UDC537.874+550.388.2

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LOW-FREQUENCY (ELF–VLF) RADIO ATMOSPHERICS STUDY AT THE UKRAINIAN ANTARCTIC AKADEMIK VERNADSKY STATION

ABSTRACT. This paper describes the results of the atmospherics measurements in the extremely low-frequency (ELF) and very low-frequency (VLF) frequency ranges performed at the Akademik Vernadsky station (64.26W; 65.25S) during February–April 2019**.** The main **objective** of the study was the implementation of a single-site technique for monitoring the lower ionosphere parameters and locating globally distributed powerful lightning discharges. **Methods.** The receiving and analyzing VLF complex was used at the station to record two horizontal magnetic and vertical electric components of atmospherics in the frequency range 750 Hz – 24 kHz. A single-site lightning location method is based on the analysis of tweek-atmospherics (tweeks).It was implemented in the receiving system software. This allowed obtaining real-time information about lightning position, height and electron density variations in the lower ionosphere.The records of VLF atmospherics were synchronized via GPS timestamps with records of ELF transients resulted from globally distributed powerful lightning discharges. **Results** of analysis of tweeks recorded at the Akademik Vernadsky station indicates that lightning discharges are registered at distances from 2,000 km to about 10,000 km within the azimuthal sector, covering almost the entire South American continent, southern Africa and the Gulf of Guinea. Practically, no tweeks from the Pacific were recorded. This can be attributed to the non-reciprocity of attenuation of radio waves propagating in the west-east and east-west directions. In addition to the fundamental mode, we observed also the second and higher order modes of tweeks. This allowed estimating the lower boundary altitude and the electron density in the lower ionosphere. We demonstrated the advantages of simultaneous recordings of VLF atmospherics and ELF transients. Employing the vertical electric and two horizontal magnetic components measured by the VLF complex allowed for more accurate and unambiguous determining the source azimuth and resolving polarity of the charge transfer in the parent lightning discharges. Combining the ELF and VLF records, we can determine a distance to lightning and, then, parameters of the current moment of the lightning discharge. **Conclusions.** The performed experimental studies has shown the prospect of further combined ELF–VLF monitoring at the Akademik Vernadsky station, enabling detection of globally distributed powerful lightning discharges and changes in the lower ionosphere related to various phenomena of space weather, atmospheric and of terrestrial origin.

Keywords: ELF transient, single-site technique, lightning location, ELF-VLF radio waves, Earth-ionosphere waveguide, tweek-atmospheric, lower ionosphere.

INTRODUCTION

Natural radio emissions in the extremely low-frequency (ELF) and very low-frequency (VLF) bands are used for determining the coordinates, current and the charge moment of their sources (lightning discharges), as well as for probing the lower ionosphere edge. At the same time, the different principles are used at various frequencies for the location of lightning strokes. There are national and commercial systems for monitoring the local thunderstorm activity operating at frequencies of tens of kilohertz, such as

Cite: Shvets A. V., Nickolaenko A. P., Koloskov A. V., Yampolsky Yu. M., Budanov O. V., Shvets A. A. Low-frequency (ELF–VLF) radio atmospherics study at the Ukrainian Antarctic Akademik Vernadsky station. *Ukrainian Antarctic Journal*, 2019. № 1(18), 116–127.

the National Lightning Detection Network (NLDN). Such systems cover large areas, for example, the entire territory of the United States, they use from a few dozen to hundreds of synchronously operating observatories and ensure the accuracy of the lightning location of 1 – 2 km (Cummins et al., 1998, 2006, Orville et al., 2001, 2002, Biagi et al., 2007). A specific feature of these networks is their locality, they usually serve the territory of a particular country, and these locations are usually provided on a commercial basis.

The Worldwide Lightning Location Network (WWLLN) works at frequencies from units to a hundred of kilohertz (http://wwlln.net/). It exploits simultaneous records of atmospherics by the global network containing several dozen stations. At the same time, global coverage is obtained with the lightning stroke location errors of about 10 km (Abarca et al, 2010, Abreu et al., 2010, Hutchins et al., 2012).

The lightning location systems operating in the bands of sonic and ultrasonic frequencies have to use a significant number of observation points, and this increases the cost of observations. When recording the natural bursts of radio emission are in the frequency range of the global electromagnetic (Schumann) resonance covering the interval from 4 to 40 Hz, the position of super-powerful lightning discharges might be monitored from a single observatory. The relevant signal are regarded as Q-bursts or ELF transients (Ogawa et al., 1967, Kemp and Jones, 1971, Kemp, 1971, Lazebny and Nickolaenko, 1976, Boccippio et al., 1995, Füllekrug and Constable, 2000, Füllekrug et al., 2000, Sato and Fukunishi, 2003, Ogawa and Komatsu, 2007, Nickolaenko et al., 2008). However, the error in determining the coordinates of super-powerful lightning strokes causing the Q-bursts or ELF transient events is about 1000 km (Nickolaenko and Hayakawa, 2002, 2014).

A special position among the above-mentioned lightning location techniques is occupied by the so-called "Kharkov technique" (Rafalsky et al., 1995a, 1995b). It exploits the signals of tweek-atmospheric and therefore its application is associated with the nocturnal propagation conditions. An advantage of the Kharkov technique is that it simultaneously allows evaluating the effective height of the lower ionosphere for both: the particular propagation path with an error of a few hundred meters and the distance toward the causative lightning discharge with an error less than 100 km for distances up to 2000 km (Brundell, et al., 2002).

In the present paper, we apply the advanced Kharkov technique (Shvets et al., 2014, 2017). The experiments performed at Ukrainian Antarctic Akademik Vernadsky station during February–April 2019 measurement campaign allowed locating sources of tweek atmospherics at distances of up to 10000 km with concurrent estimating of temporal variations of the effective height of the ionosphere during the night (Shvets et al., 2019).

MATERIALS AND METHODS

Receiving and registering equipment

A receiving and registering equipment was used for measurements of the vertical electric and two horizontal magnetic field components in the VLF range. The complex has been developed in the A.Ya. Usikov Institute for Radiophysics and Electronics of National Academy of Sciences of Ukraine (IRE NASU) (Shvets et al., 2016). The required threshold sensitivity of the VLF receiver was calculated accounting for characteristics of natural electromagnetic background obtained in Antarctica (Chrissan and Fraser-Smith, 1996a, b). Two orthogonal equilateral triangular magnetic frames 3.6 m^2 in the area with 64 turns of copper wire of 0.51 mm in diameter were mounted on a 3 m high wooden mast to receive the magnetic field components. As an electric antenna, an aluminum rod was used of 0.66 m length, mounted through a ceramic insulator to the housing of the antenna amplifier, which was mounted on top of the mast (Fig. 1). The calculated spectral density of the device's noise in the magnetic channels was 0.85 $fT \cdot Hz^{-1/2}$, and 0.24 $\mu V \cdot Hz^{-1/2}$ for the electrical component.

