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CURRENT SYSTEMS OF LARGE-SCALE GEOMAGNETIC VARIATIONS: EVOLUTION OF MODELING

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Abstract. The magnetic field in the near-Earth space is generated by the current systems, with energy supply directly from the Sun (conductivity), from the interplanetary environment (electric field, plasma), and from the surface layer (dynamo-wind). The rapid progress in modeling the electric fields and current systems responsible for the spatio-temporal distribution of large-scale geomagnetic variations has been made at different Institutes and scientific centers for the last decades. Bright ideas are used to develop new models, to advance the theoretical background, to improve the techniques of calculations. All this refers to the problem of fitting the magnetosphere-ionosphere current systems to the magnetic field observation both on the ground and onboard spacecraft as well as to the inverse problem of reconstructing magnetosphere-ionosphere current systems from geomagnetic data. The research team of the Polar Geophysical Institute of Kola Scientific center of Russian Acadamy of Science has always been an active participant of this activity. Yu. P. Maltsev was one of the leading scientists of the research team. His ideas and proposals were original and had a strong impact on the concept about the sources of Earth's magnetic field variations. We present a review of history and of the present state of the near-Earth current system modeling. At the same time we emphasize the studies by Yu. P. Maltsev, which are the most important for modeling *Sq*-variation of the geomagnetic field, high-latitude variations parameterized by the solar wind and interplanetary magnetic field and the *Dst*-variation during magnetic storms.

The first to model current systems were Yury Maltsev and his team. In the end of 1960s the technique of reconstructing equivalent current systems was the main method of studying current sources of the large-scale geomagnetic variation, that are registered on the basis of ground based observations. Widely used nowadays, this technique allows to construct a simple current system that is located at the height of ionospheric *E*-layer and generates a magnetic disturbance described by specific spatial distribution of horizontal vector. This current system, as equivalent to realistic current system (that in fact produces a specific magnetic variation) is obtained from horizontal vectors of the magnetic disturbance by 90-degree turn clockwise. The well-known equivalent current system of magnetic variation, caused by ionospheric wind system (*Sq*-variation) is modeled as vortices in dayside hemisphere with focuses located close to midday meridian at magnetic latitude about $\pm 30^o$ [*Matsushita, S. and W. H. Campbell,* 1967]. Since quiet daily geomagnetic variations constitute the main type of long-period regular variations, it is important to distinguish them, also for the reason that some of the indices (for example, K-indices) are derived from geomagnetic data by extracting Sq-variations.

Magnetospheric contributions to geomagnetic daily variations have been investigated by several authors: *Mead* noticed some magnetospheric contributions. But "they are found to be small compared to the observed *Sq* fields" [*Mead*, 1964]. Olson showed that the magnetospheric contributions have a variability with UT and season similar to what is observed but also found, however, that the amplitudes are "just less than one fifth" [*Olson*, 1970]. After that he reexamined the magnetospheric role in producing daily variations on the ground and concluded that up to 30% of the observed Sq-variation might be due to magnetosperic ring current and current systems at the magnetopause and the magnetotail [*Olson*, 1989].

In the middle of 1970s *W.Lyatsky* and *U. Maltsev* carried out one of the first calculations of current spreading to the midlatitude and low-latitude ionosphere, caused by high-latitude field-aligned currents. *[Lyatsky and Maltsev*, 1975]. For the first time *W.Lyatsky* and *U. Maltsev* established that generation of *Sq*-variation could be caused by three-dimensional magnetosphere-ionosphere current systems, but not by the ionospheric dynamo-wind. To examine this conclusion some scientific teams began to calculate three-dimensional current systems by using different models of the ionospheric conductivity and original systems of field-aligned currents. As a result, on the one hand, there were distinguished the current systems of high-latitude geomagnetic variations parameterized by the Interplanetary magnetic field and Solar wind [*Feldstein and Levitin*, 1986 and references therein] and, on the other – a geomagnetic variation that is a prolongation of classical midlatitude *Sq*-variation to the high-latitude ionosphere [*Levitin et al.,* 1982 and references therein]. In the next papers of *Yury Maltsev* and *W. Lyatsky* in this research area, the nature of these variations was described and the parameters of formation and decay of current systems, parameterized by Solar wind, were determined. The results of their studies allowed to explain such important phenomena as electric current system in high latitudes, the polar wind, the plasmosphere and the main ionospheric trough, the current above the auroral arc and the existence of the arc itself, the behaviour of both natural and artifical geomagnetic pulsations were described in monograph [*Lyatsky and Maltsev*, 1983] that became the manual course for all soviet geophysicits. In this monograph it was considered that basic processes lie at the basis of magnetosphere-ionosphere interaction: the transfer of electromagnetic fields from one region into another, the diffusion exchange of cold plasma and the precipitation of energetic particles from the magnetosphere into the ionosphere.

