OBSERVATION OF TWEEK-ATMOSPHERICS AFTER SOLAR FLARES AT THE "AKADEMIK VERNADSKY" UKRAINIAN ANTARCTIC STATION

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ABSTRACT

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 Akademik Vernadsky Ukrainian Antarctic Station in 2021. These data were selected for 6 nights of summer, autumn and winter of the southern hemisphere, during periods of disturbed magnetosphere after solar flares. 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°. By experimental results it has been shown that, under conditions the three-hour planetary index K_p = 4...6, the measuring complex at the Akademik Vernadsky Ukrainian Antarctic Station stably detects ELF – VLF atmospherics propagating at night in the near-Earth waveguide. Processing records of such signals using the same algorithm as for tweek-atmospherics under normal conditions of an undisturbed magnetosphere demonstrates the coordinates of the sources of atmospherics. This also applies to the area of the Southern Magnetic Anomaly in the Brazilian region, where satellite observation of lightning discharges is nearly impossible after solar flares. The vast majority of thunderstorm centers for period studied were confined to continental regions, also tweek sources have been observed with coordinates associated with a latitude band around 40 S of the Atlantic and Indian Oceans. Data on the location of tweek sources (lightning discharges) coincide quite closely with predictions according to climate patterns. By studying the spectra of tweeks, there has also been detected an effect of non-reciprocity of the propagation in the East – West and West – East directions. The mechanism of this phenomenon should probably be close to the same mechanism during the reflection of ELF – VLF radiation in the undisturbed ionosphere. A sharp maximum in the average number of harmonics (that is, a minimum of attenuation coefficients) was observed when tweek atmospherics arrived from a geographic azimuth of 110°. This feature can be explained by the joint manifestation of the non-reciprocity effect and the specific layout of the Southern Magnetic Anomaly relative to the receiving point at the Akademik Vernadsky Ukrainian Antarctic 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. The radiation generated at the lightning discharge sites creates atmospheric signals inside the near-Earth waveguide. 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 [1, p. 1476]. The use of a waveguide model with isotropic conducting boundaries made it possible to satisfactorily explain the dispersion properties of tweeks [2, p. 58]. A number of tweek peculiarities were discovered later, namely: tweeks are recorded when the signal source and receiver are at night conditions, or even during a solar eclipse [3, p. 667], 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 explained by isotropic waveguide model. These facts can be explained using theory from [4, p. 151], [5, p. 60].

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 [6, p. 53], [7, p. 40]. 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 [6, p. 53], [7, p. 40] 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 [7, p. 40], [8, p. 289]. 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 [9, p. 98], [10, p. 27], [11, p. 20], 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 from observations of atmospherics [12, p. 1491], [13, p. 101]. The azimuthal dependence was revealed ([10, p. 27], [11, p. 20], [14, p. 461]) 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 [15, p. 44], [16, p. 18] an azimuthal dependence in the tweek spectra was observed by the calculated mean number of tweek harmonics at source distances of 8…10 Mm, according to the experimental records database accumulated at the Ukrainian Antarctic Station "Akademik Vernadsky" in 2019 – 2021. Tweek-atmospherics in this database have source at the distances of 1.5…10 Mm or more.

The correlation matrix upon this database was calculated for three parameters, and partial correlation coefficients were obtained in [17, p. 4]. The cause-and-effect relationship was studied 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. 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 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.

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 [18], 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 [9, p. 98]. 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.

The homogeneity of the ionosphere is a rather serious confinement for the tweek propagation model [5, p. 60], [19, p. 1185]. These theoretic results are acceptable only for a non-disturbed nighttime ionosphere with a drastic increase of electron density in the *E*-layer. During periods of time when conditions in the Earth's magnetosphere are disturbed as a result of solar flares, observations of experimentally recorded tweeks must be compared with the pattern observed under normal conditions.

The purpose of this work is to study the implementation of observations of tweek-atmospheric signals in the circumpolar conditions of the Ukrainian Antarctic "Akademik Vernadsky" Station during periods of disturbed magnetosphere in different seasons of the year.