The complex operates continuously. Signals outputs of the receiver were digitized with 48 kHz sampling frequency and stored in hourly binary files containing the 40 ms waveforms of two horizontal magnetic and the vertical electric components of atmospherics, which exceeded in amplitude a fixed threshold.

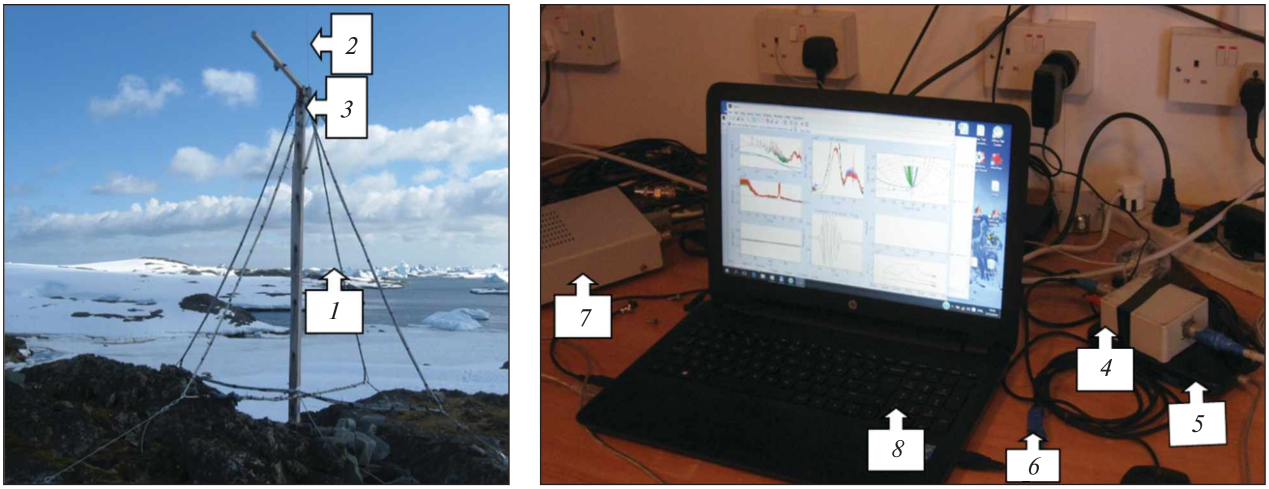

Fig. 1. The receiving and registering components: *1* — air-loop magnetic antennas; *2* — rod electric antenna; *3* — antenna amplifiers; *4* — main amplifiers; *5* —analog-to-digital converter; *6* — USB power supply for antenna and main amplifiers (5 V —> ± 12 V convertor); *7* — GPS receiver; *8* — personal computer

The arrival times were fixed with the timestamps from GPS receiver with the accuracy of the ADC's sampling period, about 20 microseconds. For this purpose, the PPS were fed to the fourth channel of the ADC and it was identified from the station's time-server through the local network.

Current spectra and waveforms of the input signals and of the atmospherics together with the coordinates of lightning discharges determined by tweeks are displayed in real the time on the computer display. Operation of the VLF complex in the case of short-term interruption of power supply from the electrical network is provided by the use of the laptop's battery. It provides power to the data acquisition system and the entire receiving part of the complex for up to a few hours. Further, in case of power failure, after the mains power is restored the computer's operating system and data acquisition program will start automatically, minimizing operator involvement in maintaining the complex.

Deducing the lower ionosphere parameters by tweek-atmospherics

A method for analyzing the tweeks (Shvets and Gorishnaya 2011; Shvets et al., 2017a, 2018) allows to estimate the cut off frequencies and respective effective heights of the Earth-ionosphere waveguide in the ELF-VLF range for the fundamental and the higher order waveguide modes. It was shown in the works (Shvets et al., 2014, 2017a, 2017b; Nickolaenko et al., 2016, Gorishnaya, 2014) based on the analysis of the experimental tweek records, that with an increase in the mode number and, accordingly, the frequency of the incident wave, the effective height of the waveguide decreases. That is explained by a decrease in the penetration depth of the low-frequency wave into the ionosphere with increasing frequency.

We use an approximate theory developed by Ryabov (1994) and Sukhorukov (1992a, 1992b, 1996), in which the features are considered of formation of the tweek field at night conditions in the ionosphere near the critical frequencies of the waveguide to interpret the experimental results obtained in this work. The following assumptions were used in the model of the Earth-ionosphere waveguide to obtain analytical dependences connecting the propagation parameters of the ELF-VLF radio waves with the parameters of the ionospheric plasma. The waveguide is assumed to be infinite and flat with perfectly conducting Earth. The following condition is satisfied for the nighttime lower ionosphere at frequencies $f \leq 5$ kHz : $\omega << \nu << \omega_{Be}$, where ω is the circular frequency of the incident wave, ν is the collision frequency of electrons with neutral particles, $\omega_{Be} = \dfrac{eB_0}{m_e}$ is the electron gyrofrequency, B_0 is the geomagnetic field induction. A model was used in calculations of a uniform sharply bounded ionosphere with a lower boundary found at the height h_E (Sukhorukov, 1992a; Ryabov, 1994). The quasi-longitudinal approximation is applied in propagation of low-frequency radio waves in the ionosphere, which is satisfied under the condition: $\tan I >> \dfrac{\omega\left|\omega_{Be}\right|}{2\omega_{pe}^2}$, where I is the inclination angle, ω_{pe} is the electron plasma frequency. The critical frequencies of the quasi-transverse electric normal waves (left-handed polarized), prevailing in the tweek field (Yamashita, 1978), are expressed as follows (Sukhorukov, 1992a; Ryabov, 1994):

$$f_{cm} = \frac{cm}{2h_E}\left(1 - \frac{1}{\pi m \mu}\right), \qquad (1)$$

where c is the speed of light in vacuum; m is the mode number; $\mu = \dfrac{\omega_{pe}}{\sqrt{\omega\left|\omega_{Be}\sin I\right|}}$ is the refraction index at frequency $\omega = 2\pi f_m$, $f_m = \dfrac{cm}{2h_E}$.

