Ukrainian Journal of Remote Sensing
journal homepage: www.ujrs.org.ua

https://doi.org/10/36023/ujrs.2022.9.4.218

UDC 537.87+550.388.2

Correlational Analysis of the ELF – VLF Nighttime Atmospherics Parameters

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Tweek-atmospherics (tweeks), along with radio transmission by VLF radio stations, are used to study the lower ionosphere. Electromagnetic pulse radiation, which has been excited by the lightning discharges, has a maximum spectral density at extra low frequencies range (ELF, 300...3000 Hz) and very low frequencies (VLF, 3...30 kHz). The Earth-ionosphere cavity serves as a waveguide for electromagnetic waves in these frequency ranges. On the spectrogram of the tweek, the initial part is a linearly polarized broadband signal, and then a number of individual harmonics are observed. Their instantaneous frequencies decrease, asymptotically approaching approximately multiples of the cutoff frequencies of the waveguide. The single position method for lightning location and estimation of the ELF wave's reflection heights in the lower ionosphere by tweeks has been implemented into the computational algorithm. The clusters with approximately the same azimuths and distances to sources which have been obtained during the same night have been identified upon the ensemble of tweek-atmospheric records. The data were accumulated at the Ukrainian Antarctic Station "Akademik Vernadsky" in 2019. The location of the receiving complex in the near-polar region makes it possible to register tweek sources in two world thunderstorm centers with geographic azimuths from –60° to 130°. The results of processing these data have been used by studying the correlation matrix and partial correlation coefficients to identify causal relationships between the three main parameters of the tweek, such as (1) the average azimuth of the arrival of tweeks in regard to the magnetic meridian, (2) the average distance to the center of the cluster of tweek sources (lightning discharges), and (3) the average number of tweek harmonics. The same correlation analysis was applied to two groups with distances to sources of 2.2...7.5 Mm and 7.6...9.5 Mm used for study in detail. It is shown that the partial correlation coefficients between the number of tweek harmonics and the difference of the magnetic azimuth from the magnetic east are 0.624 (for the entire range of distances), 0.696 (for far tweek sources) and 0.595 (for main middle range), so, they always exceed the values of 0.1% significance level. The correlation of tweek spectrum with the distance to the tweek source in the range of 2.2…7.5 Mm has been shown to be comparable in magnitude or to exceed the correlation of tweek spectrum with the magnetic azimuth. The elimination of this masking effect by calculating the partial correlation coefficients made it possible to reveal the magnetic azimuth dependences of the tweek spectra if tweek propagates in a region outside the geomagnetic equator. Thus, the effect of non-reciprocity of propagation of ELF – VLF waves in regard to the magnetic meridian in the east–west and west–east directions is found in the spectra of tweek-atmospherics. It results in an increased probability of detecting tweeks with higher harmonics if their directions of arrival are close to the geomagnetic east. It is also shown that this effect, as a result of increased attenuation during the propagation of ELF – VLF radiation from the west and weakened attenuation during propagation from the east, leads to a highly significant correlation (with probability level more than 99.9%) between the magnetic azimuths of tweeks and the lengths of their paths to the receiving station.

Keywords: lower ionosphere diagnostic, ELF – VLF radiowaves, tweek-atmospherics, lightning location.

1. Introduction

Electromagnetic pulse radiation which has been excited by the lightning strokes has a maximum spectral density at the frequency band embraced by extra low frequencies range (ELF, 300...3000 Hz) and very low frequencies range (VLF, 3...30 kHz). The Earth-ionosphere cavity serves as a waveguide for electromagnetic waves in these frequency ranges. At night, so-called tweek-atmospherics, or tweeks, are often observed. They are characterized by a longer duration than that of daytime atmospherics, up to 10…100 ms. In the spectrogram of the tweek, the initial part is a linearly polarized broadband signal, then a number of individual harmonics are observed, and their instantaneous frequencies decrease, asymptotically approaching approximately multiples of the cutoff frequencies of the waveguide. Along with radio transmission by VLF radio stations, the use of these natural signals allows to study a layer of ionosphere at altitudes of 60...90 km with a low electron concentration ($10^6…10^9$ m^{-3}).

Tweek atmospherics have been singled out as a special subspecies of atmospherics due to their extremely long duration (Burton et al, 1933). The use of a waveguide model with isotropic conducting boundaries made it possible to satisfactorily explain the dispersion properties of tweeks (Outsu, 1960). A number of tweek pecularities were discovered later, namely: tweeks are recorded when the signal source and receiver are at night conditions, or even during a solar eclipse (Reeve et al., 1972), the polarization of the tweek signal in the final, so-called tail part is typically close to left-circular polarization. Extra long tweek tails are also poorly

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explained by isotropic waveguide model. These facts can be explained using theory from (Yamashita, 1978, Ryabov, 1994).

An improved modification of the single-position (so-called "Kharkiv") method for lightning location and estimation of the lower ionosphere height by tweek-atmospherics is described in detail in (Shvets et al., 2011, Shvets et al., 2015). The stages of the modified technique are as follows: calculation of the dynamic spectra (sonograms) of a signal based on its parts of variable length, which is determined by preliminary estimations of the path parameters of a given tweek; isolation of signal harmonics in the sonogram and automatic selection of tweek parameters that give satisfactory approximations of the observed tweek harmonics for one of the three signal components. Algorithm (Shvets et al., 2011, Shvets et al., 2015) was tested on model tweek signals. It was shown that, up to 8 Mm source distances, good agreement is achieved between the model and calculated parameters of the tweek path (Gorishnya et al., 2012, Shvets et al., 2015). The estimations of reflection heights in the ionosphere for the first (fundamental) and higher harmonics, and the estimations of polarization parameters of the tweek signal by this method were made in a number of works on an ensemble of experimental tweek records (Gorishnya et al., 2010, Gorishnya, 2018, Gorishnya, 2019), obtained in tropical regions during the voyage of the research vessel (R/V) "Akademik Vernadsky" in 1991. The paths to lightning sites that serve as sources of tweeks were from 0.5 Mm to 4.5 Mm long according to estimations based on this ensemble.

