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GEOMAGNETIC VARIATIONS CAUSED BY ROCKET LAUNCHES FROM THE PLESETSK AND THE BAIKONUR COSMODROMES

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Изложены результаты системного спектрального анализа временных вариаций уровня горизонтальных компонент геомагнитного поля, сопровождавших старты и полеты ракет Союз и Протон с космодромов Плесецк и Байконур в 2014 – 2017 гг. Получены основные параметры сигналов, связанных с возмущениями геомагнитного поля. Развитая теоретическая модель волновых возмущений, генерируемых стартами и полетами ракет, находится в хорошем соответствии с результатами наблюдений.
КЛЮЧЕВЫЕ СЛОВА: системный спектральный анализ, магнитометр, старт ракеты, возмущения.

Представлені результати системного спектрального аналізу часових варіацій рівня горизонтальних компонент геомагнітного поля, що супроводжували старти та польоти ракет Союз і Протон з космодромів Плесецк та Байконур в 2014-2017 рр. Отримано основні параметри сигналів, які пов’язані зі збуреннями геомагнітного поля. Розвинута теоретична модель хвильових збурень, які генеруються стартами та польотами ракет, добре узгоджується з результатами спостережень.
КЛЮЧОВІ СЛОВА: системний спектральний аналіз, магнітометр, старт ракети, збурення.

Results from the system spectral analysis of variations in the geomagnetic field horizontal components, which are associated with the orbital maneuvering subsystem engine burns and the firing of the booster stages of the Soyuz and Proton rockets at the Plesetsk and the Baikonur cosmodromes, are presented for the 2014 – 2017 period. Main signal parameters connected with geomagnetic field disturbancies were obtained. A theoretical model of wave disturbances generated by the firing of the booster stages has been developed, and good agreement between the observations and the model output has been found.
KEY WORDS: system spectral analysis, magnetometer, rocket launch, disturbances.

INTRODUCTION

The Fourier transform is commonly used for analyzing spectra. To localize a process in the time domain, the short-time Fourier transform is employed. To improve the resolution in the period range under study, L. F. Chernogor advanced a modified short-time Fourier transform termed the adaptive Fourier transform [1]. The adaptive Fourier transform is the Fourier transform in a sliding window with a width adjusted to be equal to a fixed number of harmonic periods. However, the short-time Fourier transform has a resolution in the time domain better than the adaptive Fourier transform. To equalize the drawbacks of these transforms, the wavelet transform is used, which permits the space and time resolutions attain an optimum. The capabilities of the above integral transformations complement each other by compensating the deficiencies of one of the transforms with the merits of the others. The joint use of these integral transformations is termed the system spectral analysis (SSA).

The aim of this study is to present the results from the SSA of the time variations in the geomagnetic field associated with the orbital maneuvering subsystem engine burns and the firing of the booster stages of the Soyuz and Proton rockets at the Plesetsk and the Baikonur cosmodromes.

FACILITY AND TECHNIQUES

The measurements have been acquired with the very sensitive fluxgate magnetometer located at the V. N. Karazin Kharkiv National University Magnetic Observatory (49°39′ N geographic latitude, 36°56′ E geographic longitude; 45°20′ N geomagnetic latitude and 119°20′ E geomagnetic longitude). The magnetometer digitally acquires measurements of fluctuations with periods of 1 – 1,000 s in the geomagnetic south-north (H component) and geomagnetic west-east (D) directions. The minimum fluctuation amplitudes are fundamentally limited by the level of internal noise of 0.5–500 pT in 1 – 1,000 s period range, respectively. GPS is used for clock synchronization with an error of equal to or less than ±0.5 s [1 – 3].

The SSA was preceded by band-pass filtering in the period intervals of 1–10 s, 10–100 s, and 100–1,000 s and a thorough study of the state of space weather. The time intervals with increased magnetic activity (indices $\geq a_p \geq 3$, $A_p \geq 3$,

$K_p \geq 1$, $|D_{st}| \geq 8$ nT) have been excluded from the further analysis. Over these time intervals, the variations in the horizontal components were not caused by rocket engine burns, but space sources.

