductivity at 900 km depth, consistent with earlier *magsat* analysis. Some future possibilities for satellite induction studies are outlined at the conclusion of the article.

INTRODUCTION

The central task of geomagnetic induction studies is to isolate the induction signal $\mathbf{B}^{(I)}_{EXT}(\mathbf{r},t)$ from satellite along-track magnetic field records and to invert this signal, along with ground observatory data, for a 3-D electrical conductivity model $\sigma(\mathbf{r})$ of Earth's mantle. The eventual objective is to interpret $\sigma(\mathbf{r})$ in terms of deep-seated geodynamic processes and to construct electromagnetic images of continental roots, slabs, plumes, etc. that are complementary to seismic tomograms of the deep planetary interior. In this paper, I attempt to provide a fresh perspective of satellite induction based on spatiotemporal analysis which hopefully complements the traditional frequency-domain view that has long been adopted for global induction studies using data from fixed magnetic observatories on the ground.

The geomagnetic field sensed by a magnetometer in low-Earth orbit has several major contributions,

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_M(\mathbf{r},t) + \mathbf{B}_L(\mathbf{r}) + \mathbf{B}_{EXT}(\mathbf{r},t) + \boldsymbol{\varepsilon}(\mathbf{r},t) \,, \qquad (1)$$

where $\mathbf{B}_M(\mathbf{r},t)$ is the main field and secular variation due to core motions; $\mathbf{B}_L(\mathbf{r})$ is the field due to lithospheric magnetization;

$$\mathbf{B}_{EXT}(\mathbf{r},t) = \mathbf{B}^{(P)}_{EXT}(\mathbf{r},t) + \mathbf{B}^{(I)}_{EXT}(\mathbf{r},t) \qquad (2)$$

is the sum of the primary (P) external field, due to time-varying magnetospheric and ionospheric sources, and their corresponding induced (I) portions; and for our purposes $\boldsymbol{\varepsilon}(\mathbf{r},t)$ includes any unmodeled fields along with measurement error. The primary external field $\mathbf{B}^{(P)}_{EXT}(\mathbf{r},t)$ induces electric currents to flow deep inside the conductive Earth which, in turn, generate the induction signal $\mathbf{B}^{(I)}_{EXT}(\mathbf{r},t)$ that is observed at satellite altitude.

EM INDUCTION

EM induction studies in geophysics employ artifical and natural transmitters. In ground-based or airborne applications, it is typical to deploy a loop transmitter. An equivalent natural source of global scale is the storm-time magnetospheric ring current. The vast experience accumulated by EM geophysicists in mining, near-surface and resource exploration-scale applications is relevant to geological interpretation of satellite induction responses since: *(a)* geological heterogeneity appears at all length scales, with a $1/f$ wavenumber spectrum [1] that reveals persistent long-range spatial correlations; *(b)* the underlying electromagnetic diffusion process is invariant under the following scaling: multiplication of $\sigma\omega$ by a factor Λ and length scale by a factor $1/\sqrt{\Lambda}$, where ω is frequency.

The challenge for satellite induction geophysicists is familiar: to interpret Earth's EM response in the presence of such a spatially rough geological signal. The geological factors that shape this response recently have been discussed in the context of controlled-source excitation [2]. Percolation theory, for example, is often invoked to explain the EM response of conductive networks. A key concept in percolation is the existence of a critical element that spans otherwise unconnected clusters (Fig. 1.) Field evidence [2] indicates however that the presence of critical elements has little impact on the overall EM induction response.

Instead, the EM response is determined to a large extent by the self and mutual inductances of the conductive clusters shown in Fig.1. In this viewpoint, subsurface geology should be conceptualized as a heterogeneous sea of flux-coupled LR circuits. As an elementary example, consider the Geonics EM63 (time-domain metal detector) signature of a single ring of copper wire [2]. The response of an intact ring is strong but that of a cut ring, which is essentially an open circuit, vanishes. Continental-sized LR circuits of relevance to satellite induction interpretation are formed by the ocean/continent distribution, subducting slabs, mantle plumes, orogenies, volcanic belts and so forth. For example, a subducting slab could form an open LR circuit depending on its fate at the mantle transition zone. In that case, a subducting slab would be difficult to detect by a satellite-borne magnetometer.

