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VIRTUAL MAGNETOGRAMS – NEW TOOL FOR THE STUDY OF GEOMAGNETIC RESPONSE TO THE SOLAR WIND/IMF DRIVING

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Abstract. Processes of the solar-wind/magnetosphere interaction are commonly monitored by magnetic records on the ground. However, a serious drawback of the analysis of ground-based magnetograms is the inevitable variation of the magnetic response due to continual changes of the station location. An ideal, but impossible, solution of this difficulty that would help to discriminate temporal and spatial variations is the deployment of a "stationary" observatory with a fixed position in the solar-magnetospheric coordinate system. The desired result can be obtained with the proposed technique of "virtual magnetogram" (VM). This technique has been implemented for key magnetospheric domains (midnight auroral and dayside cusp regions) as an additional tool for monitoring the response of the geomagnetic field to solar wind and IMF forcing. VMs for a fixed reference system are reconstructed by 2D fitting and interpolation of 1-min data from world-wide distributed magnetic stations. A wide range of space physics studies, such as substorm physics, solar wind-ionosphere interaction, dayside-nightside coupling, sawtooth oscillations, etc. will benefit from the introduction of the VMs. The database of calculated VMs, as well as simultaneous interplanetary parameters and geomagnetic indices, are freely available via the site *http://vm.gcras.ru/* for all interested researchers for testing and validation.

1. Introduction

The interaction between the solar wind (SW), interplanetary magnetic field (IMF), and the terrestrial magnetosphere is the main driver of many processes occurring in the near-Earth environment. Progress in monitoring time-varying processes in space physics is hampered by the lack of convenient tools for their analysis. A trend started in the geomagnetism to transfer from the studying L2 data only (calibrated data from a single instrument) to examination of L3 products (models based on data from global magnetometer array). An example of L3 products recently introduced in the geomagnetism is new geomagnetic indices: SMU/SML/SME auroral electrojets strength (*http://supermag.jhuapl.edu*), IMAGE electrojet indicators (*http://space.fmi.fi/image/www/*), ULF wave power (*http://ulf.gcras.ru*) [*Pilipenko et al.*, 2017], and global maps of geomagnetic disturbances [*Weimer et al.*, 2010].

Images of processes of the SW/magnetosphere interaction can be monitored by time-series of magnetic records on the ground. However, a serious drawback of the analysis of ground-based magnetograms is the inevitable variation of the magnetic response due to continual changes of the station location regarding the direction of the SW flow. An ideal, but impossible, solution of this difficulty would be the deployment of a "stationary" observatory with a fixed position in the solar-magnetospheric coordinate system. This will help to discriminate temporal and spatial variations.

The desired result can be obtained with a "virtual" magnetometer suggested in this paper. A database of virtual magnetograms (VMs) for the ionospheric projections of key magnetospheric domains, such as the dayside cusp and midnight auroral oval, will facilitate enormously the quick-look analysis, event selection, and study of the ground response to various space weather events. The VM database will be an effective and simple tool complementary to advanced modeling technique for investigations of the ionospheric response to SW/IMF variations. Here we present several examples of the VMs for some space weather events.

2. Algorithm of the Virtual Magnetogram Construction

VM for ionospheric projections of key magnetospheric domains with fixed latitude/MLT coordinates is reconstructed from the data of world-wide array of magnetic stations: INTERMAGNET, Greenland Coastal Chains, MAGDAS, MACCS, IMAGE, and CARISMA. A magnetic disturbance in a selected "virtual" site is reconstructed by 2D fitting and interpolation of 1-min magnetograms from world-wide distributed magnetic stations. This algorithm has been used to generate VMs at the following locations:

a) at noon (MLT=12) for cusp latitudes $\Phi_o=70^o\pm10^o$;

b) at midnight (MLT=0) for auroral latitudes $\Phi_o=65^o\pm5^o$;

The base line - a value at 00 UT for each day, has been subtracted from the raw data.