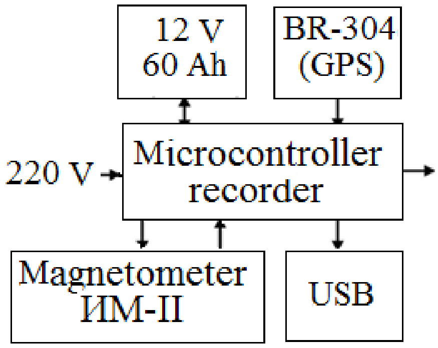

Fig. 1. The magnetometer

INFORMATION ABOUT THE COSMODROMES AND ROCKETS

The database that contains information about the effects of the firing of the booster stages of approximately 5,000 rockets and orbital maneuvering subsystem engine burns has been collected in V. N. KarazinKharkiv National University [1 – 6].

The launches took place from the various cosmodromes all over the world. The nearest cosmodromes to the V. N. Karazin Kharkiv National University Magnetic Observatories are the Plesetsk (Russian Federation) and Baikonur (Republic of Kazakhstan) cosmodromes, which are located at a distance of 1,500 km and 2,200 km, respectively.

In this paper, the largest space vehicles, Soyuz and Proton of 297 tons and 711 tons mass, respectively, are chosen for study. The effects from the rocket launches that occurred over the 2014–2017 interval have been analyzed.

OBSERVATIONS

Almost all rocket launches are associated with changes in the character of variations in the geomagnetic field (Fig. 2 – Fig. 5). In these figures verticalsolid line shows the moment of rocket launch, vertical dotted line shows the moment of sunrise. The amplitude of the oscillations most frequently increases by a factor of 1.5–2 (up to 1–2 nT). Sometimes, it decreases, and the wave oscillation, which exists before the arrival of the wave disturbance due to the rocket launch, is inhibited. The time delay between the response in the geomagnetic field and the firing of the booster stages equals to approximately 40–80 min and 65–130 min for the Plesetsk and Baikonur cosmodromes, respectively. The duration of the quasi-periodic disturbances (with the period spectra in 10–15 min period range) equals to 30–60 min and weakly depends on the distance between the cosmodromes and the Magnetic Observatory.

The SSA permits the time delay of the signal, its spectral content, and the duration to be determined with an error sufficient for many practical application [1 – 6].

MECHANISMS FOR THE GENERATION AND PROPAGATION OF THE DISTURBANCES

Propagation speed for the arrival of the disturbance can be calculated from the distance between the cosmodrome and the Magnetic Observatory and the time delay between the response in the geomagnetic field and the orbital maneuvering subsystem engine burns and the firing of the booster stages. It turns out to be dependent on the geospace state, the time of day, season, and to be equal to approximately 0.3–0.6 km/s. As is well known, such a speed is characteristic of the internal gravity waves (IGWs) in the terrestrial atmosphere. These waves are waves in the neutral density with periods of approximately 10 – 180 min, and with gravity as a restoring force. Their phase speed, for periods equal to or greater than 10 min, is smaller than the speed of sound in the atmosphere, which increases with altitude in 100–400 km range from 0.3 to 1 km/s.

The IGW amplitude attains a maximum value on a relative scale between 200 and 250 km altitude where their phase speed usually do not exceed 0.5–0.6 km/s. Their damping depth is equal to 3,000–5,000 km, therefore such waves propagate virtually on a global scale.

The IGWs modulate the electron density in the ionosphere as they propagate through the atmosphere, i.e., they generate traveling ionospheric disturbances, from which periodic variations arise in ionospheric currents, causing quasi-periodic variations in the geomagnetic field with the same period. Through modeling, we demonstrate that the IGW relative amplitude of 2–3% causes variations in the horizontal components of the geomagnetic field of approximately 1nT, which has been observed in the experiments [3, 5].