The east–west asymmetry of first quasi-transverse electric (QTE) mode propagation with frequencies ~2…3 kHz in the Earth-ionosphere wavequide is known fron observations of atmospherics (Krasnushkin et al., 1967, Lynn et al., 1967). The azimuthal dependence was revealed (Shvets et al., 1998, Gorishnya, 2018, Gorishnya, 2019) in the tweek polarization at the first harmonic, where it manifested itself at source distances of 1.5...4.5 Mm as non-reciprocity of east–west propagation.

In later works (Gorishnya, 2020, Gorishnya, 2021a) an azimuthal dependence in the tweek spectra was observed on the base of the number of tweek harmonics at source distances of 8…10 Mm, according to the experimental records database accumulated at the Ukrainian Antarctic Station (UAS) "Akademik Vernadsky" in 2019–2021. Tweek-atmospherics in this database have source at the distances of 1.5…10 Mm or more.

Within the frequency range of 1.6…20 kHz, up to 9 harmonics are revealed in the experimental recordings of tweek atmospherics. Current surveys near the world's thunderstorm centers are detecting broadband tweeks, with instances of tweeks that include higher harmonics up to the 6th (Maurya et al., 2012), but generally do not determine signal arrival directions. Using experimental material, it was previously shown that at source distances of more than 1.5 Mm, tweeks have 2...4 harmonics in the spectrum (Gorishnya et al., 2010). The ratios of the reflection and attenuation parameters in the lower ionosphere, as well as the background noise level, lead to the fact that, for source distances to the receiver about 10 Mm, tweek harmonics are usually not observed, except for the fundamental one.

According to the theoretical assumptions, outside the narrow equatorial band an azimuthal dependences in the tweek's propagation at distances of 4...10 Mm should manifest themselves significantly. The predicted low number of harmonics in the spectrum of tweeks forces us to use the largest possible ensemble of recordings to observe these features statistically.

This work purpose is to study the azimuthal dependence of the ELF – VLF spectrum of a tweek (i.e., the number of its harmonics) on array with tweek paths from 1.5 Mm to the limits of reliable detection of about 10 Mm, as well as a detailed consideration of other causal relationships between ELF and VLF propagation characteristics of night atmospherics through correlation analysis.

2. Data and processing methods

Through three orthogonal components of the tweek recording one can determine the arrival azimuth of tweeks. The dynamic spectrum (sonogram) of the tweek-atmospheric for frequencies ≤25 kHz by sectors of variable length is obtained, and than the computational algorithm (with a probability less than 1) detects in sonogram the first (fundamental) harmonic and harmonics of a higher order, if they are present in the signal. For each tweek-atmospheric, a pair of values [h, D] is calculated based on all harmonics available for processing, where h is the average effective height of the reflecting layer in the lower ionosphere along the tweek path, and D is the distance to the tweek source. Automatic selection of tweek parameters that give satisfactory approximations of the tweek harmonics is performed in such a way as to achieve the best fit for all harmonics taken into account simultaneously. Also, the effective heights and source distances are calculated separately, determined in pairs from the frequency dispersion dependence of each harmonic of the tweek.

Three-component records of the tweeks were obtained as a set of implementations 40 ms long. The intensity of the thunderstorms often leads to the superposition of signals after a lightning discharge, the impulse radiation from which exceeded the threshold value and caused the start of recording. Such overlays of tweek-atmospherics turn out to be an interference signal to each other and prevent obtaining parameter estimations from a given record.

The UAS "Akademik Vernadsky" is located near the polar circle, at 65°14´44" S, 64°15´28" W, geomagnetic coordinates at 2019 are 55.7°S and 6.3°E. The receiving unit and the details of its operation were described in (Shvets et al., 2019). Tweeks are observed when the receiving station is in the night hemisphere, e.i. during the local nighttime.

It was shown (see in (Maurya et al., 2012, Gorishnya, 2014)) that through the effective heights of the reflecting layer determined from tweeks, the daily and seasonal regular changes in the lower ionosphere heights are displayed and can be traced. There are also demonstrated the presence of a selected range of reflection heights of

87…89 km, in which tweeks with a high number of harmonics are observed more often in any range of *D*, and for heights ≥90 km, the harmonic's number was 2…4 (Gorishnya, 2014). Since the reflection heights, as shown in (Gorishnya, 2021b), do not correlate with the distances to the tweek source and the azimuths of its arrival, their influence on the correlation coefficients of the other three parameters (distances, azimuths, and spectrum) will be insignificant.

Given this circumstance, we can study the correlation matrix of only three parameters, and to use data on thunderstorms regardless of local time at the place of tweek-atmospherics excitation, as well as to use data on thunderstorms accumulated during the entire night or any part of it. For large and extra-large lengths of the tweek path, the local time of night can (depending on the path layout) vary greatly at the source point and the reception point, and the accordance of the effective reflection height of the tweek and some local time is an additional computational problem, which in this case will not need to be dealt with.

The reception point on UAS "Akademik Vernadsky" can record tweeks generated by two world thunderstorm centers in the tropics of the Americas and Africa. The work (Christian et al., 2003) reported that about 78% of lightning on Earth occurs around ±30° of the geographic equator. So, tweek observations in the polar Arctic and Antarctic regions usually reveal distances to the atmospheric sources of 4...6 Mm (Saini et al., 2010) or 0.7…7 Mm (Yusop et al., 2014). Current records of tweeks in our database are very numerous, however they have a range of azimuths from 290° to 130°.That means their bulk arrived from the northern and eastern sectors relatively to the observation site. Tweeks with western azimuths are rare (no more than 2% per night). Single observed tweeks from western sector have the first harmonic only and path lengths of 2.5...5 Mm.