To estimate a magnetic disturbance in a pre-selected "virtual" site the algorithm of averaging with weight coefficients has been used. From available observatories those are chosen that are within the pre-selected latitudinal range. Then, 3 nearest observatories to a given MLT are selected. Finally, the current VM amplitude $A_0(t)$ is calculated as follows

$$A_0=\sum_{i=1}^{3} A_i d_i \Big/ \sum_{i=1}^{3} d_i \qquad\qquad d_i^{-1}=\sqrt{(MLT_i - MLT_0)^2+(\Phi_i-\Phi_0)^2}$$

where $A_i=\{X,Y\}$ is amplitude at "virtual" site (i), d_i is the weight coefficient depending on the MLT/latitude difference between the "virtual" site location and a particular station.

The reconstructed VMs are written in output ASCII files x_ddmmyy.mgn, y_ddmmyy.mgn, and plotted and saved in graphic file. To facilitate an analysis, besides two VMs for noon and midnight, the SW/IMF parameters, and geomagnetic indices (SYMH, AE, PC) are added and plotted. VMs have been calculated separately for the Northern and Southern hemispheres.

3. Examples of VM for various space weather events

As a validation test, the derived VMs have been presented, on a case by case basis, for the following types of the space weather events:

- substorm activations during a magnetic storm;
- the response of the dayside near-cusp ionosphere current system to IMF variations;
- sawtooth oscillations.

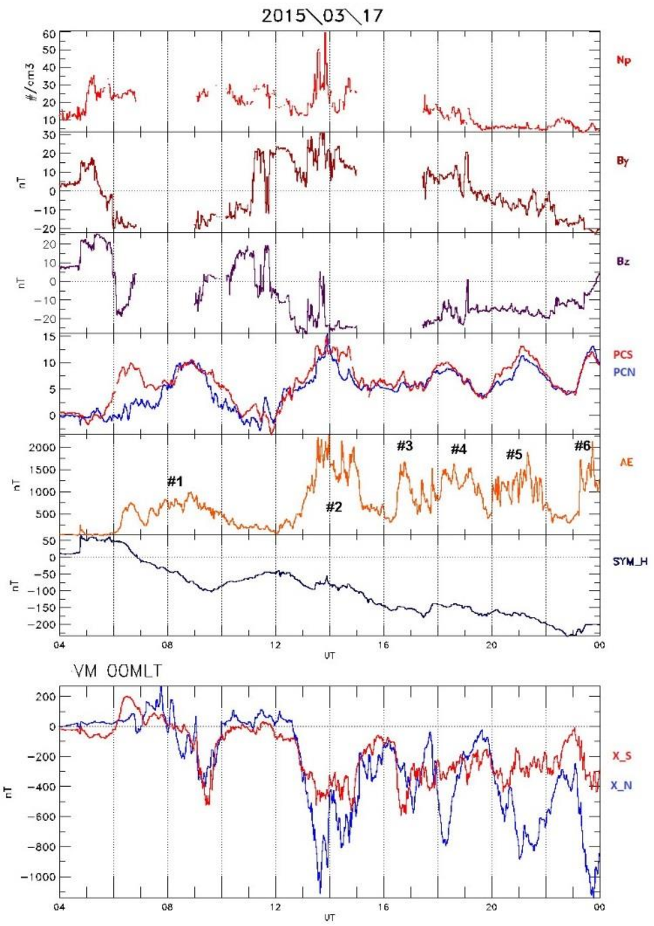

Figure 1. The space weather parameters (Np, IMF By, IMF Bz, PCN/PCS indices, AE-index, SYMH-index, and the midnight virtual magnetograms (X-component) of geomagnetic response for the Northern ($\Phi = 65^o \pm 5^o$, *blue line*) and Southern ($\Phi = -(65^o \pm 5^o)$, *red line*) hemispheres during the storm main phase 04-24 UT, March 17, 2015. All substorm activations are marked by numbers.

3.1. Substorm activations during magnetic storm

The "St. Patrick's day" geomagnetic storm on March 17, 2015 (day 076) was initiated by an interaction between high-speed SW streams in corotating interaction region (CIR) and two coronal mass ejection (CME). An interplanetary shock preceding the CME arrival was detected at ~0445 UT, March 17. Rapid and intense increase of Np up to ~40 cm^{-3} occurred on ~05 UT (Fig. 1). The storm main phase followed after the IMF Bz southward turning at ~06 UT. The IMF Bz stayed strongly southward around -20 nT for a prolonged period which caused a very gradual storm growth lasted for ~17 hours.

