Study of local manifestations of strong geomagnetic storms at middle latitude with using geomagnetic and TEC data

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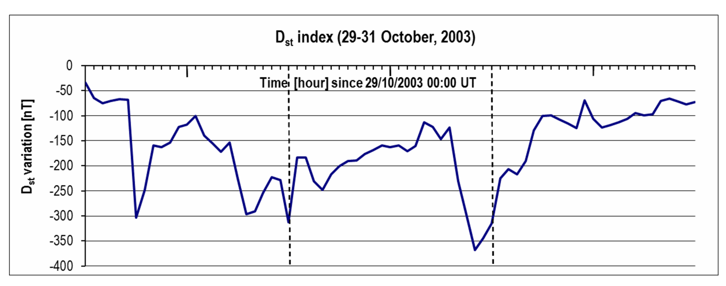
ABSTRACT

Local manifestation of the strong geomagnetic storms at mid-latitudes using *in situ* geomagnetic and TEC data is considered in this work. A case study analysis of the severe geomagnetic storm Halloween running from 29 to 31 October, 2003 was carried out. Data from geomagnetic observatories (GOs) Ebro EBR (Spain), Surlary SUA (Romania) and Beijing Ming Tombs BMT (China) and from nearby IGS GNSS sites EBRE, BUCU, SOFI, and BJFS are used in thid study. The datasets include minute values of the geomagnetic field H-component for GOs from the INTERMAGNET network, RINEX files for GNSS sites from IGS services, and hourly values of the Dst index from the World Data Center for Geomagnetism in the Kyoto University. A study of the temporal variations of the planetary geomagnetic index Dst, the H-component of the geomagnetic field recorded at three OGs, and the VTEC values obtained from the GNSS observations during the three-day storm was conducted. The continuous wavelet transform (CWT) analysis of the geomagnetic DS-index reveals local peculiarities in time-frequency decomposition of the signal for each GOs. The differences in the H-component's variation along the geographical longitude are associated with the ring current asymmetry. The co-comparison between the VTEC and the DS-index reveals some similarities in their timing variability. A change in the TEC gradient between SOFI and BUCU GNSS sites has been detected that could be associated with 2D-solitary nonlinear IGW, as well as TID of the electron density excited by them. Based on the obtained results, it is concluded that CWT is a useful tool for studying the local manifestation of strong geomagnetic storms in the time-frequency domain.

INTRODUCTION

In 2003 one interplanetary medium disturbance propagated to the Earth orbit and caused a strong geomagnetic storm called Halloween storm (G4, the largest in the last few decades), lasting from 29 to 31 October. During this storm two significant minima of the *Dst* index are determined as the second is with a value D_{st}=−383 nT in 23:00 UT on October 30, 2003. For this storm we investigate *DS(t)*, which is in relation with the disturbance storm time index D_{st}. This relation is analyzed by Chapman[1]. If the time from the moment of the sudden start of geomagnetic storm is measured, the disturbance distribution *D* of each component of the geomagnetic field *D(H), D(D)* and *D(Z)* on the magnetic parallels at the Earth surface for the time moment *t* can be expressed by the following Fourier series:



$$(1)\quad D(\theta,\lambda,t)=c_0(\theta,t)+\sum_{n=1}^{\infty}c_n(\theta,t)\sin(n\lambda+\alpha_n(\theta,t))$$

Here c_o, c_n are the Fourier coefficients, θ is the geomagnetic co-latitude to 90^0, λ is the geographic longitude, and α_n is the phase angle. The first term c_o and the infinite sum in this equation represent respectively the axially symmetric component with respect to the dipole axis, and the asymmetric part of the disturbed geomagnetic field that depends on the geographical longitude. These components are considered as a storm-time variation D_{st} and a local time-dependent disturbance *DS*, which contains 24-hour solar regular variation S_r, which is of the type of solar quiet variation S_q but with additional variation caused by asymmetric part of the ring current. Thus, we can write:

$$(2)\quad D(t)=D_{st}(t)+DS(t)$$

where *DS(t)* is a geomagnetic index that characterizes locally the storm. The variation of horizontal component $D_{st}(H)$ of the geomagnetic field is a function of the co-latitude and is larger at low latitudes. For one GO Eg.(2) can be written:

$$(3)\quad H(t)=D_{st}(t)+DS(t)$$

where *H(t)* is the horizontal component's variation of the geomagnetic field as a function of the time *t*.