The total number of records received is up to 30,000 per night. For example, within an hour from 4 to 5 a.m. UTC on March 1, 2019 the total number of records was 1355. About a third of records has been identified as tweeks, the rest are atmospherics with spectra of a different nature. For the study, a period of time was chosen near the equinox, from February 23 to March 5, 2019. There were no magnetic storms during this period (three-hour planetary index K_p < 5). On the day of February 27, 2019, a weak solar flare was observed, which caused a disturbed magnetosphere on the nights of February 28 and March 1 (index K_p = 3+…4+, reached 5 once). Involving data for these two days for comparison, one can point out that the total number of observed tweeks for February 28, 2019 was 452, tweeks for the entire night of March 1 – 1775 records. At night, under conditions of a calm and slightly disturbed magnetosphere, the number of recorded tweeks ranged from ~1500 (February 23, 2019, March 4, 2019) to 6700 (at February 25, 2019), for March 2, 2019 – 2329, in other cases, about 3300...3700 per night.

Using the data for specific time interval (for example, a part of a night or a full night), we separated groups of tweeks generated by a common thunderstorm source that were close in range and azimuth.

To separate such groups, a procedure based on the density of spatial clustering for applications with noise (Density-based spatial clustering of applications with noise, DBSCAN) is used (Ester et al., 1996). The DBSCAN algorithm was proposed in 1996 as a solution to the problem of partitioning (originally spatial) data into arbitrary-shaped clusters. Most algorithms that produce planar partitioning create clusters that are close to spherical in shape, since they minimize the distance of documents from the center of the cluster. The authors of DBSCAN have experimentally shown that their algorithm is able to recognize clusters of various shapes. DBSCAN requires two parameters to be set: the distance ε and the minimum number of points *M* (in this case, *M* = 7 is set), which should form a dense region in the ε-neighborhood of each cluster point.

Fig. 1 shows an example of tweek mapping. The location on the map of clusters of tweek sources (lightnings) is depicted for March 3, 2019, the clusters were allocated automatically as a result of the DBSCAN algorithm, and the numbers indicate the tweek source magnitude. The crosses indicate the sources of tweeks. The dotted line shows lines of equal azimuth and equal distance from the receiving point at the UAS "Akademik Vernadsky".

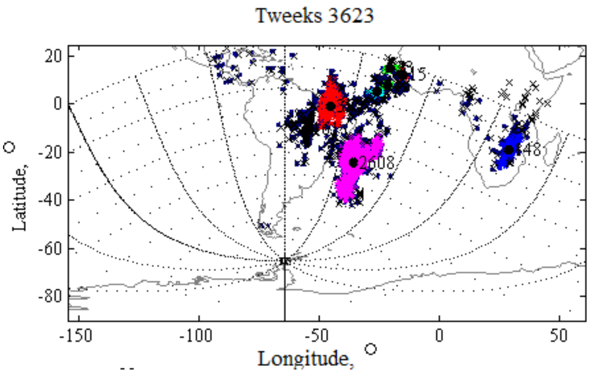

Fig. 1. Example of tweek mapping for March 3, 2019

A thunderstorm center near the Brazilian coast (where the climatic maxima of thunderstorms are observed), associated with the features of the relief of the Brazilian Highlands, often turns out to be a strip extended along the "line of sight" for a reception point in Antarctica. So, we varied the distance ε used as a clustering criterion, to achieve the more detailed division of groups of tweeks.

For a sample of ≥20 specimens, the calculation of averages for various sample values will be highly reliable. However, for the sake of a wider coverage of azimuths and source distances, and of an increase in the number of thunderstorm centers studied, all data in the case of *M* ≥ 7 were involved. The data are given in Table 1 and Table 2, where the date of the night of recordings, the clustering parameter ε, the geographic azimuth of the cluster center *Az* and the distance to it, the average number of tweek harmonics over the cluster <*N*>, and the number *M* of tweeks in the cluster with the 1st (fundamental) harmonic are represented.

Table 1

Day	ε, km	*Az*, °	*D*, Mm	<*N*> harmonics	*M* of tweeks		Day	ε, km	*Az*, °	*D*, Mm	<*N*> harmonics	*M* of tweeks
27.02	240	107	7.6	1.976	344		24.02	320	40	8.7	1.071	42
3.03	280	34	7.6	1	10		3.03	280	42	9	1	131
5.03	260	101	8	1.74	158		5.03	260	57.5	9	1.083	12
25.02	380	102	8	1.462	80		5.03	260	98.5	9	1.454	11
4.03	280	23	8.1	1	31		23.02	220	42	9	1.109	64
5.03	260	38	8.2	1.051	194		4.03	280	62.5	9.2	1	8
25.02	220	37	8.3	1.071	154		27.02	340	44	9.3	1	101
3.03	280	101	8.3	1.728	158		4.03	280	37.5	9.3	1.122	41
25.02	380	109	8.4	1.56	25		2.03	360	333.5	9.4	1	30
27.02	240	34	8.5	1.2	20		5.03	260	76.5	9.5	1.028	35
27.02	240	117	8.6	1.381	21		3.03	400	76.5	9.5	1	12

Table 1 covers thunderstorm cells that can be described as "distant cells", with ranges of 7.6 to 9.5 Mm. Their geographical azimuths differ and cover the northern and eastern sectors of directions, from 330° to 120°. Of the 22 such groups, most are the large ones (out of ≥20 specimens, and 9 consist of ≥60 specimens), 5 have 8...12 specimens.