The long main phase shows a series of bursty intense enhancements, as can be seen from the AE-index increases above 2000 nT, associated with a more or less isolated substorms. The VM confirms the occurrence of 6 auroral activations (Fig. 1, bottom panel). Moreover, VM provides a more detailed fine structure of the substorm activity and more clearly indicates onsets of each substorm. For the substorm #1, VM shows the occurrence of two substorms which is hard to distinguish from AE index data only. This splitting into two substorms during 06-11 UT time interval is especially evident from the VM for the Southern hemisphere.

3.2. Response of dayside ionosphere current system to IMF variations

Extensive studies with global arrays of magnetometers involved showed that dayside ionospheric convection and current systems at high latitudes are driven by the IMF variations. This effect can be clearly seen with VM technique (Fig. 2) for the event of April 27, 1995. Comparison of IMF Bz variations with the VM (X-component) at noon confirms that the dayside high-latitude ionospheric convection and magnetic response are indeed controlled by quasi-periodic variations of the IMF (bottom panel).

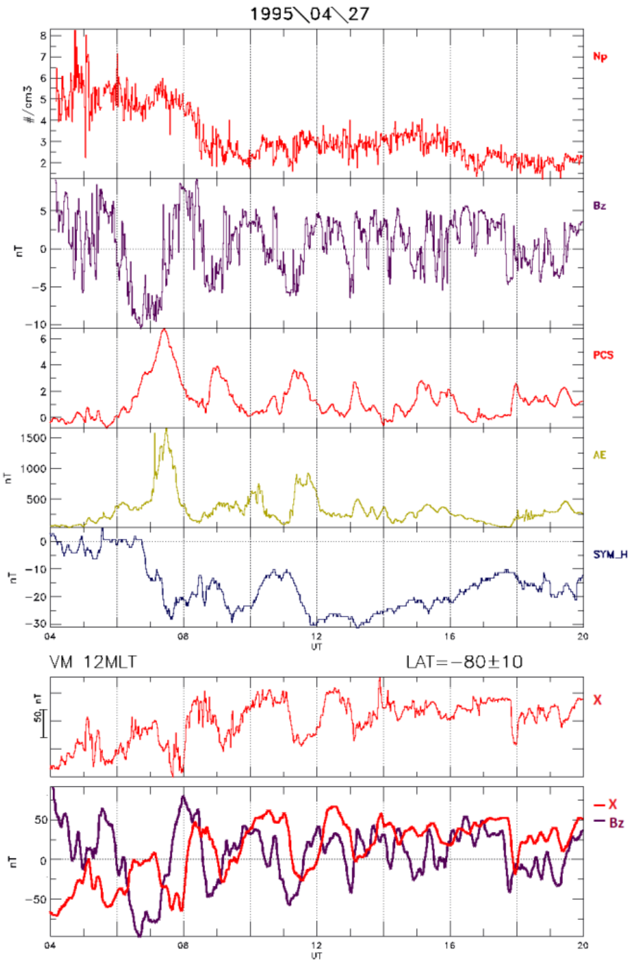

Figure 2. VM technique for the event 1995/04/27. The space weather parameters: Np, IMF Bz, PCS index, AE-index, and SYMH-index are given in panels 1-5. The noon VM (X-component) of geomagnetic response for the Southern (Φ = -(80°±10°), *red line*) hemisphere is shown in 6-th panel. Comparison of the smoothed IMF Bz variations with the noon VM has been added at the bottom panel.

3.3. Sawtooth event

Besides substorms, the magnetosphere response modes include sawtooth events, which share common features with isolated substorms. A sawtooth event consists of a series of gradual decrease and rapid increases in energetic particle flux at geosynchronous orbit (i.e., particle injections), while an isolated substorm has one variation cycle. In fact, sawtooth oscillations are a sequence of storm-time substorms, when nearly simultaneous energetic particle flux enhancements and magnetic field variations occur at all MLTs for each sawtooth cycle. It was suggested that the sawtooth oscillations are directly driven by series of SW pressure enhancements, whereas even a modest dynamic pressure enhancement can result in significant changes in the magnetosphere when the IMF stays strongly southward for a long interval [*Lee et al.*, 2004]. Alternatively, it was suggested that the sawtooth oscillations are a repetitive internal magnetospheric response with an intrinsic occurrence periodicity of 2–3 hours to sustained enhanced SW energy input.