We can obtain estimates of the height h_E and electron concentration N_e at the height h_E from formula (1) using the measured cut off frequencies of the 1st and the 2nd order modes, f_{c1} and f_{c2} respectively, determined from a tweek record:

$$h_E = \frac{c}{2f_1},\ f_1 = \frac{1}{\sqrt{2}-1}\left(\frac{f_{c2}}{\sqrt{2}} - f_{c1}\right) \qquad (2)$$

$$N_e = \frac{\omega_{pe}^2 M_e \varepsilon_0}{e^2},\ \omega_{pe}^2 = \frac{2\left|\omega_{Be}\sin I\right|}{\pi}\frac{f_1^3}{\left(f_1 - f_{c1}\right)^2}. \qquad (3)$$

An example of the tweek's two-mode spectrogram of the longitudinal magnetic field component is shown in Fig. 2. The first and second order harmonics correspond to propagating normal waves of the first and the second order in the waveguide. Black dots depict the maxima in the spectrogram that were determined by the automatic identification procedure, and these are used in the solution of the inverse problem: simultaneous finding the waveguide cut off frequencies and the source distance.

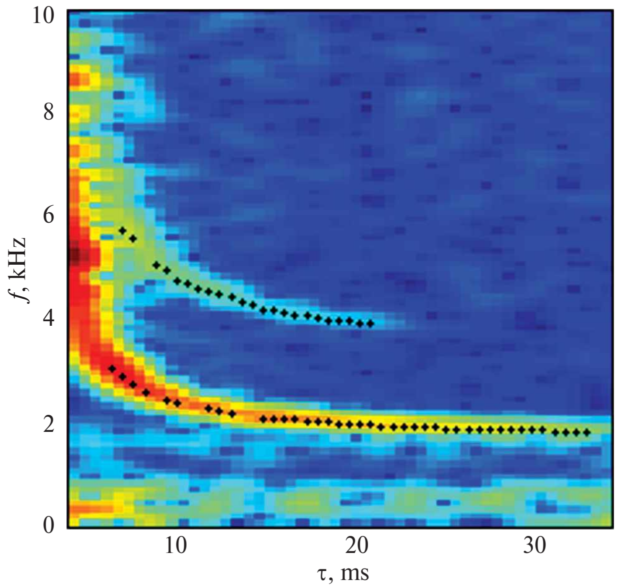

Fig. 2. A spectrogram of the longitudinal magnetic component of a tweek with the observed first and second order harmonics

The following cut off frequencies of the two waveguide modes were found f_{c1} = 1661 Hz, f_{c2} = 3355 Hz, while the source – observer distance was ρ = 5325 km. The source azimuth was 41° counted from the geographical North. The following parameters of the ionosphere model were found: the lower ionosphere is h_E = 87.3 km and the electron density is N_e = = 2740 cm^{-3}, both were computed by using Eqs. (2) and (3). We use in the computations the average over the propagation path geomagnetic field inclination I = –52° and the total geomagnetic field induction B_0 = 30000 nT.

The parameters sought correspond to the difference between the cut off frequencies, this follows from Eqs. (2) and (3). This significantly increases the requirements to the accuracy of frequency estimates. To regularize the estimates of the output parameters, we use the averaging over the ensemble of tweek records.

Variations in the ionosphere parameters were obtained from the analysis of tweek atmospherics recorded during the night of March 28–29, 2019 at Akademik Vernadsky station. As a whole, 12,592 atmospherics were recorded during this night, and about 2,900 waveforms were identified as tweeks. The

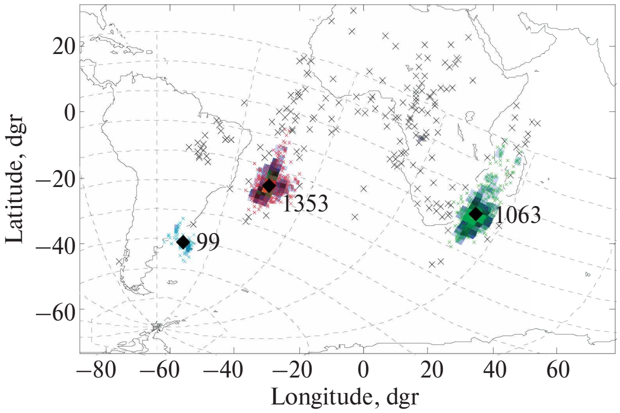

Fig. 3. Distribution of lightning discharges determined by tweeks at the Akademik Vernadsky station during the night of March 28–29, 2019. Bold rhombs indicate the positions of the center of gravity of the thunderstorm center; the number of lightning discharges is indicated next to it. Lightning discharges not grouped in clusters are indicated by black x-marks

geographic map with spatial lightning distribution is shown in Fig. 3. It was obtained from the tweek records containing two harmonics obligatory for solving the inverse problem (2)–(3).The azimuthal and distance grids are shown by the dotted lines in the map with the 30 degrees and the 1000 km interval respectively. Three active thunderstorm centers might be distinguished: one is found in the Atlantic Ocean at adistance of 5500 km, the other is nearby the southern tip of Africa at a distance of 7200 km, and the third one is a relatively weak center positioned to the south of the La Plata Rivermouth at a distance of ~2900 km from the Antarctic observatory. The active areas were found by using adensity-based algorithm for discovering clusters (Ester et al., 1996), and the averaged parameters of propagation paths were obtained with the tweeks arrived from each separate cluster.