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. The algorithm, which is currently used by the measuring complex since the fall of 2020, also determines the effective reflection heights for the three lower harmonics of the tweek.

The Akademik Vernadsky Ukrainian Antarctic Station (UAS) 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 [20, p. 116]. Tweeks are observed when the receiving station is in the night hemisphere, e.i. during the local nighttime.

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 [21] 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 [22] or 0.7…7 Mm [23, p. 2502]. 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.

In the ensemble of tweek records for the first six months of 2021, data were selected for periods of disturbed magnetosphere, when after solar flares the three-hour planetary index $K_p \geq 4$. These data have been collected on nights during the southern hemisphere summer (February 7, March 3), equinox season (from 0 to 9 a.m. UTC at March 14 and March 25) and southern hemisphere autumn (night from April 16 to April 17) and winter (June 15 from 18 to 24 p.m. UTC).

It was shown (see in [18], [24, p. 20]) 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 [24, p. 20]. Since the reflection heights, as shown in [25, p. 34], do not correlate with the distances to the tweek source and the azimuths of its arrival, we can 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.

We separated groups of tweeks generated by a common thunderstorm cell that were close in range and azimuth.

Group-average values of geographic azimuth, distance *D* to tweek sources, and the average number of harmonics in the tweek spectrum <*N*> were calculated for several dozen of thunderstorm cells. The number of tweeks in a group averaged about a hundred, varying from 30 to 700. About 10 tweek groups with 10...30 records were also received from low-power thunderstorm cells. Such obtained data are plotted on a map (see Fig. 1). Cases where the number of tweeks in a group was less than 30 are highlighted with gray icons.

Excitation of tweek-atmospherics is possible when radiation is reflected from the layers of the night ionosphere. At the early evening at the receiving point of the "Akademik Vernadsky" station, tweeks with sources up to more than 11 Mm are recorded at azimuths of about 120 degrees. The average number <*N*> was 1.12, when the significant thunderstorm center was observed near the Seychelles Islands at June 15 (it is not shown in Fig. 1).