PECULARITIES OF THE HALLOWEEN STORM

During Halloween storm in the north hemisphere, small-scale disturbances were generated at the fronts of Large-Scale Traveling Ionospheric Disturbances (LS TID). The calculated mean velocity of LS TID varied between 700 and 1600 m/s and the relative TID amplitude was of order 10-20%. The ionospheric response to the geomagnetic storm on October 29 was such that the northern crest of the equatorial anomaly was displaced northward up to latitudes 20-22°. Perevalova et al. [2] have evaluated Total Electron Content (TEC) values, which increased up to 130 TECU (in TEC units of $10^{16}m^{-2}$ = 1.0 TECU) in the northern crest. In quiet conditions the northern crest of the anomaly has been observed at latitudes 10-17° in morning, day time and evening sectors, and the TEC value has not exceeded 80 TECU.

DATA USED

For the investigation purposes, we used the minute values of the geomagnetic field component H for three GOs (Fig. 1) taken from the INTERMAGNET network (Table 1), RINEX data for nearby GNSS sites EBRE, BUCU, SOFI, and BJFS taken from IGS services, and the hourly values of the Dst index taken from the World Data Center for Geomagnetism in the Kyoto University. DS component per each GOs is determined by Eq. (2) using the datasets for geomagnetic field component *H* and D_{st} index.

Table 1. Geomagnetic observatories (GOs) and GNSS sites used in this study

Type	Name, Country	Code (ID)	Geographic	
			Latitude N (0)	Longitude E (0)
GO	Ebro, Spain	EBR	40⁰ 57'	0⁰ 20'
GNSS	Ebro, Spain	EBRE	40⁰ 49'	0⁰ 29'
GO	Surlari	SUA	44⁰ 41'	26⁰ 15'
GNSS	Bucurest	BUCU	44⁰ 28'	26⁰ 07'
GNSS	Sofia	SOFI	42⁰ 33'	23⁰ 24'
GO	Beijing Ming Tombs	BMT	40⁰ 18'	116⁰ 12'
GNSS	Fangshan	BJFS	39⁰ 36'	115⁰ 53'