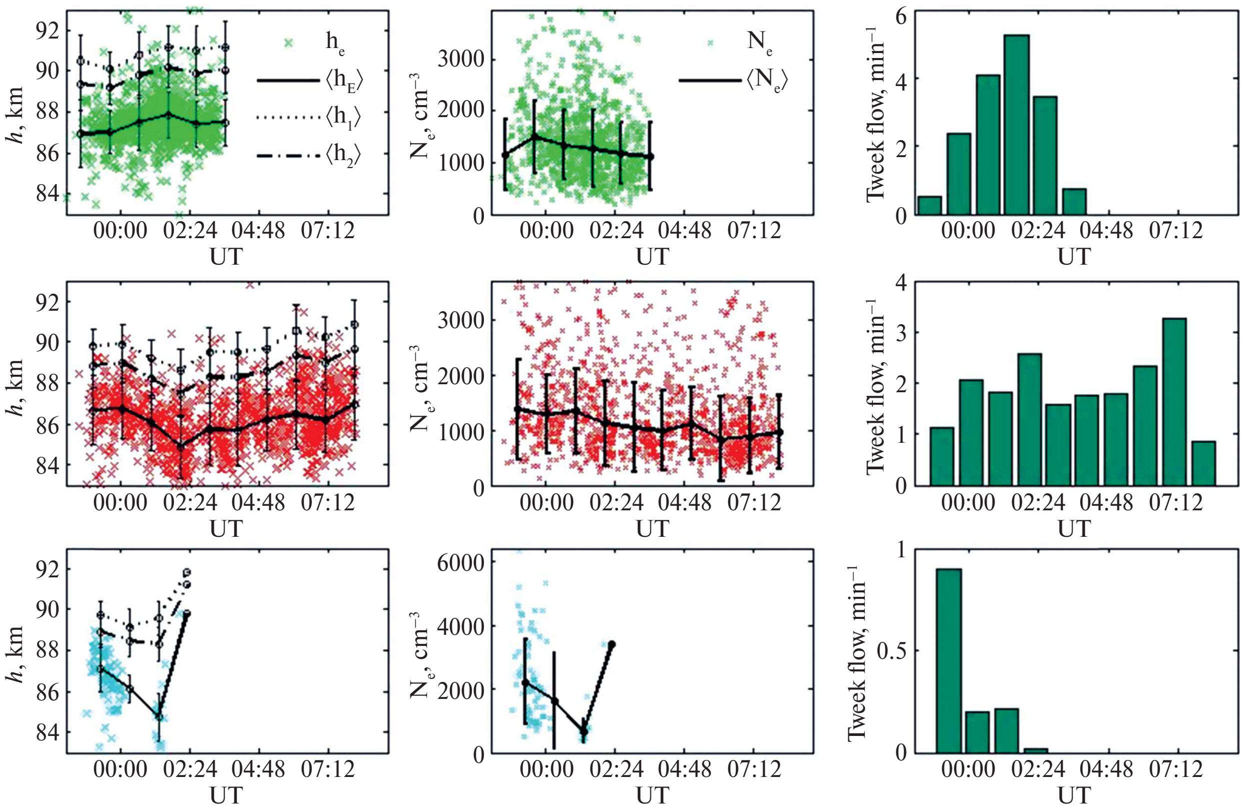

Fig. 4. Variations in the parameters of the lower ionosphere obtained from the analysis of tweeks: the left column is the effective height for the first and second order modes and the height of the lower boundary of the ionosphere; the middle column presents variations of the relevant electron concentration. The right column shows the variations of the tweek flow from the thunderstorm centers. The color of the dots on the graphs corresponds to the color of the thunderstorm centers shown on the map in Fig. 3

The number of strokes causing tweeks in these thunderstorm centers were 1355, 1063 and 99, respectively. Some tweek records were excluded from the consideration: when these resulted in the effective second mode height exceeding the first order mode one, when the electron density exceeded the median N_e value by the factor of 3 or more. The number of such unrealistic entries was found to be approximately 5% of all recorded events.

We present in Fig. 4 the temporal variations of the ionosphere parameters along the three propagation paths deduced from tweek records. The left plots in this figure show variations of the hourly averaged effective height deduced from the first and the second order modes. The middle column depicts the median values of the relevant electron concentration. The right plots show alterations in the tweek rate arriving from each thunderstorm center. The dot colorsin Fig. 4 correspond to cluster colors in the map in Fig. 3.

The tweek flux from different centers is determined both by the ionosphere conditions along the propagation path and by the intensity of thunderstorm centers. The tweeks arrive during the period between the sunset at the observatory and the sunrise at the center nearby Africa (top line of plots in Fig. 4) The South America east coast center (middle row) is active all through the night. The last center was active during a short period only at the beginning of the night at the observatory, probably, owing to the end of its own activity.

Determining parameters of power lightning discharges by synchronous records of ELF and VLF atmospherics

The measurement of the ELF transients at a few (Sato et al., 2003; Koloskov et al., 2004) and even at a single station (Burke and Jones, 1996; Huang et al., 1999; Füllekrug and Constable 2000; Ogawa and Komatsu, 2007 2009) provides diagnostic of global lightning activity and transient luminous events (TLEs). The single wave form of ELF transient enables us to estimate the source charge moment (Cummer and Inan, 1997; Cummer, 1998). Methods to estimate the charge moments of powerful discharges from SR data was suggested by Burke and Jones, (1996) and applied by Huang et al. (1999). Thus, by using ELF transients, one can estimate the global lightning occurrence, its spatial distribution, and the global charge transfer (Sato et al., 2003, 2008).

Synchronous records of three field components of the VLF atmospherics (vertical electric and two magnetic components) and two orthogonal ELF horizontal magnetic field components were obtained during the season of the 24th Ukrainian Antarctic Expedition (UAE).The details of the ELF receiving equipment are described in paper by Koloskov et al., (2004). The synchronization performed in the absolute time allowed us determining VLF atmospherics and ELF transients caused by the same lightning stroke. Such a record is demonstrated in Fig. 5 where we show a dense sequence of ELF transients arriving during one-second interval. About one-half of ELF transients might be associated with VLF atmospherics shown in red. The VLF atmospherics are somewhat ahead of the ELF transient owing to higher propagation velocity in the Earth-ionosphere wave guide and due to the phase delay circuits of the ELF receiver. Absence of VLF atmospherics relevant to some of ELF transients might be explained by the registration algorithm applied only when asingle VLF atmospheric might be recorded in a discrete 200 ms time interval.

Application of VLF atmospherics in the direction finding considerably improves accuracy (Fullekrug et al., 1996; Price and Asfur, 2002). Presence of three field components in the VLF atmospheric measurements allows computing the horizontal components of the Poynting vector and the unambiguous determination of the radio wave arrival direction (Rafalsky et al., 1995a, 1995b). This advantage also allows determining the polarity of the parent lightning discharge and this is important for observations of distribution and dynamics of positive lightning strokes associated with TLEs in the mesosphere and the lower ionosphere –the sprites and elves.