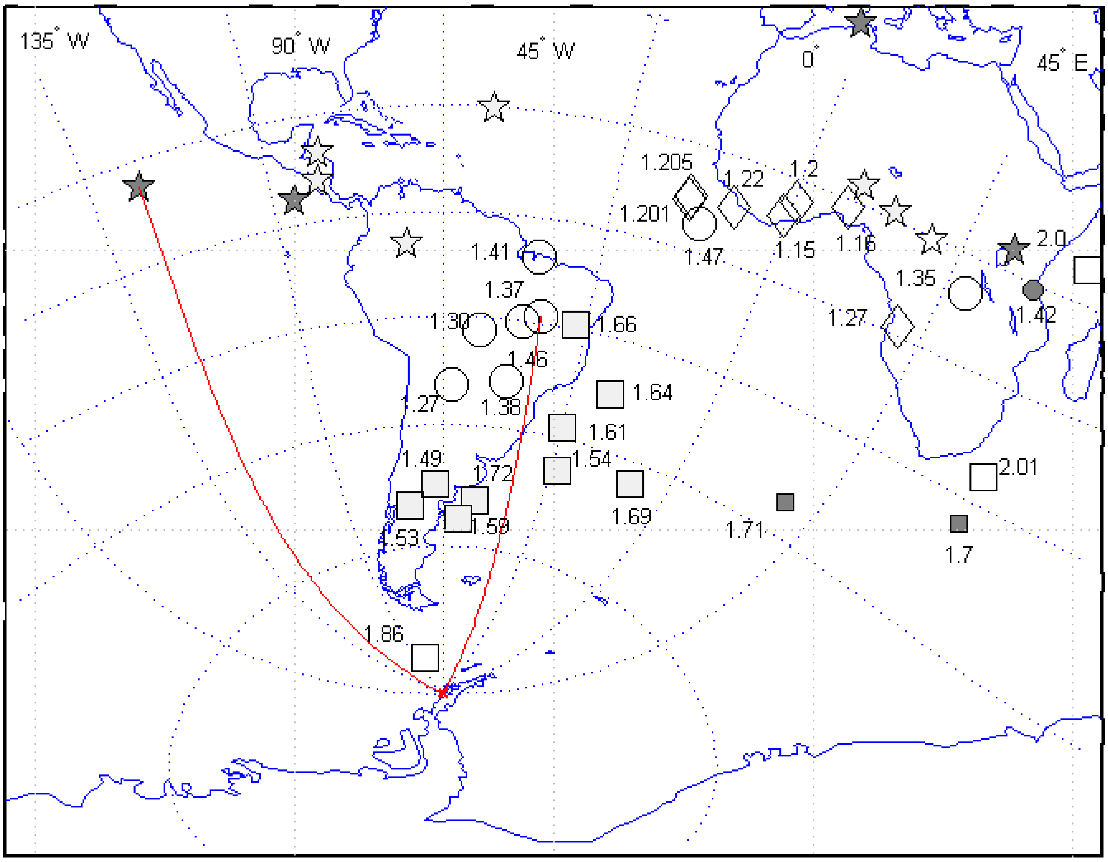

Figure 1. The average number of harmonics in a thunderstorm cluster and the geographic location of recorded thunderstorm cells during magnetic storms.

The dotted lines in Fig. 1 show circles of equal distance from the receiving point (2 Mm, 4 Mm, 6 Mm, 8 Mm and 10 Mm) and azimuths with an interval of 30 degrees. Groups of tweeks with a strong participation of high-frequency harmonics (<*N*> over 1.5) are displayed in Fig. 1 by squares, those where <*N*> = 0.27...0.5 are shown by circles, and diamonds show groups with a small but significant presence of records with the second and higher harmonics in the spectrum (<*N*> = 0.15...0.27). The numbers next to the icons indicate the number <*N*>. The stars show groups of tweeks with a predominance of the fundamental harmonic (<*N*> < 0.12). Examples of great circle lines corresponding to tweek's routes are given.

3. Comparison with propagation under normal conditions and discussion of results.

It has been established that after solar flares there is an increased precipitation of charged particles into the *E*-layer of the ionosphere (90...130 km) in the polar regions of the Earth [26, p. 807], which includes the area where the receiving station of the UAS "Akademik Vernadsky" equipment is located. Nevertheless, according to our experiments, under conditions $K_p = 4...6$, the measuring complex at the "Akademik Vernadsky" station stably detects atmospherics propagating at night in the near-Earth waveguide.

Processing records of such signals using the same algorithm as for tweek-atmospherics under normal conditions of an undisturbed magnetosphere demonstrates the coordinates of the sources of atmospherics.

The mean annual land to ocean flash ratio is 10:1 [21]. The average global annual flash rate for the oceanic regions was found to be 5 fl/s, while continental regions ranged from 31 to 49 fl/s during the year [21].

The vast majority of thunderstorm centers for these nights (see Fig. 1) were confined to continental regions. Also clearly visible are data with coordinates associated with a latitude band around 40 S of the Atlantic and Indian Oceans.

Observations of tweek-atmospherics under normal night conditions and calculations of their cluster-average spectral composition were carried out previously (see in [17, p. 4]). For comparison, we have shown in Fig. 2 data for 66 clusters of tweek sources for 2019 which correspond to thunderstorm cells. Their geographical azimuths differ and cover the northern and eastern sectors of directions, from 305° to 120°.

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. Figure 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 on thunderstorm cells with tweek path lengths from 7.6 Mm to 9.5 Mm are shown as rhombs. Data on tweeks whose source's distances corresponded to 2.2...4.5 Mm and 4.6...7.5 Mm are depicted with crosses and stars, respectively.