As indicated above, the specific reflection mechanism of ELF – VLF tweek radiation from the lower ionosphere at night, in contrast to daytime conditions, depends on the electron gyrofrequency, and, therefore, on the geomagnetic field at the reflection height in the lower ionosphere. This manifests itself as dependences of the tweek attenuation parameters on the angle of their propagation vector with the horizontal component of the magnetic field at this height. For the first few harmonics of the tweek, the least attenuation is theoretically predicted when coming from the geomagnetic east. Fig. 2 shows the average number of tweek harmonics in a cluster as a function of the modulus of the difference between its magnetic azimuth and 90°. Data from Table 1 are shown as rhombs.

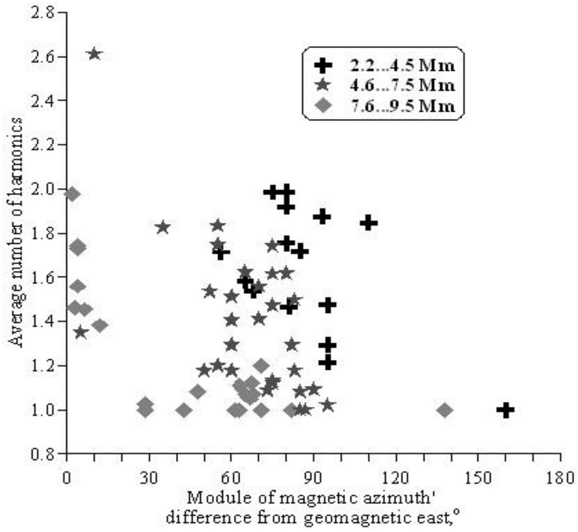

Fig. 2. The average number of harmonics in a thunderstorm cluster as a function of the modulus of the magnetic bearing difference with geomagnetic east

The significant difference in the spectra is shown on Fig. 2. During the late summer season, at such long distances the thunderstorm cells were observed in Mexico, in the equatorial Atlantic, and along the African coast of the Gulf of Guinea. Less than 10% of the tweeks with the sources localized in these areas had the 2nd harmonic, and the 3rd and higher ones were not observed at all. However, in addition to these two global thunderstorm centers in the tropics, climatic patterns lead to heavy thunderstorms during the rainy season in southern Africa and over Madagascar. The movement of the geomagnetic poles has led to the fact that in the 2019 epoch the direction of the arrival of tweeks from such sources to the “Akademik Vernadsky” station almost exactly coincided with the geomagnetic east. As a result, the probability of observing higher harmonics of the tweek, except for the fundamental one, from these thunderstorm sources increased sharply.

For clusters of tweeks from Table 2, the data in Fig. 2 are shown with stars and crosses. Large thunderstorm centers were divided into adjacent clusters. In the 2.2…7.5 Mm zone, there are tweeks with the 3rd harmonic, and occasionally with the 4th. Out of 46 clusters, large ones absolutely predominate (out of ≥18 specimens, and 34 clusters consist of ≥60 specimens), 4 embrace 7…14 specimens.

The tweek paths from Table 2 lay almost completely outside the region of the magnetic equator of the 2019 epoch. This means that the theoretical predictions of the tweek propagation model should hold for their set. Let us explain this circumstance in more detail.

After a short (2...3 ms) head part of the tweek, then a "mixed polarization" region is observed, formed by a system of elliptical left-hand polarized quasi-*TE* modes (QTE) and right-hand polarized quasi-*TM* (QTM) modes of the waveguide. It lasts 10...15 ms for a distance from the source of 3 Mm, and is about 30...50 ms for tweeks with long paths of 8 Mm. In the region of circular frequencies ω close to the tweek critical frequencies ω_k, it is more correct to consider the tweek modes as *L*- and *R*-modes (left and right circularly polarized) (Sukhorukov et al., 1992). This part of the tweek waveform is called the tail of the tweek.

Table 2

Day	ε, km	*Az*, °	*D*, Mm	<*N*> harmonics	*M* of tweeks		Day	ε, km	*Az*, °	*D*, Mm	<*N*> harmonics	*M* of tweeks
23.02	220	355	2.2	1.846	14		28.02	420	50	5.3	1.2	40
28.02	420	49	2.6	1.714	7		4.03	280	30	5.5	1.471	153
27.02	440	12	2.8	1.875	8		27.02	280	45	5.5	1.513	115
1.03	260	10	3	1.292	24		4.03	280	45	5.5	1.293	41
27.02	240	40	3.5	1.582	171		27.02	240	30	5.6	1.742	2347
2.03	280	25	3.5	1.986	984		28.02	260	22	5.9	1.178	73
5.03	120	25	3.6	1.753	1529		24.02	320	95	5.9	2.611	18
23.02	220	30	3.6	1.985	69		5.03	120	30	6	1.131	574
28.02	420	24	3.6	1.467	77		25.02	320	50	6	1.747	79
3.03	80	37	3.8	1.538	236		3.03	80	45	6	1.178	73
4.03	280	10	3.8	1.214	694		2.03	280	18	6	1	51
24.02	280	20	3.8	1.717	2903		23.02	220	53	6.1	1.536	138
23.02	220	10	4	1.476	700		24.02	220	55	6.2	1.176	68
25.02	280	305	4.2	1	7		23.02	220	20	6.5	1.084	166
25.02	120	25	4.5	1.919	5578		24.02	220	45	6.5	1.404	198
1.03	200	40	5	1.622	1261		1.03	200	20	7	1.082	159
1.03	200	50	5	1.834	211		24.02	320	100	7	1.351	37
3.03	80	35	5	1.56	2069		24.02	280	23	7	1.293	157
5.03	120	25	5	1.617	298		3.03	280	15	7	1.091	551
5.03	260	70	5	1.825	120		4.03	280	10	7	1.021	48
28.02	260	35	5.2	1.411	197		4.03	280	32	7	1.088	748
2.03	280	30	5.2	1.615	1158		25.02	120	22	7.2	1.498	209
23.02	220	30	5.3	1.12	83		28.02	380	20	7.4	1	18