After determining the arrival azimuth and the source distance, we can find both the polarity and the magnitude of the source current moment, and the duration of current in the lightning dischargeby using

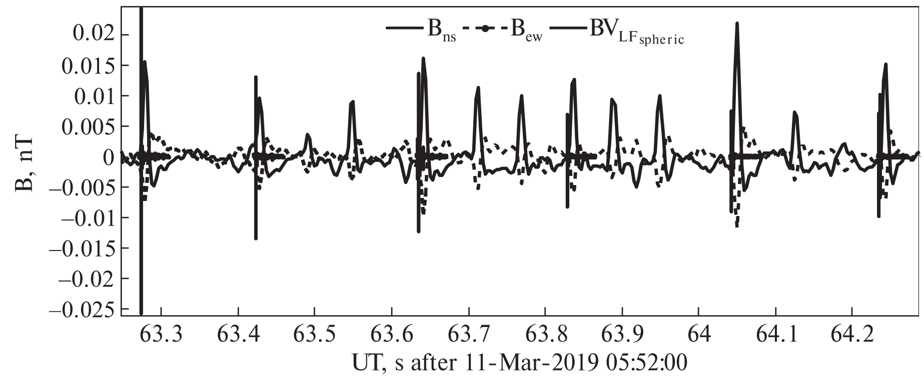

Fig. 5. Synchronous records of the ELF magnetic components (B_{ns} and B_{ew}) and the transversal magnetic component of VLF atmospherics

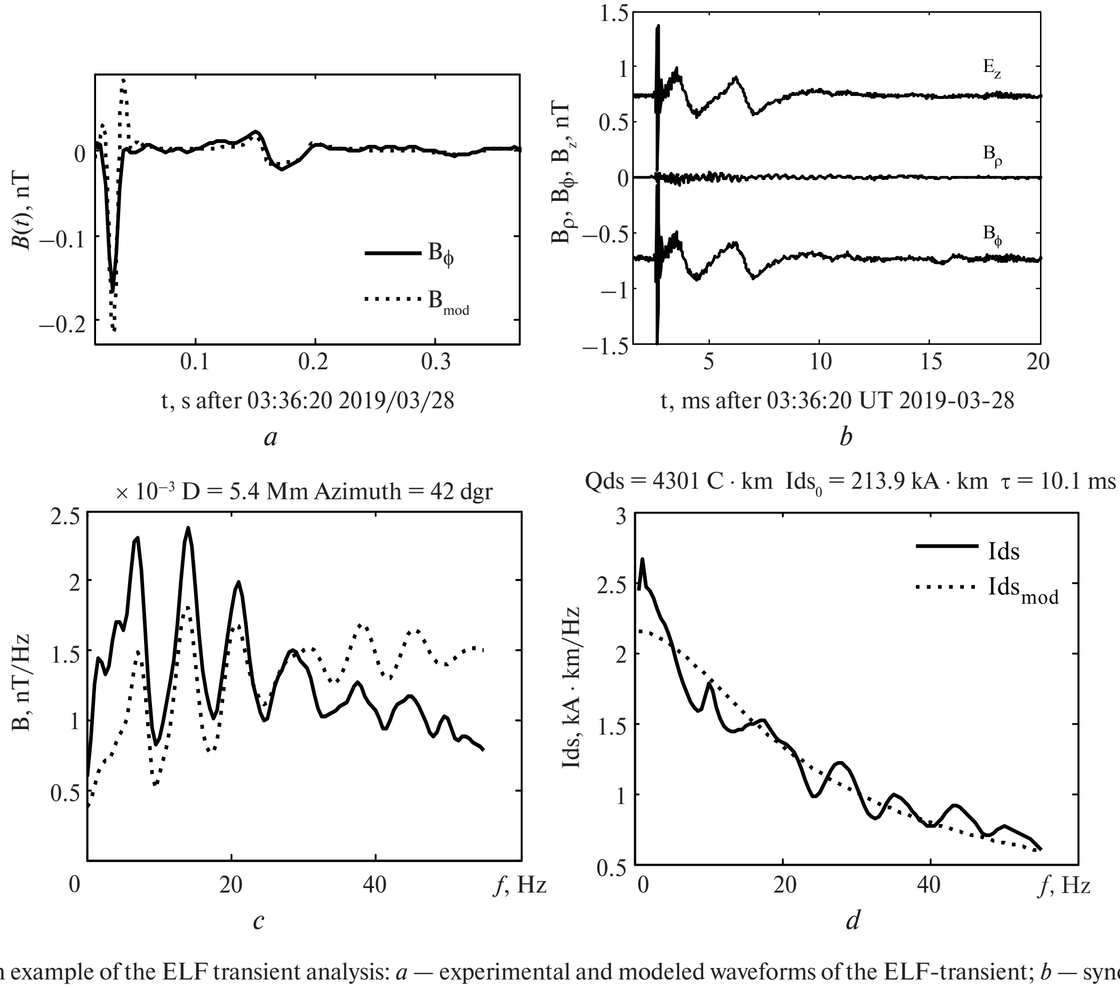

Fig. 6. An example of the ELF transient analysis: *a* — experimental and modeled waveforms of the ELF-transient; *b* — synchronously recorded tweek atmospheric; *c* — experimental and modeled spectra of the ELF-transient; *d* — experimental and fitted current moment of causative lightning discharge

the transverse magnetic field component of the ELF transient. For this purpose, a simple exponential model is used describing the continuing current of the stroke, which is responsible for the ELF. The model was proposed by Burke and Jones (1996) for deriving parameters of the causative lightning discharge. The current moment is expressed in the time and the frequency domain in the following way:

$$Ids(t) = Ids_0 e^{-t/\tau}, \quad Ids(\omega) = \frac{Ids_0\tau}{1+i\omega\tau}, \qquad (4)$$

where Ids_0 is the current moment and τ is the time constant of the continuing current moment. The spectrum of the current moment is obtained by dividing the measured spectrum of an ELF transient by the frequency response of the Earth-ionosphere cavity, computed for the known source – observer distance (Burke and Jones, 1996).

We apply the method combining the synchronous record of VLF atmospheric and the ELF transient for locating the parent powerful discharge. As the first step, the tweek atmospheric arrival direction is found (Fig. 6, *b*), thus we found the bearing of the causative lightning discharge during the nighttime registrations (Shvets et al., 2017b). This technique has limited distance, which cannot exceed a few thousand kilometers. Besides, it might be applied only in the ambient night conditions when tweeks are detected.

As the second step, we find the source distance by using the waveform of an ELF transient arriving from the direction found from the VLF atmospheric. We rotate to coordinate system so that recorded orthogonal magnetic components B_{WE} and B_{SN} of ELF transient turn into the longitudinal component B_ρ and the transverse component B (Fig. 6, *a*). The arrival azimuth is used found from synchronously recorded VLF atmospheric (Fig. 6, *b*). The transverse magnetic field of the ELF transient starts with the initial pulse corresponding to the direct wave from the source to the observer along the short arc of the great circle path.

