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"Toward an improved source model for satellite induction studies"

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Abstract

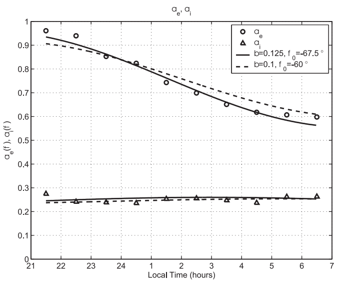
The traditional approach to estimation of the electrical conductivity of Earth's mantle is based on interpretation of ground-based observatory recordings of geomagnetic variations of external origin on time scales from hours to months. This approach has a serious inherent limitation: the global distribution of magnetic observatories is irregular and sparse, leaving large areas of the Earth (especially the ocean basins) unsampled. Recent magnetic satellite missions, such as Ørsted, CHAMP, and SAC-C provide nearly complete global coverage, and thus offer exciting possibilities for new insight into 3D patterns of mantle conductivity. Electromagnetic induction studies with satellite data have usually assumed a symmetric magnetospheric ring current source. However, there is growing evidence for significant source asymmetry. Recently, Balasis and Egbert (2006) using observatory magnetic data show clear evidence for large scale non-dipole source structure. The observed asymmetry agrees with that inferred previously by Balasis et al. (2004), from the local time dependence of biases in CHAMP satellite induction transfer functions. Furthermore, Vennerstrom et al. (2007) found that the long-distance effect of the high-latitude field aligned currents constitutes the major source to external magnetic field related magnetic east-west disturbances at mid- and low latitudes. The development of a current source model of the magnetosphere and ionosphere based on the aforementioned results would be suitable for purposes of global induction studies with measurements from the foreseen ESA's Swarm mission. Progress on this effort will be reported.

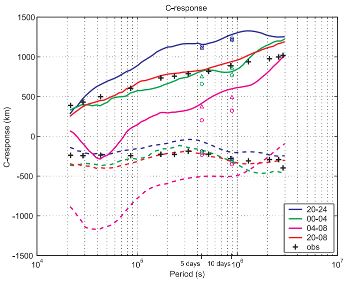
Introduction

The current satellite magnetic missions offer new opportunities to determine the electrical conductivity of the Earth. However, satellites are nearly stationary in local time (LT) and therefore sample the inducing and induced fields quite differently than geomagnetic observatories, which rotate with the Earth. Balasis et al. (2004) showed that estimates of induction transfer functions (TFs) obtained from CHAMP magnetic data under the traditional symmetric magnetospheric ring current source (Y_0^1) assumption depend systematically on LT, suggesting that source fields contain also a coherent nonaxisymmetric component. An extended magnetospheric source model that incorporates a coherent nonaxisymmetric quadrupole (Y_2^1), and allows for Earth rotation qualitatively explains the observations.

Although satellite electromagnetic induction studies have usually assumed a symmetric magnetospheric ring current source, there is growing evidence for significant source asymmetry. Balasis and Egbert (2006) applied empirical orthogonal function methods to mid-latitude night-side hourly mean geomagnetic observatory data to search for evidence of nonzonal low-frequency source fields. The dominant spatial mode of variability in residuals, obtained by subtracting symmetric ring current and ionospheric fields of the CM4 comprehensive model, has a substantial Y_2^1 quadrupole component and is highly correlated with D_{st}. This pattern of temporal variability, which implies enhanced ring current densities in the dusk sector, persists even when peak storm-time data are omitted. The observed asymmetry agrees with that inferred previously by Balasis et al. (2004), from the LT dependence of biases in satellite induction TFs. Temporal correlation of the leading mode with D_{st}, and consistency of its spatial structure with recent empirical ring current models, suggest a magnetospheric origin.

Local time effects in CHAMP satellite estimates of EM induction TFs





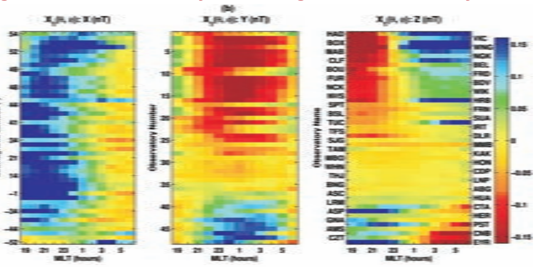
In the frequency domain the internal and external components are related by $g_{10}(\omega)=Q_1(\omega)q_{10}(\omega)$, where $Q_1(\omega)$ is the transfer function for a radially symmetric Earth excited by external sources of spherical harmonic degree 1 and angular frequency ω.

The observed local time dependence of $\alpha_e=q_{10}(t)/D_{st}(t)$ suggests that there are coherent non-axisymmetric components to ring current variations (left Figure).

An extended magnetospheric source model that incorporates a coherent non-axisymmetric quadrupole (Y_2^1), and allows for Earth rotation qualitatively explains the observations (right Figure). This additional term simply accounts for stronger ring current fields on the dusk side compared to the dawn side.

Empirical Orthogonal Function Analysis of Magnetic Observatory Data

EOF # 1 spatial pattern $H_1(\theta,\varphi)$.