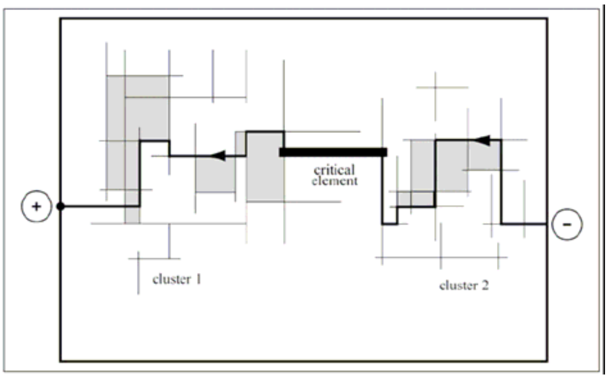

Figure 1. A critical element in a percolating network, from [2].

THE SQ SOURCE

The most significant external ionospheric source is the Sq current system at ~100 km altitude. The Sq currents cause the regular daily geomagnetic variation, or geomagnetic tide, that is observed at ground stations. Two sun-stationary Sq current vortices, one in each of the sunlit northern and southern hemispheres, are driven by solar extreme ultraviolet (EUV) radiation. The nightside ionosphere is comparatively quiet. The conductive Earth rotates beneath the Sq current vortices. In this way, the Sq source acts as an EM transmitter that is on in the daytime and off at night.

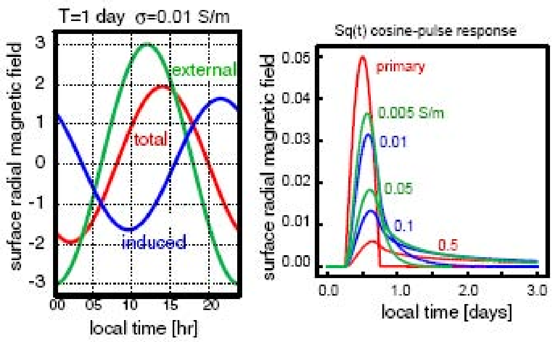

Figure 2.(a, left) Normalized Sq response of a uniform sphere in the frequency domain. (b, right) Normalized Sq cosine-pulse responses in the time domain, for uniform spheres of various conductivities.

There is considerable day-to-day variability in the strength of the Sq current system. It is traditional in geomagnetic field modeling to assume that the external ionospheric field is modulated by the daily solar F10.7 cm radio flux. However, recent satellite EUV measurements [3] reveal important differences between solar EUV and radio frequency fluences. A more accurate description of the external ionospheric field would therefore be achieved if the F10.7 index could be replaced, if available, by some satellite-derived EUV index. This has not yet been done but should lead to a much better estimate of the corresponding Sq induction response.

The Sq inductive response is usually estimated in terms of T=1 day time harmonics. The amplitude and phase of Earth's response depends on the mantle electrical conductivity distribution (Fig.2*a*). However, the Sq source is not well-modeled by a time series of superposed diurnal harmonics. It is perhaps more appropriate to model the time-varying Sq(t) source seen at ground stations as the positive half of a cosine pulse that rises in the morning, peaks around noon, diminishes during afternoon, and essentially vanishes between dusk to dawn (Fig 2*b*). An elementary computation reveals that robust induced currents are energized during afternoon and evening and are still circulating within the conductive Earth when the next pulse arrives the following day. As such, it could be advantageous to look for the Sq induction signal, directly in the time domain, as the satellite passes through local dusk into the externally-quiet night time sector.

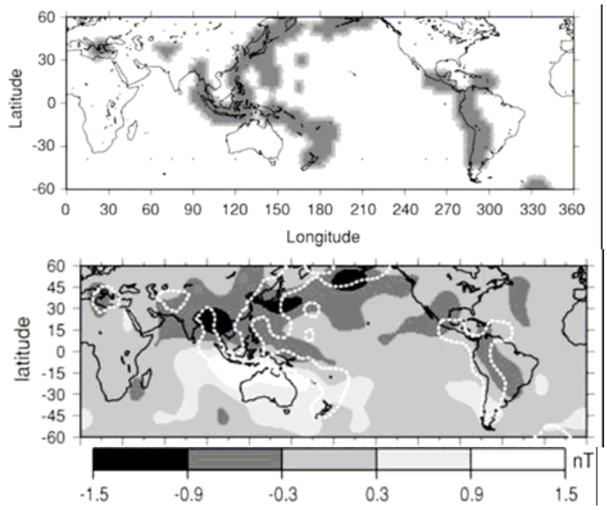

Figure 3.(top) Global distribution of subducting slabs. (bottom) Computed Sq induction response, in particular the magnetic Z-element at local noon, of slabs at period T=1 day. From [5].