The pulse on set in the transverse magnetic component must have the same sign as the onset in the vertical electric field component. The negative onset indicates that the parent lightning stroke had the positive polarity. The strong direct pulse is followed by a delayed smaller pulse of the opposite polarity. This is a signal that travelled along the long great circle path and arrived to the observer from the source antipode. It is called 'antipodal wave'.

We superpose the fronts of the direct wave of the measured and the modeled ELF transient, and afterward we adjust the source distance in the model pulse until their antipodal waves also become coincident. Prior to this procedure, we compensate the phase distortions (Yatsevich et al., 2014) caused by the frequency response of receiver circuits. It is very important to determine the actual sign of the onset in the direct wave because it is linked to the polarity of the parent lightning discharge.

The spectrum of the observed ELF transient and the model spectrum of the pulse arriving from the same source – observer distance are shown in Fig. 6, *c*. The spectrum of the current moment is shown in Fig. 6, *d* estimated from experimental data (thick line). The model spectral parameters of the continuing current in Fig. 6, *c* were obtained by fitting the measurements by the model (4) using the least squares algorithm.

We also determined the charge moment transferred by the stroke to the ground $Qds = 2Ids_0\tau = 4301$ C × × km. The contribution from the image of the cloud in the ground was included (Burke and Jones, 1996).

DISCUSSION AND CONCLUSION

In addition to the fundamental harmonic, we also observed the second and the higher-order modes in tweeks recorded at Akademik Vernadsky station when the distance to causative lightning strokes has reached 7500 km. The approximate analytical solution for tweek propagation near the cut off frequencies by Sukhorukov et al., (1992a,b 1996), and Ryabov (1994) allows to employ these modes for estimating the height of the lower ionosphere boundary and the relevant electron density along the particular propagation path. It was established that during the night, March 28–29, 2019, the electron density slowly varied between ~800 and ~1400 cm^{-3} while the lower ionosphere height was found between 85 and 88 km depending on particular propagation paths. These parameters are in good agreement with the results of rocket measurements of the electron density profiles (Friedrich et al., 2018), which demonstrated very steep growth of electron concentration from 1 to ~1000 cm^{-3} in the altitude interval 80–90 km combined with much slower variations at higher altitudes.

We demonstrated the advantages of synchronous records of VLF atmospherics and ELF transients. First, employing the vertical electric and two orthogonal magnetic components measured by the VLF complex allows the accurate and unambiguous finding of the source azimuth. This also allows establishing the polarity of parent lightning strokes. Using synchronous records of ELF transients and tweek atmospherics, we can determine the distance to the lightning discharge and then, the parameters of the current moment of this stroke. A novel technique was also applied to determine the distance toward the lightning discharge by matching the pulsed waveforms corresponding to the short and the long arcs of the great circle path. The technique was tested on the model ELF transient waveforms and afterward, it was applied toward experimentally measured signals. In this case, the source azimuth was established from the VLF atmospheric while the source – observer distance was found by using the ELF transient. This last technique allowed obviating the limitations arising in analysis of ELF transients when employing the distance found from the tweeks.

Analysis of tweeks recorded at UAS indicates that lightning discharges were detected at distances from 2,000 km to about 10,000 km covering a wide area that includes almost entire South American continent, southern Africa and the Gulf of Guinea. Practically, no tweeks were recorded from the Pacific. This might be explained by the higher attenuation of radio waves propagating from west to east direction and, probably, to relatively low level of lightning activity over the ocean at night. The total number of tweeks registered by automated distinguishing system ranged from about 1,000 to 10,000 during different nights. This from 10 to 40% of the total number of atmospherics arrived.

Our experimental study demonstrates the prospects of combined ELF–VLF monitoring at the UAS, which enables continuous nocturnal detection of the globally distributed powerful lightning discharges and the changes in the lower ionosphere related to various processes of atmospheric and terrestrial origin and the phenomena in the space weather.

Acknowledgements. The authors express their gratitude to the State Institution National Antarctic Scientific Center, Ministry of Education and Science of Ukraine (http://uac.gov.ua) for partly funding within the research work (0119U003049, 0119U103575, 0119U103674), and for organizational and logistical support of these studies at Akademik Vernadsky station. The topic of this study corresponds to the main scientific tasks of the departmental research works “Inversiya” (0117U004040) and “Yatagan-3” (0116U000035).

REFERENCES

1. Abarca, S. F., Corbosiero, K. L., Galarneau, T. J. 2010. An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth. *Journal of Geophysical Research*, 115(D18206). doi:10.1029/2009JD013411.
2. Abreu, D., Chandan, D., Holzworth, R. H., Strong, K. 2010. A performance assessment of the World Wide Lightning Location Network (WWLLN) via comparison with the Canadian Lightning Detection Network (CLDN). *Atmos. Measure. Techniques*, 3(4), 1143–1153. doi:10.5194/amt- 3-1143-2010.
3. Biagi, C. J., Cummins, K. L., Kehoe, K. E., Krider, E. P. 2007. National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004. *Journal of Geophysical Research*, 112(D0 5208). doi:10.1029/2006JD007341.
4. Boccippio, D. J.,Williams, E.R., Heckman, S.J., Lyons, W.A., Baker, I.T., Boldi, R. 1995. Sprites, ELF transients and positive ground strokes. *Science,* 269, 1088 – 1091.
5. Brundell, J.B., Rodger, C.J., Dowden, R.L. 2002. Validation of single-station lightning location technique. *Radio Sci.,* 37 (4). doi:10.1029/2001RS002477.
6. Burke, C. P., Jones, D. L. 1996. On the polarity and continuing currents in unusually large lightning flashes deduced from ELF events. *Journal of Atmospheric and Terresfrial Physics,* 58(5), 531—540.
7. Chrissan, D.A., Fraser-Smith, A.C. 1996a. Seasonal Variations of Globally Measured ELF / VLF Radio Noise. *Technical Report D177-1.* Stanford University Dept. of Electrical Engineering, STAR Lab.
8. Chrissan, D.A., Fraser-Smith, A.C. 1996b. Seasonal Variations of Globally Measured ELF / VLF Radio Noise. *Radio Science,* 31(5), 1141—1152.