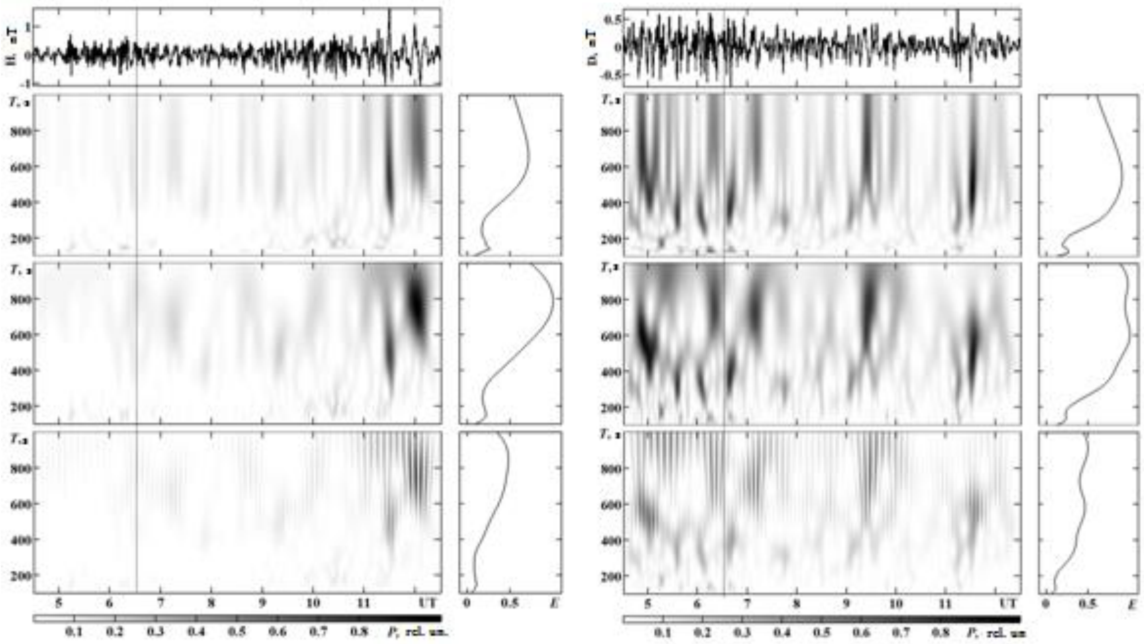

Fig. 2. H- and D-component variations in the 100–1000-s period interval during *Soyuz 2.1.b* launch on May 25, 2017 from the Plesetsk cosmodrome.