In order to extract the Sq induction signal from satellite magnetometer records, we must recognize its signature in the residual data, after main field and lithospheric field removal. It is known that the regular daily variation seen at ground stations on quiet days responds primarily to the Sq source. Identification of quiet days is problematic, but fortunately multi-year local-time stacking [4] helps to suppress irregular daily variations and storm-time disturbances. The stacked Sq signals at individual ground stations then can serve as templates which, after upward continuation to satellite altitude, may be usefully compared to along-track satellite records, particularly at night time. High coherence between the satellite along-track data and the upward-continued Sq templates would be indicative of the sought-after Sq induction signal.

Interpretation of the Sq induction signal in terms of 3-D mantle conductivity shall require forward modeling. Several authors have developed 3-D forward codes that solve EM induction problems in a heterogeneous sphere. For example (Fig.3), the simulated Sq induction frequency-domain response to a realistic distribution of subducting slabs in the mantle is provided in [5]. The Sq response of a 3-D heterogeneous Earth has also been simulated directly in the time domain [6].

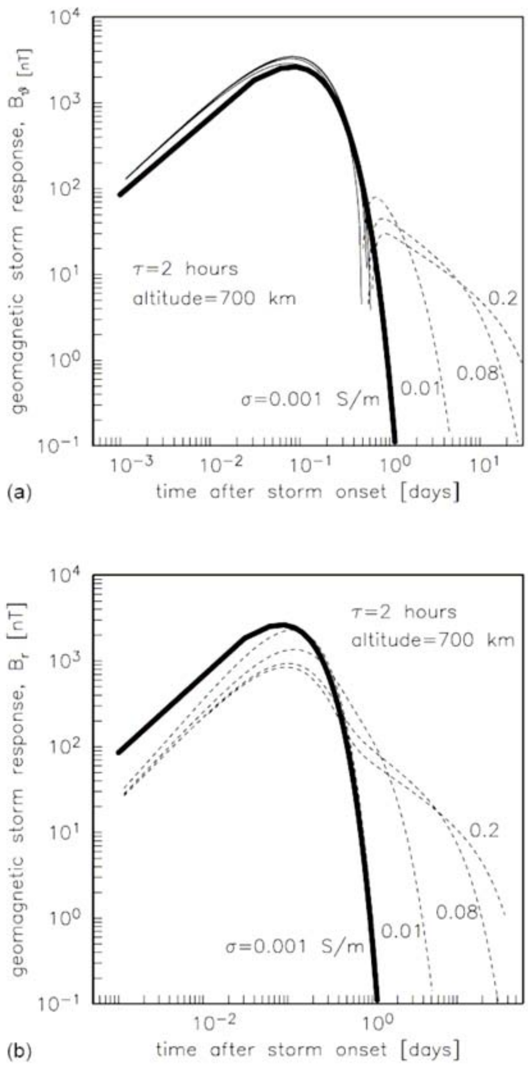

Figure 4. Effect of Earth conductivity, assuming a uniform sphere, on Dst transient magnetic fields (a) southward $B_\theta(t)$ *and (b) vertical* $B_r(t)$ *measured at satellite altitude during a simulated geomagnetic storm, from [8].*

THE DST SOURCE

The chief external magnetospheric source relevant for satellite induction studies is the ring current at 3-4 Earth radii that persists through geomagnetic quiet times but can become greatly energized during storms. The strength of the ring current, which is concentrated near the geomagnetic dipole equator, is estimated using the Dst index.

Recent work based on CHAMP data [7] has revealed a local-time dependence of Earth's long-period induction response. This result is consistent with a non-axisymmetric ring current, or else magnetotail currents organized in a coordinate frame that is tied to the Earth-Sun line. In either case, Earth's rotation will yield an apparent daily geomagnetic variation of magnetospheric origin at ground stations. This effect could have a significant impact on Sq induction studies, which typically attribute daily variation to an ionospheric source.