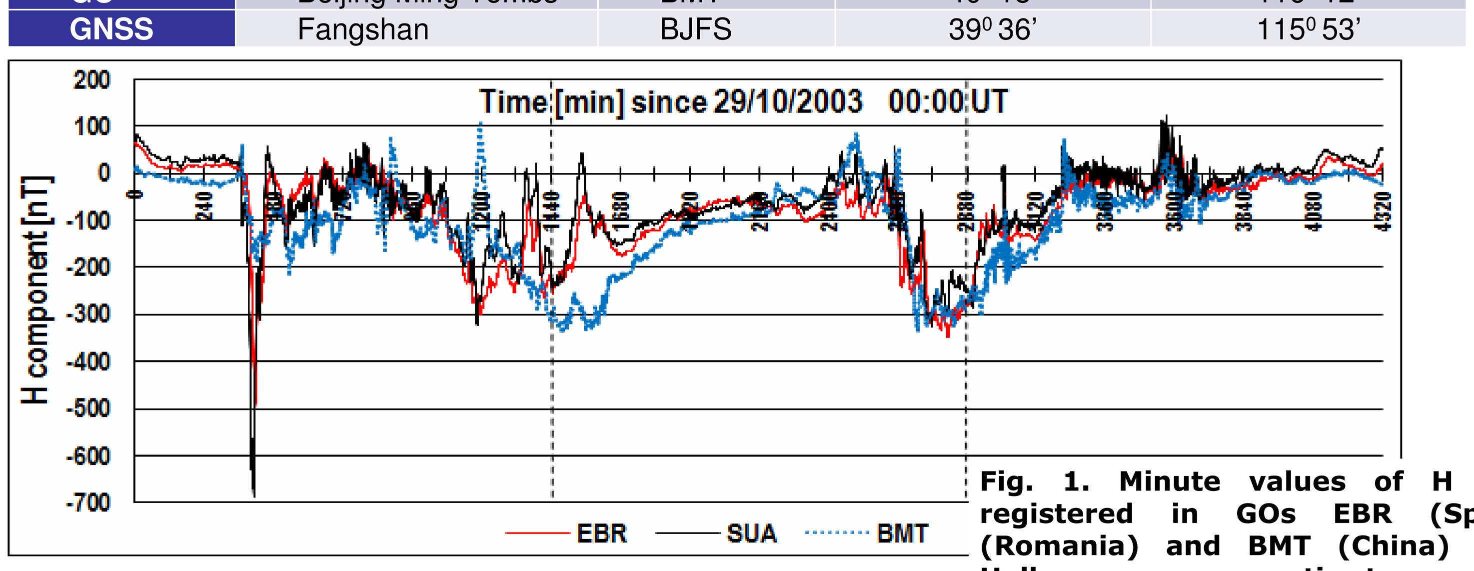


Fig. 1. Minute values of H component registered in GOs EBR (Spain), SUA (Romania) and BMT (China) during the Halloween geomagnetic storm

CONTINUOUS WAVELET TRANSFORMS

To perform analysis of minute values of the geomagnetic data from GOs at middle latitudes we use the continuous wavelet transform (CWT). CWT is better than DWT for analyzing singularities in functions by separating noise and signal. CWT is given by the following equation:

$$(4)\quad C(a,b)=W_{\psi}f(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}f(t)\psi\left(\frac{t-b}{a}\right)dt$$

The coefficients are visualized as a heat map on the plane (X,Y). The main property of this transform is the reconstruction of the signal *f* from the coefficients C(a,b). This is possible due to the Calderon formula only if the following admissibility condition is satisfied $C_{\psi}=\int_{-\infty}^{\infty}\frac{\psi(\omega)}{|\omega|}d\omega<\infty$.

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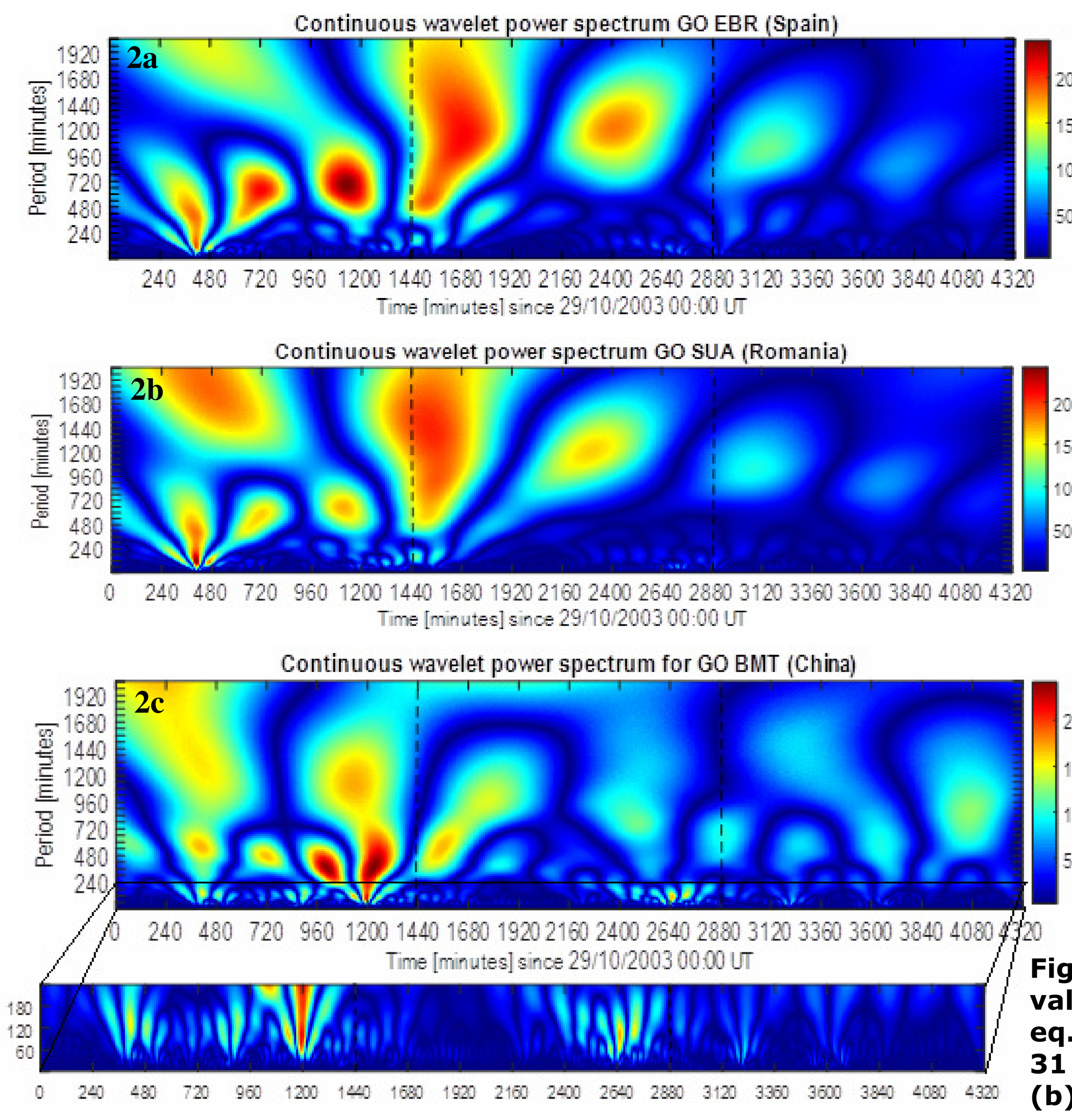
WAVELET ANALYSIS