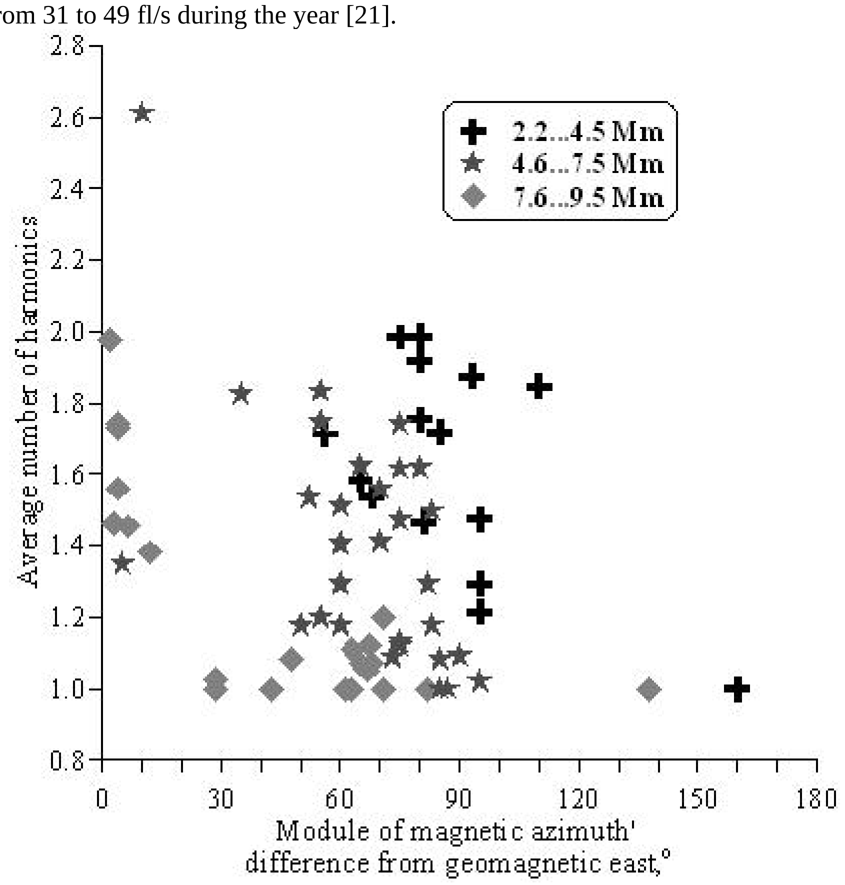

Figure 2. The average number of harmonics in a thunderstorm cluster as a function of the modulus of the magnetic bearing difference with geomagnetic east.

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 the data in Fig. 1, only 2 nights were included in the summer season. Thunderstorm cells in southern Africa were not recorded by tweeks at that time. Thunderstorm days (more precisely, nights with thunderstorms) in this region during this season account for approximately 50% of the total. Thus, the absence of thunderstorms on these nights does not indicate anything significant.

Data on the location of tweek sources (lightning discharges) coincide quite closely with predictions according to climate patterns. By studying the spectra of tweeks, one can also detect the effect of non-reciprocity of the propagation in the East – West and West – East directions. The mechanism of this phenomenon should probably be close to the same mechanism during the reflection of ELF – VLF radiation in the undisturbed ionosphere.

Certain differences in the manifestation of such an effect can be indicated. A sharp maximum in the average number of harmonics (that is, a minimum of attenuation coefficients) was observed when tweek atmospherics arrived from a geographic azimuth of 110°. For geographic azimuths 40...80° (which corresponds to a magnetic azimuth 25...65°), the probability of detecting higher harmonics in a tweek with a large path length turned out to be greater: the average number of harmonics ranged from 1.15 to even 1.47 at distances of 8...10 Mm. Only for path lengths of 10 Mm and more $<N> \leq 0.1$ (stars in Fig. 1). For similar arrival azimuths under standard ionosphere, the data demonstrated that $<N>$ is less than 1.1 for tweek path lengths greater than 7.5 Mm.