A simplistic model of a geomagnetic storm involves a rapid switch-on of a symmetric ring current lasting a few hours followed by a slow exponential decay of several days. It is traditional in geomagnetic induction studies to use such a simplified, although unrealistic, description of the external source. The time-variation of ring current intensity in this viewpoint is given by

$$I(t) = I_0 \, t^{\alpha} \exp(-t/\tau) \, u_0(t) \,, \qquad (3)$$

where $u_0(t)$ is the Heaviside step function. The spatial form of Dst ring-current excitation is typically a $P_1^0(\theta)$ zonal harmonic expressed in geomagnetic dipole coordinates.

Closed-form transient solutions based on equation (3) for ring-current geomagnetic induction in a uniform sphere, and two eccentrically nested spheres, are provided in [8]. The results indicate that the electrical conductivity of the uniform sphere (Fig.4) strongly affects satellite induction responses during the late-time storm recovery period. Furthermore, Fig.4 shows that the early time vertical magnetic field is reduced in amplitude compared to the primary exciting field (heavy line) while the southward magnetic field is enhanced. The nested sphere anomalous induction response, shown in [8], is significant only during the late-time storm recovery period. This suggests that there is no early-time (storm-buildup period) induction signature of a mantle conductivity heterogeneity at satellite altitude.

As in Sq induction studies, several authors have developed forward modeling codes which can evaluate the global EM response of a heterogeneous sphere to simplified Dst excitation. For example, the code described in [9] performs a 3-D finite element analysis using a Coulomb-gauged potential formulation of the governing diffusive Maxwell equations. A near-surface conductance map which describes the conductivity-thickness product of the oceans and sedimentary basins overlying crystalline basement is a typical component of the forward model description.

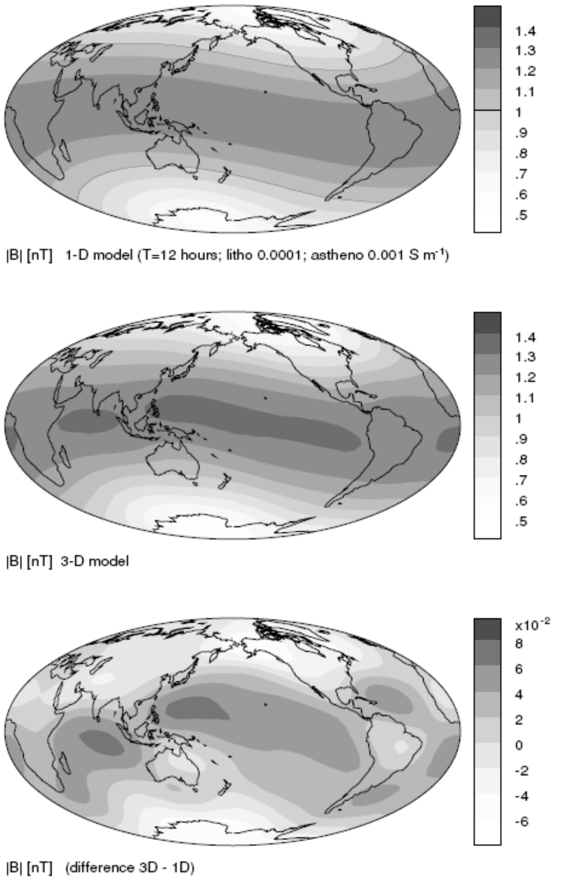

*Figure 5. Dst magnetic intensity |**B**| induction response at period T=12 h. The conductivity model includes (top) a 1-D mantle only; (middle) a 1-D mantle and the near-surface conductance map. (bottom) The difference between top two plots. From [9].*

The Dst source generates an induction response that contains power at higher spherical harmonics than the $P_1^0(\theta)$ excitation field due to the spatial heterogeneity. An example of this is shown in Fig.5. Notice that the resistive continents generate a strong response that can be distinguished from that of the low-latitude oceans. Several studies [e.g. 10,11] have modeled the Dst induction response of lateral conductive anomalies buried in the mantle beneath the near-surface conductance layer.