We have carried out numerous experiments with CWT of the *DS* index using various families of wavelets, as *db, coif, bior, gaus, morl, symlet*, and windowed Fourier transform with a suitable chosen width of the windows. The calculations were implemented in Octave/Matlab.



Continuous wavelet power spectrum (CWPS) of *DS* index variation for the three GOs: Ebro EBR (Spain), Surlary SUA (Romania), and Beijing Ming Tombs BMT (China), is shown on Fig. 2 (a-c). The wavelet time-scale spectrum is a two-argument function C(a,b), where *a* is the length of the periods measured in period units, and *b* is the shift parameter, measured in time units. A plane (X,Y) corresponds to the time-period plane (b,a), since the variable *a* is along the ordinate Y (periods, in minutes), and the variable *b* corresponds to the abscissae X (time, in minutes). The wavelet coefficients C(a,b) characterizing the probability amplitude of regular period component localization exactly at the point (a,b), are laid along the Z axis. On Fig. 2 the heat map of the coefficients C(a,b) is shown, which is the projection of C(a,b) to (b,a) (or (X,Y) plain).

Fig.2. Wavelet transformation of minute values of the DS index derived according eq.(2) during the geomagnetic storm 29 - 31 October 2003 for GOs EBR (a), SUA (b) and BMT (c).

INTERPRETATION OF RESULTS

- The longitude dependent difference of *H*-component for three GOs on Fig. 1 can be explained by the asymmetry of ring current, especially in one of the same temporal intervals since the beginning of Halloween storm.
- Some peculiarities in relatively longer periods of the *DS* index depending on the longitudes in western and eastern part of the northern hemisphere are visible on Fig.2a-c, as well as an irregular power at several different periods lasting from 30 min to 3 h. They are grouped and quite regularly distributed over time similarly to the S_r regularity (regular variation at disturbed conditions) by type S_q. We guess that these features are due to the ionospheric influence, which is discussed in [3] from theoretical point of view. The experiments carried out for quiet days (not presented here) show that such short-period peculiarities do not exist.
- The second type of features are the typical long-term periods above 3 hours lasting up to two days after the beginning of storm in Oct 29, 2003. These disturbances are regular and related to daily variations of the geomagnetic field, which are caused by the ionospheric current system.
- Regular disturbances (daily variation) of the ionosphere are associated with daily variation of VTEC determined at each GNSS site in northern hemisphere shown in Figs. 3 a-c. VTEC values increase almost twice for the firs day of the Halloween storm. Short period variations of VTEC during the first stormy day in the interval 5-15 TECU above 40 TECU of VTEC graphs can be explained by a penetration of the charged particles in the ionosphere. A gradient of the electron concentration between SOFI and BUCU GNSS sites is discovered during the all storm time duration (Fig. 3d).