Yury Maltsev made an important contribution to studying of the geomagnetic field *Dst*-variation. Models of the geomagnetic field in the magnetosphere are the basis for numerous studies of the energetics, topology and dynamics of the large-scale structure of the magnetosphere. Because of both the significance of such field models and the versatility of their applications, the choice of a proper model is exceptionally important. Models must be verified by comparisons with observations. These comparisons reveal geophysical conditions, under which some models describe magnetic fields in the magnetosphere more precisely than others. The studies of magnetic field variations and their structure in the inner magnetosphere during magnetic storms is becoming most intriguing. The drifts of energetic particles within this region produce intense ring currents leading to a significant deformation of the dipole geomagnetic field. Storm time radiation belts are formed. Charged particles that make up the radiation belts are energized and then dissipated in the upper atmosphere. Dynamical models that more accurately describe the inner magnetosphere, especially during stormy periods, are needed in view of ongoing rapid expansion of human activities into the near-Earth space. When constructing dynamical magnetic field models and calculating the energy budget for the magnetosphere and its basic structural parts for particular events, the set of parameters that define the characteristics of the magnetic field model should be based upon available observations. For example, the time-spatial features of the dynamical magnetic field model are directly associated with both the current intensities, which generate variability of this field, and the location of currents in the magnetosphere. The structure of the magnetic field in the magnetosphere depends substantially on the location and intensity of the magnetospheric tail current. The present understanding of the contribution of the tail currents to the near-Earth magnetic field during magnetic storms is discussed in fundamental reviews. These reviews were prepared by teams of authors citing results presented at international scientific conferences held during recent years. *Gonzalez et al.* [1994] evaluated the contribution of different sources (ring current, magnetopause currents, introduced currents in the solid Earth) to the Dst-variation. They stated: "Other possible contributions to from additional currents (ionospheric, field-aligned, tail currents etc) have not been quantified as yet". In the extended review by *Kamide et al.* [1998], which covers a wide range of ideas regarding magnetic storms, the currents as one of the sources of magnetic fields in the magnetosphere are not considered at all. During the magnetic storm, *Kamide et al.* estimate the Dst-variation of the magnetic field but do not even mention the contribution of tail currents to the Dst field formation. In the review by *Daglis et al.* [2003] only mentioned that during substorms the intensification of the near-Earth magnetotail current can modify the geomagnetic variations recorded at midlatitude observatories. The contribution of the magnetotail current system to the *Dst*-variation during the main phase of magnetic storms has been consistently neglected. Variations of *Dst** (corrected *Dst*-index) are described fully as a sum of symmetric and asymmetric parts of the ring current field only.