9. Ester, M., Kriegel, H.-P., Sander, J., Xu, X. 1996. A density-based algorithm for discovering clusters in large spatial databases with noise. *Proceedings of 2nd International Conference on Knowledge Discovery and Data Mining (KDD-96)*. 226—231.
10. Cummer, S. A., Inan, U. S. 1997. Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics. *Geophysical Research Letters*, 24, 1731—1734.
11. Cummer, S. A., Inan, U. S., Bell, T. F., Barrington-Leigh, C. P. 1998. ELF Radiation Produced by Electrical Currents in Sprites. *Geophysical Research Letters,* 25(8), 1281—1284.
12. Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., Pifer, A. E. 1998. A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res*., 103, 9035—9044.
13. Cummins, K. L., Cramer, J. A., Biagi, C. J., Krider, E. P., Jerauld, J., Uman, M. A., Rakov, V. A. 2006. The U. S. National Lightning Detection Network: Post-upgrade status. *Second Conference on Meteorological Applications of Lightning Data. Am. Meteorol. Soc*., *Atlanta, Ga., 29 Jan. to 2 Feb.*
14. Friedrich, M., Pock, C., Torkar, K. 2018. FIRI-2018, an updated empirical model of the lower ionosphere. *Journal of Geophysical Research: Space Physics*, 123, 6737—6751. doi: https://doi.org/10.1029/2018JA025437.
15. Füllekrug, M., Reising, S.C., Lyons, W. A. 1996. On the accuracy of arrival azimuth determination of sprite-associated lightning flashes by Earth-ionosphere cavity resonances. *Geophys. Res. Lett.,* 23(25), 3691–3694.
16. Füllekrug, M., Constable, S. 2000. Global triangulation of lightning discharges. *Geophys. Res. Lett.,* 27, 333–336.
17. Füllekrug, M., Constable, S., Heinson, G., Sato, M., Takahashi, Y., Price, C., Williams, E. 2000. *Global lightning acquisition system installed.* EOS Trans AGU 81(30):333.
18. Gorishnya Y. V. 2014. Electron density and lower ionosphere height estimations by results of analysis of multimodal tweek-atmospherics. *Radiophysics and electronics*, 19(1), 20—28. (In Russian).
19. Huang, E., Williams, E., Boldi, R., Heckman, S., Lyons, W., Taylor, M., Nelsonfi,T., Won, C. 1999. Criteria for sprites and elves based on Schumann resonance observations. *Journal of Geophysical Research*, 104(D14), 16,943—16,964.
20. Hutchins, M.L., Holzworth, R. H., Brundell, J. B., Rodger, C. J. 2012. Relative detection efficiency of the World Wide Lightning Location Network. *Radio Science*, 47 (RS6005). doi:10.1029/2012RS005049.
21. Kemp, D.T., Jones, D. Ll. 1971. A new technique for analysis of transient ELF electromagnetic disturbances within the Earth–ionosphere cavity. *J. Atmos. Terr. Phys*., 33, 567–572.
22. Kemp, D.T. 1971. The global location of large lightning discharges from single station observations of ELF disturbances in the Earth–ionosphere cavity. *J. Atmos. Terr. Phys*., 33, 919–928.
23. Koloskov, A. V., Budanov, O. V., Bezrodny, V. G., Yampolski, Yu. M. 2004. Location of Superpowerful Lightning Flashes through Polarization Magnetic Measurements in Schumann Resonance Waveband. *Radio Physics and Radio Astronomy*, 9(4), 391—403.
24. Lazebny, B.V., Nickolaenko, A.P. 1976. Synchronous observations of the ELF bursts in the frequency range of the Schumann resonances. *Geomagnetism and Aeronomia*, 16(1), 121—126, (in Russian).
25. Nickolaenko, A. P., Hayakawa, M., Ogawa, T., Komatsu, M. 2008. Q-bursts: A comparison of experimental and computed ELF waveforms. *Radio Sci.,* 43(RS4014). doi: 10.1029/2008RS003838.
26. Nickolaenko, A.P., Hayakawa, M. 2002. *Resonances in the Earth-ionosphere cavity*. Kluwer Academic Publishers, Dordrecht-Boston-London.
27. Nickolaenko A., Hayakawa, M. 2014. Schumann Resonance for Tyros (Essentials of Global Electromagnetic Resonance in the Earth–Ionosphere Cavity). *Springer Geophysics Series XI*. Springer Tokyo Heidelberg New York Dordrecht London. doi: 10.1007/978-4-431-54358-9.
28. Nickolaenko, A.P., Shvets, A.V., Hayakawa, M. 2016. Extremely Low Frequency (ELF) Radio Wave Propagation: A review. *International Journal of Electronics and Applied Research (IJEAR)*, 3(2), 1—91. http://eses.net.in/online_journal.html.
29. Ogawa, T., Tanaka, Y., Fraser-Smith, A.C., Gendrin, R. 1967. Worldwide simultaneity of a Q–burst in the Schumann resonance frequency range. *J. Geomagn. Geoelectr*., 19, 377–384.
30. Ogawa, T, Komatsu, M. 2007. Analysis of Q-burst waveforms. *Radio Sci*., 42(RS2S18). doi:10.1029/2006RS003493.
31. Ogawa, T, Komatsu, M. 2009. Q-bursts from various distances on the Earth. *Atmospheric Research*, 538—545.
32. Orville, R. E., Huffines, G. R. 2001. Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989—98. *Mon.Weather Rev*., 129, 1179—1193.
33. Orville, R. E., Huffines, G. R., Burrows, W. R., Holle, R. L., Cummins, K. L. 2002. The North-American Lightning Detection Network (NALDN)—First results: 1998—2000. *Mon. Weather Rev*., 130, 2098—2109.
34. Price, C., Asfur, M., Lyons, W., Nelson, T. 2002. Improved ELF/VLF method for globally geolocating sprite-producing lightning. *Geophys. Res. Lett*., 29, 1031, doi:10.1029/2001GL013519.
35. Rafalsky, V.A., Nickolaenko, A. P., Shvets, A. V., Hayakawa, M. 1995a. Location of lightning discharges from a single station. *J. Geoph. Res*., 100(D10), 20,829—20,838.
36. Rafalsky, V. A., Shvets, A. V., Hayakawa, M. 1995b. One-site distance-finding technique for locating lightning discharges. *J. Atmos. Terr. Phys*., 57, 1255—1261.