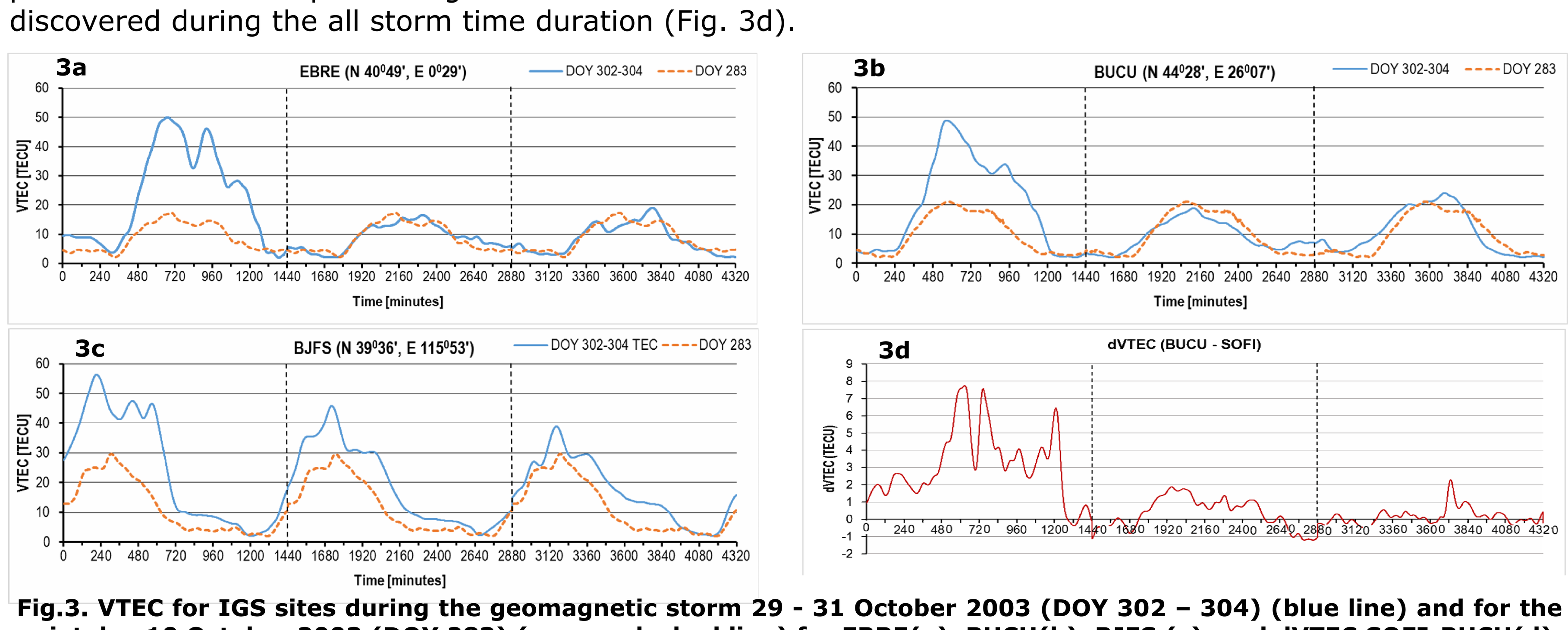


Fig.3. VTEC for IGS sites during the geomagnetic storm 29 - 31 October 2003 (DOY 302 – 304) (blue line) and for the quiet day 10 October 2003 (DOY 283) (orange dashed line) for EBRE(a), BUCU(b), BJFS (c), and dVTEC SOFI-BUCU(d).

DISCUSSION AND CONCLUSION

Based on the obtained results, we can conclude that the wavelet transform is a very useful tool to study the local manifestation of strong geomagnetic storms in the time-frequency domain.

- The ionospheric influence is very clearly distinguished in the short periods (less than 3 hours) from the ring current influence on the *DS* index, thanks to the properties of the Wavelet Analysis. This observation is new, up to our knowledge. The observed peculiarities on wavelet graphs can be related to the soliton-like structures studied previously in [3].
- Time periods domain of the geomagnetic *DS* index based on the wavelet analysis is obtained. Different periods of the geomagnetic field variations and their changes in time are identified. Based on the VTEC data analyses from nearby GNSS sites to the relevant GOs we discovered a relationship between *DS* and VTEC index variability in temporal scale.
- The differences in the *H* component's variation of the geomagnetic field along the geographical longitude are associated with the ring current asymmetry.

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