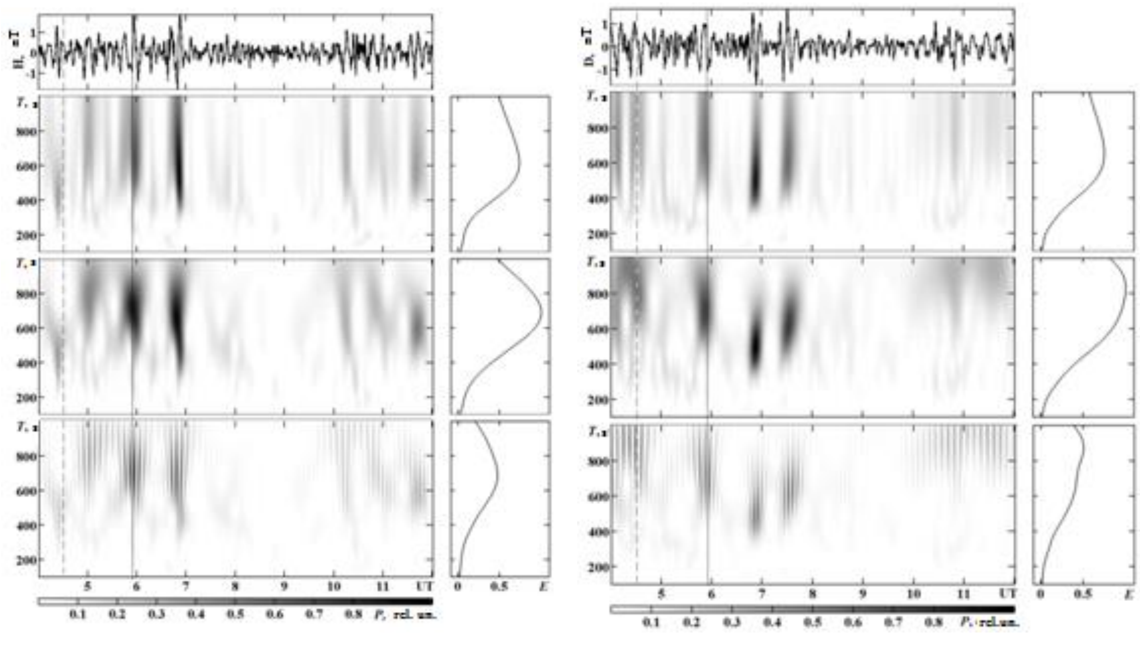

Fig. 3. H- and D-component variations in the 100–1000-s period interval during *Soyuz U* launch on February 22, 2017 from the Baikonur cosmodrome.

CONCLUSIONS

Observations of variations with periods of 1 – 1,000 s in the geomagnetic field that were associated with the firing of the booster stages that took place at different cosmodromes all over the world have been made over the years. The SSA revealed the basic parameters of the wave trains caused by the firing of the booster stages. A theoretical model of wave disturbances generated by the firing of the booster stages has been developed, and good agreement between the observations and the model output has been found.

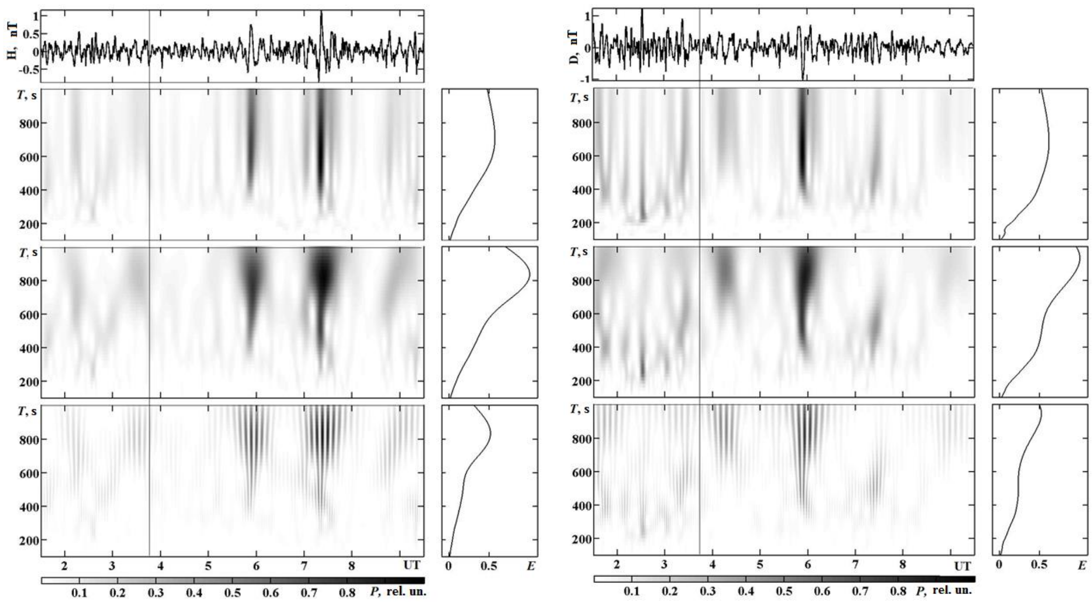

Fig. 4. H- and D-component variations in the 100–1000-s period interval during *Proton M* launch from the Baikonur cosmodrome on June 8, 2017.