The attenuation coefficients of the *m*-th mode of the quasi-*TM* modes are $\alpha_m^{qTM}(EW) > \alpha_m^{qTM}(WE)$, for east–west and west–east propagation respectively, the reverse of the situation for the quasi-*TE* modes, where the case of $\alpha_m^{qTE}(EW) < \alpha_m^{qTE}(WE)$ is observed. For $(\omega - \omega_k)/\omega_k << 1$ everywhere there are conditions of great inequality, $\alpha_m^{qTM} >> \alpha_m^{qTE}$. This results in near-left circular polarization in the tail of the tweek. For the applicability of theoretical models of the propagation of a tweek-atmospheric signal (Ryabov, 1994, Sukhorukov et al., 1992), which have been developed to date, the condition of quasi-longitudinal propagation in regard to the geomagnetic field in the reflecting layer of the ionosphere is to be satisfied for the tweek tail.

This condition is not satisfied in a narrow, latitudinally elongated region near the equator, where the magnetic inclination is 90° ± 15°. This area shifts depending on the location of the geomagnetic poles.

3. Correlation matrix and discussion of results

Using the recording of three components of the tweek field (two magnetic, B_ρ and B_φ, and one electric E_z) allows determining the true (within 0….360°) azimuth of the arrival of tweeks. Based on the data on the geomagnetic field for the 2019 epoch and the magnetic coordinates of the station, the magnetic bearing to the tweek source has been then determined (within 0….360°). Despite the irregular shape of the clusters, as described above, the bearings of the cluster center identified by the algorithm were taken as the average bearing of the clusters for the data in Tables 1 and 2, which seems to be sufficient for statistical correlation analysis. The same approach was taken for the distances to the cluster.

The causal relationship between three parameters was studied:

- $x1$ – average number of harmonics of tweek-atmospherics in a cluster;
- $x2$ – modulus of difference between magnetic bearing φ in regard to magnetic meridian and 90° (direction to magnetic east);
- $x3$ – distance *D*.

After considering the complete set of n = 68 clusters of tweek-atmospherics, we find that the correlation matrix of the sample $\boldsymbol{R} = \{\boldsymbol{r}_{ij}\}$ has the form:

$$\begin{Bmatrix} 1 & -0.273 & -0.520 \\ -0.273 & 1 & -0.410 \\ -0.520 & -0.410 & 1 \end{Bmatrix}$$

The significance of different correlation coefficients $\boldsymbol{r}_{ij}$ can be estimated using Student's distribution (Cramer, 1975). The hypothesis of independence of values x_i and x_j should be rejected from the point of view of the *p*-percentage level of significance if the modulus of $\boldsymbol{r}_{ij}$ exceeds the value of $t_p / \sqrt{t_p^2 + \nu}$, where t_p denotes the *p*-percentage value of t at $\nu = n - 2$ degrees of freedom.

For the usual 5-, 1-, and 0.1- percent significance levels (which are traditionally referred to as nearly significant, significant, and highly significant, respectively), magnitude values $t_p / \sqrt{t_p^2 + \nu}$ are summarized in Table 3.

Additional information can be obtained by calculating the partial correlation coefficients $\boldsymbol{r}_{ij \cdot k}$ (Cramer, 1975).

For the significance limits of the partial correlation coefficients, the expressions are the same as for $\boldsymbol{r}_{ij}$, but with $\nu = n - 3$. The values calculated for them are also shown in Table 3. In the same Table 3 there are given both the values $t_p / \sqrt{t_p^2 + \nu}$ for the sets of "distant clusters" of Table 1 where the number $n = 22$ and the beforementioned values for the sets of main area clusters from Table 2 with $n = 46$.

Assuming a normal distribution of the correlation coefficients, we use the standard error method, and as a result, we obtain that, with p-percentage probability, the correlation coefficients $\boldsymbol{r}$ for a sample of size n are in the confidence interval equal to $]\boldsymbol{r} - \lambda_p \cdot \boldsymbol{d}(\boldsymbol{r});\ \boldsymbol{r} + \lambda_p \cdot \boldsymbol{d}(\boldsymbol{r})[$, where the standard error is $\boldsymbol{d}(\boldsymbol{r}) = (1 - \boldsymbol{r}^2)/\sqrt{n}$.

Table 3

The number of degrees of freedom	p = 5%	p = 1%	p = 0.1%
$\nu = 19$	0.433	0.549	0.665
$\nu = 20$	0.423	0.537	0.652
$\nu = 43$	0.294	0.380	0.475
$\nu = 44$	0.291	0.376	0.470
$\nu = 65$	0.241	0.313	0.394
$\nu = 66$	0.239	0.311	0.391

Using the usual form of notation $\boldsymbol{r} \pm \boldsymbol{d}(\boldsymbol{r})$, and leaving three decimal places, one can summarize the data in Table 4. The average values of three considered parameters in every sample and their sample standard errors are denoted in Table 4 as well in the usual form of notation $\boldsymbol{x} \pm \boldsymbol{d}(\boldsymbol{x})$.