Yury Maltsev was the first scientist who caught sight of the fact that the magnetotail current system influence on *Dst*-variation could exceed the ring current influence [*Maltsev et al.*, 1996 and references therein]. Later the authors of Paraboloid model of the magnetospheric magnetic field obtained the same result [*Alexeev et al.*, 1996; Feldstein et al., 2005 and references therein]. It is usually believed now that Dst is a superposition of the magnetic fields due to the current on the magnetopause (DCF), ring current (DR) and magnetotail current (DT). The relative contribution of these sources to the *Dst*-variation during the storm main phase is a topic for lively scientific discussions today. A range of different views on the importance of magnetotail currents has recently been expressed in the literature. *Alexeev et al.* [1996] propose an approximately comparable contribution of DR and DT to the *Dst*-variations. According to *Turner et al.* [2000] and *Baker et al.* [2001], there is only a 25 % contribution of DT to *Dst* during magnetic storms. On the other hand, *Liemohn et al.* [2001a] and *Kozyra et al.* [2002] reported a strong agreement between modeled DR and observed *Dst* fields, which implies a minimal (even no) contribution of DT to *Dst* at the maximum of the storm main phase. Such a diversity of results is a consequence of using different magnetic field models, on the one hand, and of using different methods to identify the boundary in the inner magnetosphere between the magnetotail current (which produces the DT contribution) and ring current (which produces the DR contribution), on the other hand. This inner boundary of the magnetotail current is located at 3.5–4.0 *Re* [*Alexeev et al.*, 1996; *Maltsev et al.*, 1996], 6 *Re* [*Turneret al.*, 2000], and outside of geosynchronous distance at 6.6 *Re* [*Liemohn et al.*, 2001a, b;*Kozyra et al.*, 2002]. In addition, there are differences in the representation of the ring current that contributes to magnetic field asymmetry and distortion in the inner magnetosphere. Models by Alexeev, Maltsev and Tsyganenko 89, used by *Turner et al.* [2000], do not divide the inner magnetospheric current into separate parts as symmetric and asymmetric ring currents.

In RAM model [*Liemohn et al.*, 2001a, b; *Kozyra et al.*, 2002] the partial ring current is a major source of the magnetic field and energy in the inner magnetosphere. During a magnetic storm the inner edge of the plasma sheet shifts earthward in response to strong convection electric fields. Plasma sheet populations move along open drift paths deep into and through the inner magnetosphere accessing the dayside magnetosphere. During the course of these drifts, plasma sheet particles are adiabatically accelerated to ring current energies and form a partial ring current. The divergence of current on open drift paths injects current into the ionosphere on the dusk side and draws current out of the ionosphere near-midnight. According to the RAM model during storm main phase when the convection electric field is strong, the bulk of the ring current ions is moving along open drift paths and therefore the main part of the energy in the ring current is contained in the partial ring current. During a storm recovery phase, when the IMF *Bz* turns northward and the convection weakens, open drift paths are converted to closed ones and the symmetric ring current develops within a region and an energy range where electric field drifts become small compared to gradient and curvature drifts [c.f., *Liemohn et al.*, 2001b]. Higher energy particles, whose magnetic field drifts significantly exceed electric field drifts, do not have convective access from the plasma sheet to the inner magnetosphere but move along closed drift paths that encircle the Earth. However, fluctuations in the large-scale electric and magnetic fields cause these particles to diffuse inward slowly building the high energy tail of the ring current over the course of the storm. The region of the magnetosphere where high energy particles move on closed drift paths without encountering the magnetopause is called the trapping region. The location of the trapping boundary, enclosing this region, depends on particle energy. During a storm recovery phase and magneto-quiet times, when the partial ring current is weak or absent, the boundary between the magnetotail currents and the symmetric ring current flowing within the trapping region should be relatively easy to identify. During the storm main phase when the bulk of the ring current energy is contained in the partial ring current topologically connected to the magnetotail along open drift paths, the transition between magnetotail-like currents that close through the magnetopause and the partial ring current that closes through the ionosphere is more difficult to define. Both the partial ring current and the innermost part of the magnetotail current are located near the plasma sheet inner boundary.

The main difference in topology between the magnetotail and partial ring currents is that the partial ring current closes through the ionosphere and the tail current closes through the magnetopause. There are regions in the inner magnetosphere where a portion of the current closes through the ionosphere and a portion continues moving outward until it encounters the magnetopause and closes. This ambiguity may contribute to the discrepancy in estimate of the relative contributions of magnetotail and partial/symmetric ring current to the *Dst*-index during storms. An important feature of the topology of the magnetotail currents in the Paraboloid Model (PM) is the closure of the inner portion of the magnetotail current through the dayside magnetopause. It is connected with the assumption in the PM that magnetic field lines of the magnetotail currents close inside the magnetosphere. This has important consequences for the location of the magnetopause and for the relative contributions of the magnetotail and magnetopause currents to the *Dst* index. Several major magnetic storms were simulated with the result that DT reached values that were a significant fraction of DR in all cases. These latest results by *Tsyganenko et al*. [2003] on the relative magnitude of the contributions of DT and DR to the *Dst* disturbance of the geomagnetic field are consistent with significantly earlier statements by *Maltsev et al.* [1996].

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