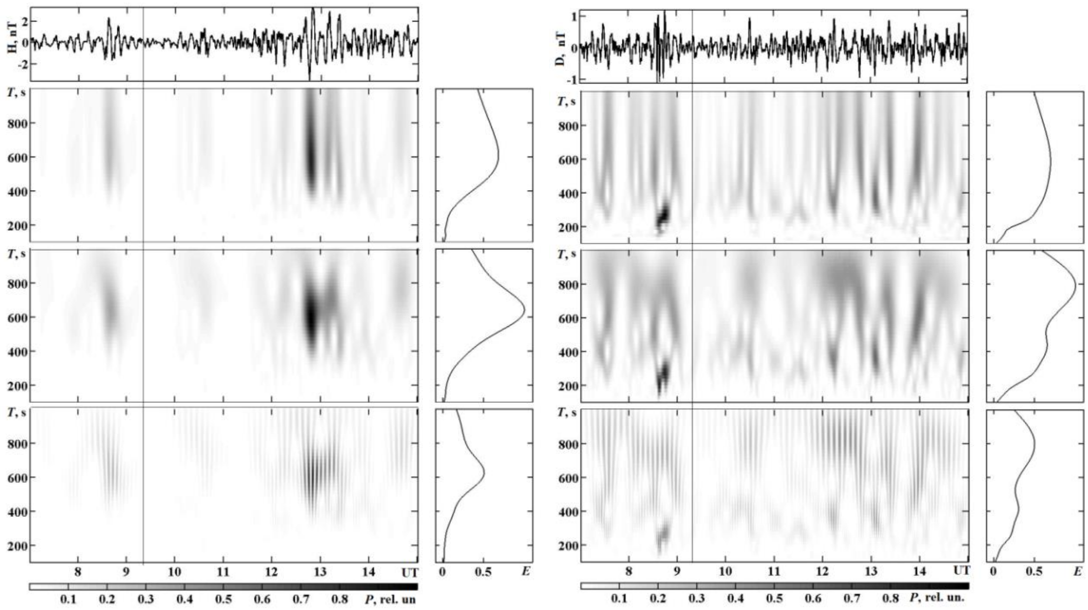

Fig. 5. H- and D-component variations in the 100–1000-s period interval during *Soyuz 2.1.a* launch from the Baikonur cosmodrome on June 14, 2017.

REFERENCES

1. L. F. Chernogor, *Radiophysical and Geomagnetic Effects of Rocket Engine Burns*, (in Russian). Kharkiv, Ukraine: Kharkiv V. N. Karazin National University Press, 2009.
2. L. F. Chernogor, Blaunstein N., *Radiophysical and Geomagnetic Effects of Rocket Burn and Launch in the Near-the-Earth Environment*. Boca Raton, London, New York: CRC Press. Taylor & Francis Group, 2013.
3. L. F. Chernogor, "On a possible impact of rocket and space technology on the Earth's magnetic field,"(in Russian), in: *Impact of Rocket and Space Technology on the Environment,*Adushkin V. V., Kozlov S. I., Silnikov M. V., Eds. Moscow: GEOS, 2016, pp. 483 – 517.
4. K. P. Garmash et al., "Geomagnetic Pulsations Associated with Rocket Launches from Cosmodromes all over the World," (in Russian), *Space Science and Technology*, vol. 15, no. 1, pp. 31 – 43, Jan. 2009.
5. L. F. Chernogor, "Magneto-Ionospheric Effects of Active Experiments Conducted on February 18, 2004" *Cosmic Research*, vol. 49, no. 4, pp. 292 – 307, Aug. 2011.
6. L. F. Chernogor, "Geomagnetic Effect of Launches and Flights of Large Spacecraft" *Cosmic Research*, vol. 51, no. 6, pp. 413 – 426, Nov. 2013.