37. Ryabov, B. S. 1994. Tweek formation peculiarities. *Geomagnetism And Aeronomy*. English Translation, 34(1), Russian Edition: January–February 1994, 60–66.
38. Sato, M., Fukunishi, H. 2003. Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events. *Geophys. Res. Lett.*, 30(16), 1859. doi:10.1029/2003GL017291.
39. Sato, M., Takahashi, Y., Yoshida, A., Adachi, T. 2008. Global distribution of intense lightning discharges and their seasonal variations. *Journal of Physics D: Applied Physics,* 41, 234011 (10pp). doi:10.1088/0022-3727/41/23/234011.
40. Shvets, A. V., Gorishnyaya, Y. V. 2011. Lightning location and estimation of the lower ionosphere effective height using dispersion properties of tweek-atmospherics. *Radiophysics and Electronics*, 16(4), 53–59, (In Russian).
41. Shvets, A. V., Serdiuk, T. M., Gorishnyaya, Y. V., Hobara, Y., Hayakawa, M. 2014. Estimating the lower ionosphere height and lightning location using multimode “tweek”-atmospherics. *JASTP,* 108. 1 – 9.
42. Shvets, A.V., Krivonos, A.P., Serdiuk, T.N., Hayakawa, M. 2017a. A Technique for Automatic Monitoring the Lower Ionosphere and Lightning Location by Tweek-Atmospherics. *International Journal of Electronics and Applied Research (IJEAR*), 4(1), 37–51. http://eses.net.in/online_journal.html.
43. Shvets, A.V., Krivonos, A.P., Ivanov, V.K. 2016. A complex for multicomponent measurements of the ELF-VLF electromagnetic fields. *Radiophysics and electronics*, 7(21), 4. 49–55. (In Russian).
44. Shvets, A.V., Serdiuk, T., Krivonos, A., Hayakawa, M. 2018. Automatic method for monitoring the lower ionosphere and lightning location by tweek-atmospherics. *Proc. of the 2018 International Symposium on Electromagnetic Compatibility (EMC Europe 2018)*. Amsterdam, The Netherlands, August 27—30, 2018, 789—794.
45. Shvets, O.V., Nickolaenko, O.P., Koloskov, O.V., Yampolski, Y.M., Budanov, O.V., Shvets, A.O. 2019. First results of observations of tweek atmospherics at Akademik Vernadsky station. *IX MAK 2019*, *Kyiv, Ukraine, 14—16 May, 2019*. 176—178.
46. Shvets, A.V., Krivonos, A.P. 2017b. Preliminary results of monitoring the lower ionosphere based on the analysis of tweek-atmospherics. *Radiophysics and electronics*, 22(3), 14—22. (In Russian).
47. Sukhorukov, A. I., Shimakura, S., Hayakawa, M. 1992a. Approximate solution for the VLF eigenvalues near cut-off frequencies in the nocturnal inhomogeneous Earth-ionosphere waveguide. *Planet. Space Sci.*, 40(10), 1363—1369.
48. Sukhorukov, A. I., Shimakura, S., Hayakawa, M. 1992b. On The Additional Dispersion of a Whistler in the Earth-Ionosphere Waveguide. *Planet. Space Sci.*, 40(9), 1185—1191.
49. Sukhorukov, A.I. 1996. ELF-VLF atmospheric waveforms under night-time ionospheric conditions. *Annales Geophysicae*, 14, 33–41. doi:https://doi.org/10.1007/s00585-996-0033-7.
50. Yamashita, M. 1978. Propagation of tweek atmospherics. *Journal of Atmospheric and Terrestrial Physics,* 40. 151—156.
51. Yatsevich, E.I, Shvets, A. V., Nickolaenko, A.P. 2014. Impact of the ELF Receiver on Characteristics of the Observed Q-bursts. *Radiophysics and Quantum Electronics*, 57(3), 176—186. doi: 10.1007/s11141-014-9502-0.

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ДОСЛІДЖЕННЯ НИЗЬКОЧАСТОТНИХ ННЧ-ДНЧ РАДІОАТМОСФЕРИКІВ НА УКРАЇНСЬКІЙ АНТАРКТИЧНІЙ СТАНЦІЇ «АКАДЕМІК ВЕРНАДСЬКИЙ»

РЕФЕРАТ. У даній статті описано результати вимірювань атмосфериків в діапазонах наднизькочастотних (ННЧ) і дуже низькочастотних (ДНЧ), виконаних на Українській антарктичній станції (УАС) «Академік Вернадський» (64.26 W; 65.25 S) протягом лютого—квітня 2019 року. **Основною метою** дослідження була реалізація однопозиційного методу для моніторингу параметрів нижньої іоносфери та локації потужних грозових розрядів, розподілених по всій планеті. **Методи**. Приймально-аналізуючий ДНЧ-комплекс використовувався на станції для реєстрації двох горизонтальних магнітних і вертикальної електричної компоненти атмосфериків в діапазоні частот 750 Гц — 24 кГц. Однопозиційний метод локації блискавок заснований на аналізі твік-атмосфериків (твіків) і реалізований в програмному забезпеченні приймальної системи. Записи ДНЧ атмосфериків були синхронізовані з допомогою часових міток GPS-приймача із записами перехідних ННЧ процесів, викликаних глобально розподіленими потужними грозовими розрядами. Результати аналізу твіків, зареєстрованих на УАС «Академік Вернадський», вказують на те, що розряди блискавки реєструються на відстанях від 2000 км до, приблизно, 10 000 км в межах азимутального сектора, що охоплює майже весь континент Південної Америки, південь Африки і Гвінейську затоку. Практично жодного твіка з Тихого океану не було зафіксовано. Це можна пояснити обопільним ослабленням радіохвиль, що поширюються в напрямках захід—схід і схід—захід. Окрім основного типу нормальних хвиль в твіках спостерігались нормальні хвилі другого і більш високих порядків. Це дозволило оцінити висоту нижньої межі і щільність електронів в нижній іоносфері. Представлено переваги одночасного запису ДНЧ атмосфериків і перехідних ННЧ процесів. Використання вертикальної електричної і двох горизонтальних магнітних компонент, виміряних комплексом ДНЧ, дозволило однозначно і більш точно визначити азимут джерела і визначити знак заряду який переноситься при розряді блискавки. Поєднуючи записи ННЧ і ДНЧ, ми можемо визначити дальність до блискавки, а потім параметри токового моменту грозового розряду. **Висновки**. Проведені експериментальні дослідження показали перспективу подальшого комбінованого ННЧ-ДНЧ моніторингу на УАС «Академік Вернадський», що дозволяє виявляти потужні грозові розряди і зміни в нижній іоносфері, пов'язані з різними явищами космічної погоди, атмосферного і земного походження.

Ключові слова: перехідні ННЧ процеси, однопозиційний метод локації блискавок, радіохвилі ННЧ-ДНЧ, хвилевід Земля-іоносфера, твік-атмосферик, нижня іоносфера.