Empirical orthogonal function (EOF) analysis reduces a time series of spatial data to a smaller number of time-varying spatial patterns that explain most of the variance in the data. It distributes the total variance in a dataset among a new ranked set of orthogonal patterns composed of combinations of the original variables [Preisendorfer, 1988]. EOF analyses are typically applied to geophysical data in which the original variables are locations at which complete time series of observations are taken

$$H(\theta,\varphi,t) = \sum_k X_k(\theta,\varphi)\,T_k(t).$$

Night side data show clear evidence for coherent large scale asymmetric structure.

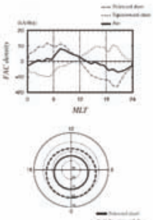
Asymmetric structure is coherent with D_{st}. Asymmetries persist even when storm commencement data are excluded.

Structure described by Y_2^{-1}, but Y_4^{-1} (and some residual Y_1^0) are required to fit spatial patterns of the 1st EOF.

Results are generally consistent with the simple Y_2^1 model of Balasis et al. [2004], and explain bias in satellite estimates TFs.

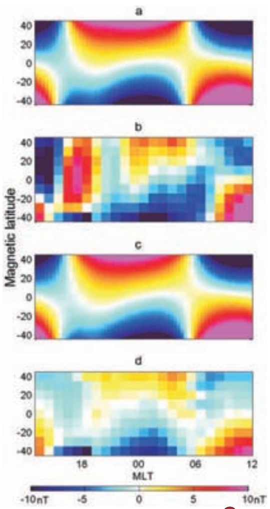
Local time distribution of net field aligned currents

Top: Figure 6 of Nakano and Iyemori [2003]. A possible three-dimensional current system on the basis of their results. In the prenoon sector the downward Region 1 currents exceed the upward Region 2 currents and net downward currents flow there. Those net downward currents should feed the auroral electrojet currents, which flows toward the nightside. In the premidnight sector the upward Region 1 currents exceed the Region 2 currents and net upward currents flow there. These net upward currents are fed by the auroral electrojets from the prenoon sector. In the postnoon and the postmidnight the Region 1 currents almost balance the Region 2 currents. It is believed that the Region 2 currents in these sectors connect with the partial ring current.



Top: Figure 7 of Nakano and Iyemori [2003]. Field-aligned current distribution for the calculation of magnetic effects of low and middle latitudes. The top panel indicates the local time dependence of the field-aligned current density per longitude for each of double sheet currents in this model. The bottom panel indicates the spatial distribution of the field-aligned currents.

Field aligned currents contribution to the mid- and low-latitude magnetic disturbance



Left: Figure 3 of Vennerstrom et al. [2007]. The influence of the IMF Bz-component on the east-west component of the magnetic disturbance at mid- and low latitudes presented as (magnetic latitude, MLT)-maps. (a) Computed perturbation due to statistical FAC pattern for Bz < 0. (b) Observed average perturbation measured by the Oersted satellite for IMF Bz < 0. (c) Computed perturbation due to statistical FAC pattern for Bz < 0 after subtraction of the perturbation due to statistical FAC pattern for Bz > 0. (d) Observed average perturbation for Bz < 0 after subtraction of the observed average perturbation for Bz >

Conclusions

EOF analysis of night-side (18:00–06:00 MLT) mid-latitude (50°S to 50°N) observatory data presents evidence for a significant Y_2^1 quadrupole component in the first mode EOF magnetic fields implying an enhancement of ring current density in the dusk sector, and meridional current on the night-side centered near local midnight.

An independent study of the long-distance effect of the high-latitude FACs gives similar structure for the magnetic east-west disturbances at mid- and low latitudes.

Obviously we need to take advantage of the existing extensive studies of the magnetosphere (e.g., Tsyganenko analytical representation) and ionosphere to guide development of the more realistic source models that will be required for progress in satellite induction studies.

An analytical representation for the disturbance magnetic field produced by the region 2 Birkeland currents and the Partial Ring Current

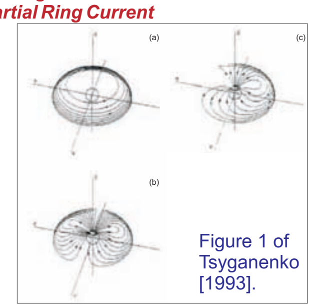


Figure 1 of Tsyganenko [1993].

The net field of the partial ring current (PRC) can be represented by a sum of axially symmetric and quadrupole (two-loop system) terms [Tsyganenko, 1993, 2000]. The axisymmetric ring current (Figure 1a) obviously does not contribute to the azimuthal field variation, which is therefore due solely to the quadrupole part containing Birkeland currents (Figure 1b), whose field decreases rapidly (as ~ r^{-4}) outside the PRC. As can be verified by calculating the contribution of the quadrupole term at different locations in the near magnetosphere [see Tsyganenko, 2000, Figure 14], a PRC with the total magnitude of 0.7 MA produces an asymmetry of 20 nT between the opposite local time sectors in the inner magnetosphere, and the disturbance is almost entirely confined inside the PRC. The resultant configuration (Figure 1c) is given by the sum of the systems (Figure 1a) and (Figure 1b). The current flow lines of the southern hemisphere are not showing in the plots, all the patters being symmetrical with respect to the equatorial plane.

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