The standard plot from the VM database for the event of Oct. 14, 2000 (Fig. 3) clearly reveals the quasi-periodic character of the nightside magnetosphere response during this sawtooth event. An analysis of one combined VM is far more easy than the standard analysis of numerous magnetograms from a global array of stations with unavoidable time-space ambiguity.

Conclusion

We have developed a provisional database (of L3-type) of "virtual" 1-min magnetograms for two fixed locations: noon and midnight meridian at typical cusp and auroral latitudes, using the data from worldwide magnetometers. Several examples demonstrated here are intended to demonstrate that the usage of pre-calculated VMs significantly facilitates the quick-look selected and analysis of space weather events. This technique might be useful to reveal a quasi-periodic response to IMF/SW discontinuities [*Murr and Hughes*, 2001], dayside-nightside coupling [*Pilipenko* *et al.*, 1998], triggering and precursors of substorms [*Yagova et al.*, 2000], sawtooth events [*Lee et al.*, 2004], etc. In particular, the VM technique provides a possibility to reveal more fine structures of substorm evolution than ordinary AE or PC indices. Here we deliberately do not discuss any physical conclusions, because our main goal is to present new tool for the event selection and analysis, and to discuss its possible application with geophysical community. Database of VM is uploaded for validation and testing to the site *http://vm.gcras.ru/*. Any comments, suggestions, and criticism are welcomed.

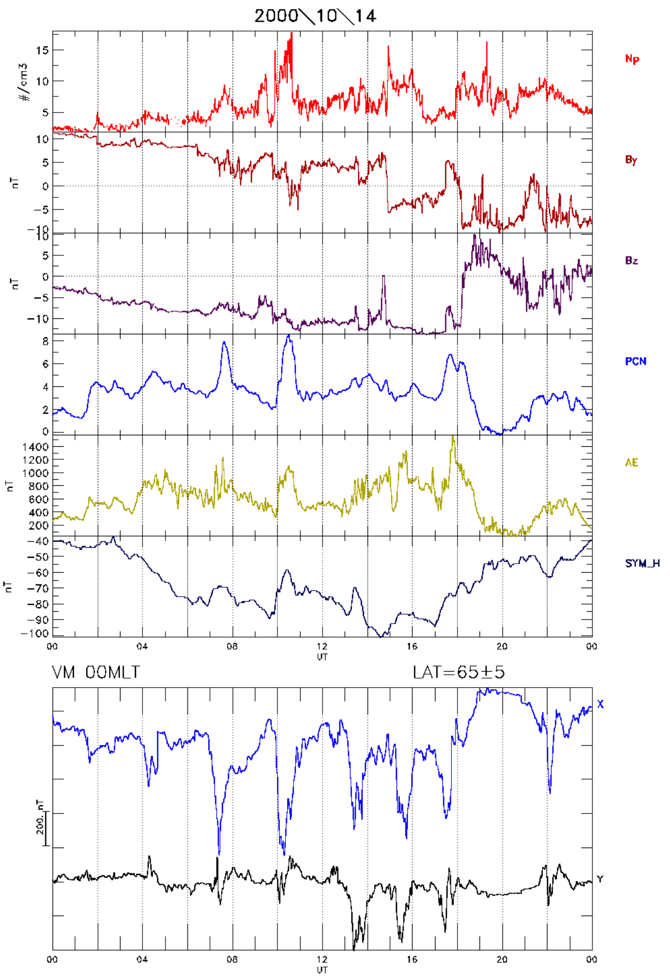

Figure 3. The standard plot of VM showing the basic space weather parameters: Np, IMF By, IMF Bz, PCN index, AE-index, SYMH-index, and the midnight VMs (X- and Y-components) of geomagnetic response for the Northern (Φ=65º±5º, *blue line*) hemispheres during the sawtooth event of Oct. 14, 2000.

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