Table 4

	for 2.2 Mm…7.4 Mm	for 7.6 Mm…9.5 Mm	for all – 2.2 Mm…9.5 Mm
N of harmonics	1.471 ± 0.342	1.229 ± 0.296	1.392 ± 0.345
| Maz – 90°|, °	73.54 ± 24.04	45.39 ± 35.11	64.43 ± 30.83
D, Mm	5.18 ± 1.38	8.66 ± 0.60	6.31 ± 2.02
$\boldsymbol{r}_{12}$	– 0.360 ± 0.128 (from 1% to 5%)	**– 0.711 ± 0.105**	– 0.273 ± 0.112 (from 1% to 5%)
$\boldsymbol{r}_{13}$	– 0.464 ± 0.116 (≈0.1%)	– 0.515 ± 0.157 (≈1%)	**– 0.520 ± 0.089**
$\boldsymbol{r}_{23}$	– 0.264 ± 0.137 (≈5%)	0.263 ± 0.198	**– 0.410 ± 0.101**
$\boldsymbol{r}_{12\cdot3}$	**– 0.565**	**– 0.696**	**– 0.624**
$\boldsymbol{r}_{13\cdot2}$	**– 0.621**	– 0.484 (from 1% to 5%)	**– 0.720**
$\boldsymbol{r}_{23\cdot1}$	**– 0.522**	– 0.171	**– 0.672**

Values of correlation coefficients exceeding the 0.1% level (highly significant) are marked in bold type. The parentheses indicate to which region the other quantities $\boldsymbol{r}_{ij}$ and $\boldsymbol{r}_{ij \cdot k}$ belong.

Thunderstorms from Table 1 were located at distances of about 8.6 Mm from the receiving station with a small spread of ±12%. In this narrow band of ranges, $\boldsymbol{r}_{13}$ exceeds the 5% significance level, just short of the 1% level. The correlation of azimuths and spectra is highly significant, which is consistent with our previous observations. The lack of correlation between azimuths and distances is observed. The calculation of partial correlation coefficients practically does not change the conclusions.

The relationship of parameters for clusters of tweeks from the main area of the middle distancies is more complex. The source range of tweeks from Table 2 changes by a factor of 3...4 from the closest to the farthest. Most of the tweeks were observed from azimuths of 40…80°. All three parameters were correlated with each other. The dependence of the tweek decay on the path length is most clearly visible, which is stronger for higher orders of harmonics, the coefficient $\boldsymbol{r}_{13}$ is significantly different from zero and close to the highly significant 0.1% level. The value of $\boldsymbol{r}_{23}$ almost reaches the 5% significance level. This means that the closer to the geomagnetic east is the direction to the source in the out-equatorial region, the weaker the tweek decays and the greater the distance it can be received from. Thunderstorms that occurred in the western sector from the receiving station also arouse tweeks, but they faded and were almost not detected.

Neglecting the effect of the spectrum (which may show a connection with the local time of night at the tweek path) increases the difference from zero of $\boldsymbol{r}_{23 \cdot 1}$ to the value $\boldsymbol{r}_{23 \cdot 1} = -0.522$. Excluding the masking effect of the source distances on tweek decay, it can be seen that the relationship between the spectrum and the azimuth is also highly significant, $\boldsymbol{r}_{12 \cdot 3} = -0.565$. The relationship between the spectrum and the distance D, if we neglect the effect of azimuth, is highly significant and reliably exceeds the 0.1% level. Without the study of partial correlation coefficients, these mutual influence effects could not be reliably detected.

Combining the data for both distance ranks, one can achieve the similar results. The relationship of the distance with the average number of harmonics and with the azimuth is very noticeable, the difference from zero in the values of $\boldsymbol{r}_{13} = -0.520 \pm 0.089$ and $\boldsymbol{r}_{23} = -0.410 \pm 0.101$ is above the 0.1% significance level. The correlation of the arrival azimuth and spectrum is found at the level of almost significant values: $\boldsymbol{r}_{12} = -0.273 \pm 0.112$. The calculation of partial correlation coefficients makes it possible to reveal stronger mutual relationships of all three quantities, and the azimuthal dependence of the spectra leads to a highly significant correlation, $\boldsymbol{r}_{12\cdot3} = -0.624$.

To discuss the results obtained, we will first have to summarize some of the previously mentioned circumstances.

It has been experimentally found that tweeks with a longer path between the atmospheric source and the receiving point have fewer harmonics in the signal spectrum. Any tweek propagation theory must account for this fact. Numerical calculations performed for realistic nighttime conditions in the lower ionosphere showed that the attenuation coefficients near the cut-off frequencies increase with the number of QTE modes in tweek spectrum (Yamashita, 1978).

The theoretical predictions on azimuthal dependencies of tweek attenuation coefficients are anything but simple. The nature of the EW asymmetry in tweek signals is similar to the well-studied asymmetry in the propagation of VLF waves with frequencies ≥10 kHz (see the recent review (Lynn, 2010) about it). These VLF waves propagate in TM-modes, and the exact theoretical solution shows that the attenuation coefficients experience a minimum for the western direction of arrival of the signal, and not one, but two maxima for the northeast and southeast directions of arrival. These calculations were confirmed by experimental studies.

For the case of the propagation of the first few tweek modes with frequencies 2…10 kHz in the Earth-ionosphere waveguide along a band around the geomagnetic equator, theoretical solutions are currently not developed. In the work (Gorishnya, 2019) observations were made that in the near-equatorial region there is no East – West asymmetry in tweek polarization (except for a narrow section at the beginning of the tweek waveform for the phase difference of the 1st harmonic). Such an asymmetry in polarization manifested itself in the region of middle geomagnetic latitudes.