The study in [11] generated a 3-D mantle distribution of electrical conductivity based on global seismic tomography and mineral physics. The 3-D time domain EM response at satellite altitude 400 km, driven by the Dst index associated with a 1979 geomagnetic storm, was computed. The results of analyzing several strong storms in this way indicated that the large electromotive force generated by the $\partial B/\partial t$ that is associated with sudden storm onset can drive induced currents deep within the mantle. During the recovery period of a strong storm, lateral mantle structure may be resolved since the induced currents flow mainly beneath the heterogeneous near-surface conductance layer that is associated with the ocean and continent distribution.

Inversion of CHAMP satellite magnetometer data for a 1-D mantle conductivity distribution is a topic of much current research interest [12,13]. The study in [12] involved a 1-D time domain inversion of CHAMP storm-time data, using 11 storm events from 2001-2003. The inversion result is based on a track-by-track spherical harmonic fit to external+induced magnetic X and Z elements observed by CHAMP. The 3-D forward modeling code was driven using the observed $X(t)$ as a boundary condition; the 1-D conductivity model was then adjusted to fit the observed $Z(t)$.

The procedure outlined above generated a best mantle electrical conductivity profile $\sigma(z)$ that shows a large increase at ~900 km depth. A conductivity jump at ~660 km, as suggested by seismic imaging and associated with the transition from spinel to perovskite mineral structure, is neither required nor completely ruled out by CHAMP storm-time data. An earlier study [14] of *magsat* data, in the frequency domain, also suggests that the major conductivity jump occurs within the mantle at a depth that is some 200-300 km deeper than 660 km. The CHAMP 1-D frequency domain inversion result in [13] is formulated in terms of a smooth conductivity profile $\sigma(z)$ within the mantle, so it is difficult to compare to the layered profiles in [12,14]. It is tempting to evaluate the deep conductivity jump suggested by inversions of satellite induction responses in terms of post-perovskite mineral phase transitions in the lower mantle, but this association has not yet received serious consideration.

DISCUSSION

Extracting the Sq and Dst induction responses from low-Earth-orbiting satellite magnetometer data is extremely challenging. The long history of surface EM geophysical prospecting methods indicates that subsurface geological structure, with its length-scale-dependent heterogeneity and persistent long-range correlations, generates an EM response that is characterized by a $1/f$ wavenumber spectrum. The observed EM response cannot be viewed as the response of a simple piecewise-constant or smooth conductivity profile, overlain by random noise. Furthermore, conventional interpretations of the EM response based on the connectivity of conductive networks that emerge from percolation theory needs to be re-visited since field experiments and basic physical arguments indicate that the EM induction response is consistent with that of a heterogeneous sea of magnetic flux-coupled LR circuits.

In the long term, the eventual aim of satellite geomagnetic induction is to perform 3-D inversions of low-Earth orbiting satellite magnetometer data to map 3-D electrical conductivity distribution of the mantle and to compare with global seismic tomographic images. There are certain advantages to performing this work directly in the spatiotemporal domain, i.e. by performing track-by-track fits instead of estimating frequency-domain response functions.

There are now several 3-D frequency-domain and time-domain forward codes available for EM geomagnetic induction in a heterogeneous sphere. Many simulation studies have been carried out and published in the literature. Time-domain and frequency-domain 1-D inversions of *magsat* and CHAMP data have been performed. The layered models that have been generated are suggestive of a deep conductivity jump in the lower mantle some 200-300 km below the seismic and mineralogical transition from spinel to perovskite at 660 km.

The traditional sources are the simplified Sq ionospheric and Dst magnetospheric currents. To properly isolate the Sq quiet-time induction signal from satellite data, better descriptions of EUV day-to-day variability and apparent geomagnetic daily variations generated by non-axisymmetric currents are required. The latter is also important in analyzing Dst induction signals during storm times. It shall also be necessary to resolve ambiguities in geomagnetic field models between lithospheric magnetization and external source variations.

I would characterize progress to date in satellite geomagnetic induction as slow but steady and generally very encouraging. The estimation of 3-D mantle conductivity $\sigma(\mathbf{r})$ based on analysis of the induction signal $\mathbf{B}^{(I)}_{EXT}(\mathbf{r},t)$ has been designated as a primary research focus of the upcoming *swarm* mission. The multi-satellite *swarm* constellation is well-suited to the task [15]. I expect that satellite geomagnetic induction studies willprobably start to receive considerable attention in the upcoming years.

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