In addition to the above, one should consider the features of the geomagnetic situation in the studied region. Close from the reception station is the largest anomaly of the geomagnetic field. This is the so-called Southern-Atlantic Magnetic Anomaly (or Southern Magnetic Anomaly, SMA), which many researchers consider as a composition of two anomalies – the Brazilian anomaly and the Cape Town anomaly. It has increased significantly in recent decades, and has a strong influence on the work of satellites in near-Earth orbit and geophysical equipment. Its existence is due to the asymmetric position of the earth's magnetic dipole, which does not pass through the center of the Earth and the Earth's axis.

We consider the geomagnetic field according to the International Geomagnetic Reference Field model IGRF-13 released in 2020. Regarding the SMA, two main features can be indicated. The total intensity of the magnetic field at the ground level is much lower. To the north of the "Akademik Vernadsky" station, on geographical azimuths from –5° to 20° and distances of 4...5 Mm there is a minimum of total intensity. Because of this, the boundary of the inner Van Allen radiation belt is located only 500 km from the Earth surface under normal conditions and can decrease up to 200 km as a result of geomagnetic storms. Such a fossa leads to the rapid emptying of the drift particles and the lack of protection against galactic rays.

This brings significant difficulties in the work of satellites carrying out optical observation of lightning. In fact, after solar flares, for several days their work becomes impossible with the orbital flight over the Brazilian coast (area of the Brazilian anomaly).

Secondly, on geographical azimuths 80° and 110° from the reception point on "Akademik Vernadsky" station (at distances of 6 and 4 Mm) there are extremums of magnetic inclination. Together with a decrease in total intensity, they create extremums of the vertical intensity of the geomagnetic field.

For the purposes of this work, this layout of the geomagnetic field's anomalies means that the tweeks with arrival azimuth of 80° pass through the area with a minimum of magnetic inclination –68°, where the angle θ (which is the deviation of the magnetic field from the vertical in the plane of geomagnetic meridian) is only 22°. This is approximately the same with the geomagnetic field of the same latitudes of other regions: Australia or Pacific Ocean. The influence on the attenuation coefficients, which leads to the effect of non-reciprocity of the propagation in the East – West and West – East directions, is approximately the same. In contrast, tweeks with azimuths of 110° and paths more than 4 Mm propagate through the area with a more inclined magnetic field, the magnetic inclination is up to –58°, that is, the angle $\theta = 32°$. The absolute value of the attenuation coefficients depends on the angle θ, and as a result, this effect is approximately equal to such that it would be at the latitudes of 30° S. It manifests itself brighter, although the tweek's routes lie closer to the pole, south of Africa.

These details can explain some asymmetry of data processed in our work (see Fig. 1) regarding the direction of strictly to the geomagnetic east, and the local maximum of $<N>$ (that is, the minima of the attenuation coefficients) for tweeks with geographical azimuth 110°.

4. Conclusions.

By experimental results it has been shown that, under conditions $K_p = 4...6$, the measuring complex at the Akademik Vernadsky Ukrainian Antarctic Station stably detects ELF – VLF atmospherics propagating at night in the near-Earth waveguide. Processing records of such signals using the same algorithm as for tweek-atmospherics under normal conditions of an undisturbed magnetosphere demonstrates the coordinates of the sources of atmospherics. This also applies to the area of the Southern Magnetic Anomaly in the Brazilian region, where satellite observation of lightning discharges is nearly impossible after solar flares. The vast majority of thunderstorm centers for period studied were confined to continental regions, also tweek sources have been observed with coordinates associated with a latitude band around 40 S of the Atlantic and Indian Oceans. Data on the location of tweek sources (lightning discharges) coincide quite closely with predictions according to climate patterns. By studying the spectra of tweeks, there has also been detected an effect of non-reciprocity of the propagation in the East – West and West – East directions. The mechanism of this phenomenon should probably be close to the same mechanism during the reflection of ELF – VLF radiation in the undisturbed ionosphere. A sharp maximum in the average number of harmonics (that is, a minimum of attenuation coefficients) was observed when tweek atmospherics arrived from a geographic azimuth of 110°. This feature can be explained by the joint manifestation of the non-reciprocity effect and the specific layout of the Southern Magnetic Anomaly relative to the receiving point at the Akademik Vernadsky Ukrainian Antarctic Station.

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