The theoretical model (Ryabov, 1994, Sukhorukov et al., 1992) is valid for data from Table 2. The data in Table 1 relating to tweeks that came from the north are outside the scope of its applicability. The homogeneity of the ionosphere is a rather serious confinement for the model (Sukhorukov et al., 1992). These results are acceptable only for a non-disturbed nighttime ionosphere with a drastic increase of electron density in the E-layer. Thus, the study of experimental data should be decisive in order to clarify the dependences.

The absence of tweeks from the western sector of 270°±20° in our data denies the possibility to observe exactly the direction of arrival, where the tweeks are attenuated the most.

In contrast to the weak azimuthal dependence near critical frequencies (in the tail of the tweek), for greater sourse distancies, the condition $(\omega - \omega_{km})/\omega_{km} \ll 1$ is not satisfied for part of the tweek signal. Far from the cut-off frequencies, but for frequencies such that

$$p_m = \omega^L_{km}/\omega < 1, \qquad (1)$$
$$p_m - 0.4 \gg \tan\theta/(2\mu),\ 1/(2\pi m\,\mu),$$

in the approximate model (Sukhorukov et al., 1992) $S_m^{L(R)}$ is a complex sine of the incidence angle of a wave onto the ionosphere, the imaginary part of which determines the attenuation coefficient $\alpha_m^{L(R)} = 8.7\,k_0 \times \mathrm{Im}\,(S_m^{L(R)})$ (in dB Mm^{-1}):

$$\mathrm{Im}(S_m^L) = \frac{1}{4k_0 h\mu\sqrt{1-p_m^2}} \times \Big\{(1+p_m^2) - \sqrt{8p_m^2-(1+p_m^2)^2} \times \\ \times \frac{2(1-p_m^2)^{3/2}\tan\theta\sin\psi}{\mu} + \frac{\nu(1+p_m^2)}{2\omega_H\cos^2\theta} \times \left[1 + \frac{(1+p_m^2)}{\sqrt{8p_m^2-(1+p_m^2)^2}}\right]\Big\}, \qquad (2)$$

where $k_0 = \omega/c$ is the wavenumber in vacuum, h is the waveguide height for the horizontally homogenous waveguide model, $\mu = \omega_0 / \sqrt{\omega \cdot \omega_H \cdot \cos\theta}$, ω_0, ω_H and ν are a plasma frequency, a gyrofrequency and an effective collision frequency, respectively, of electrons at height h, the angle θ is the deviation of the magnetic field from the vertical in the plane of geomagnetic meridian, and the angle ψ is the difference between the tweek propagation vector and the horizontal projection of the geomagnetic field.

The angle ψ equals the magnetic bearing φ at the tweek receiving point. Due to geomagnetic anomalies, the angle ψ varies along the tweek path.

The expression for the QTM$_m$ mode attenuation ($m \neq 0$) in the frequency ranges (1) differs from expression (2) in the sign before $\sqrt{8p_m^2-(1+p_m^2)^2}$ and in the replacement of ω^L_{km} with ω^R_{km}, so that the east–west asymmetry of the QTM$_m$ modes has a reverse character.

It is easy to see that the first term in the expression for the attenuation coefficient (2) is proportional to $\sqrt{\omega\cos\theta}$, the second $\propto \omega \sin\theta \cdot \sin\psi$, and the third one is proportional to the expression $\sqrt{\omega}\cdot(\cos\theta)^{-3/2}$. The first and third terms do not depend on the actual azimuth, but the difference may stem from the geographical location of the points of excitation and reception of the tweek.

Let's compare the path from the north to UAS "Akademik Vernadsky" with beginning at the approximate boundary of applicability of the model, and the path of equal length for the tweek with the east azimuth. For north path the angle θ varies from 35° at UAS to 75°, and for eastern path the angle θ varies from 35° at UAS to 22° due to geomagnetic field whereabouts at 2019 epoch.

The firth term in (2) is about 25% less for the northern path than for the eastern one. For the third term in (2), the average expression $(\cos\theta)^{-3/2}$ for the northern route is approximately three times greater than for the eastern one. But since $\nu \ll \omega_H$ in the region of applicability of the model, the total difference for the third term is approximately equal to the difference for the first, and they cancel each other out.

The second term vanishes when the tweek propagates along the geomagnetic meridian, and it is the greater in absolute value, the closer the magnetic azimuth of the tweek is to 90°. So, the values of attenuation coefficients α_m^{qTE} for tweeks with sources to the east are smaller than on meridional paths.

The difference in the attenuation coefficients for the directions west–east and east–west predicted by the model will increase with increasing angle θ up to the model applicability limit at 75°. That is, the closer to the equator, the greater the effect. For frequency 3 kHz and $\theta = 50°$, such a difference in the attenuation coefficients of the first *L*-mode (QTE_1) reaches ~3 dB/Mm^{-1}, which is comparable to the value of the attenuation coefficients themselves.

For the magnetic latitude of the receiving complex at UAS, the angle $\theta = 35°$, and the effect of azimuth on attenuation at east–west propagation direction is 50...75% of that at medium magnetic latitudes ($\theta = 50°$). However, it shows up as a significant correlation when looking at the correlation matrix.

This point, as well as the strong correlation between the tweek paths and their arrival azimuths, came as somewhat of a surprise to our research team.

The term in α_m^{qTE} responsible for this difference in the model is $\propto \omega$, and grows with the harmonic order, for equal modal angles ς ($\cos \varsigma_m = \omega_{km}/\omega$).

4. Conclusions

Clusters with approximately the same distances to sources and azimuths obtained during the same night were identified upon the ensemble of tweek-atmospheric records. The data were accumulated at the Ukrainian Antarctic Station "Akademik Vernadsky" in 2019. To obtain parameters through tweeks, a single-position method was used to locate lightning and estimate the heights of the lower ionosphere by tweek-atmospherics (Shvets et al., 2011). The correlation matrix was calculated for three parameters, and partial correlation coefficients were obtained. We studied the cause-and-effect relationship between the average azimuth of the arrival of tweeks in regard to the magnetic meridian, the average distance to the center of the cluster of tweek sources (lightning discharges), and the average number of tweek harmonics. The same correlation analysis was carried out for two groups with distances to sources of 2.2...7.5 Mm and 7.6...9.5 Mm, into which the sample was divided for in-depth study. It is shown that the partial correlation coefficients between the number of tweek harmonics and the difference of the magnetic azimuth from the direction to the magnetic east exceed the 0.1% significance level for the entire range of distances. It is shown that the effect of the distance to the tweek source on its spectrum in the range of 2…8 Mm is comparable in magnitude or exceeds the effect of the magnetic azimuth. The elimination of this masking effect by calculating the partial correlation coefficients made it possible to reveal the magnetic azimuth dependences of the tweek spectra in the case of propagation in a region outside the geomagnetic equator.

The increased probability of detecting tweeks with higher harmonics if their directions of arrival are close to the geomagnetic east is explained as the effect of non-reciprocity of east–west and west–east propagation of ELF – VLF waves in regard to the magnetic meridian upon the spectra of tweek-atmospherics. It is also shown that this effect, as a result of increased attenuation during the propagation of ELF – VLF radiation from the west and weakened attenuation during propagation from the east, leads to a highly significant correlation of the magnetic azimuths of tweeks and the lengths of their paths to the receiving station.

Acknowledgements. The work was carried out within the framework of studies by the Department of Earth Remote Sensing of the O. Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine on the topic of planned NDR (state registration number 0122U000585). The authors express their gratitude to the National Antarctic Research Center of the Ministry of Education and Science of Ukraine for organizing and conducting research at the “Akademik Vernadsky” station, as well as to the team of winterers who serviced the ELF – VLF measuring complex.

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КОРЕЛЯЦІЙНИЙ АНАЛІЗ ХАРАКТЕРИСТИК НІЧНОГО ПОШИРЕННЯ ННЧ–ДНЧ АТМОСФЕРИКІВ

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Твік-атмосферики (твіки), поряд з радіопросвічуванням хвилями ДНЧ-радіостанцій, використовують для вивчення нижньої іоносфери. Електромагнітне імпульсне випромінювання, що збуджується грозовими розрядами, має максимальну спектральну густину в діапазоні наднизьких частот (ННЧ, 300...3000 Гц) та дуже низьких частот (ДНЧ, 3...30 кГц). Порожнина Земля–іоносфера служить хвилеводом для електромагнітних хвиль у діапазонах таких частот. На спектрограмі твіка початкова частина є лінійно поляризованим широкосмуговим сигналом, потім спостерігається ряд окремих гармонік, а їх миттєві частоти зменшуються, асимптотично наближаючись приблизно до кратних частот відсікання хвилеводу. Однопозиційний метод локації блискавок та оцінювання висот відбиття ННЧ-хвиль у нижній іоносфері за сигналами твіків введено в обчислювальний алгоритм. На ансамблі записів твік-атмосфериків виділено кластери з приблизно однаковими азимутами та відстанями до джерел, отримані в ту ж ніч. Дані накопичені на Українській антарктичній станції "Академік Вернадський" у 2019 році. Розміщення прийомного комплексу в межах полярного регіону дає змогу реєструвати джерела твіків з двох планетарних грозових центрів з географічними азимутами в місці прийому від –60° до 130°. Результати оброблення цих даних використані шляхом вивчення кореляційної матриці та часткових коефіцієнтів кореляції для виявлення причинно-наслідкових зв'язків між трьома основними парметрами твіка, якими були середній азимут твіка відносно магнітного меридіана, середня дистанція до центру кластера джерел твіка (блискавок) та середня кількість гармонік твіка. Такий кореляційний аналіз проведено також для двох груп з дистанціями до джерел 2,2...7,5 Мм і 7,6...9,5 Мм, на які розділено вибірку для поглибленого вивчення. Продемонстровано, що частковий коефіцієнт кореляції між кількістю гармонік твіків та відмінністю магнітних азимутів від напрямку на магнітний схід дорівнює 0,624 для повного діапазону дистанцій, 0,696 для твіків з віддаленими джерелами та 0,595 у широкому діапазоні середніх відстаней 2,2...7,5 Мм, що у всіх віпадках відповідає рівню значущості 0,1%, тобто дуже значущому. Показано, що кореляція дистанції до джерела твіка та його спектра в діапазоні 2...7,5 Мм за величиною приблизно порівнює або перевершує кореляцію магнітного азимута твіка та його спектра. Усунення маскувального ефекту від впливу дистанції шляхом знаходження часткових коефіцієнтів кореляції дало змогу виявити, як спектри твіків залежать від магнітного азимута, якщо твік поширюється в області поза геомагнітним екватором. Таким чином, у спектрах твік-атмосфериків виявлено ефект невзаємності поширення ННЧ–ДНЧ хвиль щодо магнітного меридіана у напрямках схід – захід та захід – схід, що призводить до збільшення ймовірності виявлення твіків з вищими гармоніками, якщо напрямки їхнього приходу близькі до геомагнітного сходу. Показано також, що цей ефект невзаємності внаслідок підвищеного згасання ННЧ–ДНЧ випромінювання при поширенні із заходу та ослабленого згасання при поширенні зі сходу призводить до дуже значущої кореляції (з ймовірністю більш ніж 99,9%) між величиною магнітних азимутів твіків та довжин їхнього шляху до приймальної станції.

Ключові слова: діагностика нижньої іоносфери, ННЧ–ДНЧ радіохвилі, твік-атмосферики, локація блискавок.

Рукопис статті отримано 22.11.2022