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A TECHNIQUE FOR AUTOMATIC MONITORING THE LOWER IONOSPHERE AND LIGHTNING LOCATION BY TWEEK-ATMOSPHERICS

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Abstract

A new real-time technique is proposed for automatc identification of tweek atmospherics, distance finding to lightning and estimating the effective heights of the lower ionosphere for the fundamental and higher order modes of the Earth-ionosphere waveguide. Effectiveness of the technique is demonstrated with the experimental records of atmospherics. Application of a clustering algorithm allowed us to reveal different patterns of variations of the lower ionosphere effective height along different propagations paths. The distance finding accuracy of our tweek method had been roughly estimated by a comparison with independent data from the Blitzortung.org lightning location network to be less than 100 km with standard deviation less than 200 km in the range of distances from 500 to 1400 km.

Key words: lightning location; lower ionosphere; ELF-VLF radio waves; tweek-atmospherics; Earth- ionosphere waveguide.

1. Introduction

Tweek-atmospherics (tweeks) [Burton and Boardman, 1933] are electromagnetic waves in audio frequencies as a response of the Earth–ionosphere duct to the pulsed excitation by lightning strokes. While typical day time atmospherics' spectra have a wide minimum in the frequency range from about 1 to 4 kHz, the spectral components appear in tweeks nearby the cutoff frequencies of the Earth-ionosphere waveguide owing to reduced attenuation in the ionosphere during night time. Tweeks propagate over great distances reaching several thousand kilometers, and average properties of the lower ionosphere along the propagation path between a causative lightning stroke and an observer can be obtained [Outsu, 1960; Mikhailova and Kapustina, 1988; Yedemsky et al., 1992; Hayakawa et al., 1994, 1995; Shvets and Hayakawa, 1998; Cummer et al., 1998; Kumar et al., 2009; Maurya et al., 2012; Tan et al., 2015; Ohya et al., 2008, 2014].

The strong frequency dispersion observed in tweek signals is associated with a sharp reduction of the group velocity of radio waves propagating in the Earth–ionosphere waveguide when the signal frequency approaches the waveguide cut-off frequency. Due to strong frequency dispersion near the waveguide cutoffs, specific L-shaped patterns with short "vertical" part and "near horizontal" part of 10 – 100 ms duration are observed in the spectrograms of tweeks. Thus, tweeks can be easily identified by eye on the waveform or spectrogram, or to the ear when listening to the signal through a loudspeaker. Depending on the distance to a source and losses mainly in the ionosphere, the "horizontal" part of tweeks in spectrograms contains harmonics from 1 up to 8 – 10, corresponding to the fundamental and higher order waveguide modes [Goryshnya, 2014].

To evaluate parameters of the lower ionosphere along the propagation path of tweek-atmospherics it is necessary to know the coordinates of the source, and these might be obtained from the independent networks of lightning location [e.g. Cummer, 1998]. Such information can be obtained using the data of national or global networks of lightning location. However, those are provided on a commercial basis as a rule. Therefore, among different approaches for the analysis of tweeks, the single-site techniques which have less accuracy, but provide the only possibility for determining the coordinates of lightning in many cases, are used when information on the position of causative lightning is unknown.

Traditionally, the distance finding problem is solved by measuring the time delay between the waves of different frequencies pertinent to the same tweek, because the retard arises from the frequency dispersion in the waveguide [Outsu, 1960; Ohya et al., 2008]. By using the delay measured at several frequencies, one can estimate both the distance from the source and the height of the waveguide.

The "Kharkov" method [Rafalsky et al., 1995] employs the phase spectrum of the longitudinal magnetic field component. This field component in the range between the frequencies of cutoff of normal waves of the 1st and 2nd order is formed by a single normal wave of the first order that is used to jointly determine the height of the waveguide and the distance to the source.

For the first time a computerized system of tweek analysis for automatic monitoring lower ionosphere was developed in IZMIRAN [Yedemsky et al., 1992]. Recognizing tweeks was performed by detecting the left-hand polarization of the received magnetic field in the frequency range 1.6 – 1.9 kHz near the first order cutoff of the waveguide. Then the peak frequency in the tweek was measured and such parameters of the lower ionosphere as electron-neutral collision frequency and virtual height were inferred on the basis of the theory developed by Ryabov [Ryabov, 1994].

An automatic procedure for traditional method of analysis based on the frequency-time representation of tweeks was developed in Ohya et al. [2008]. First, the moment of an intense tweek exceeding the 80% level of the 2-minutes maximum amplitude of continuous signal is determined. Next, they find the frequency of the maximum power of the spectrum at every discrete time in the dynamic spectrum. To remove background noise emissions and other tweeks embedded on the target tweek, the procedure selects the harmonic for one tweek automatically by checking the frequency difference between two successive times. The obtained tweek harmonic is least-square fitted with the theoretical instant frequency dependence in order to obtain the ionosphere height, source range and the moment of tweek arrival. Finally, the procedure removes the cases when the fitting error becomes very large, or the estimated source range becomes “unrealistic” (either less than 1,000 km or more than 10,000 km). The fitting results are adopted when the mean difference between the data point and the fitted theoretical curve was less than 50 Hz, which is comparable to the FFT frequency resolution (40 Hz).

It is obvious that the mentioned automatic techniques can provide an analysis of only the strongest (usually fundamental) harmonic in tweek signals. In this paper we propose a real-time method for automatic recognition and analysis of tweeks with multiple harmonics that will allow us to obtain more detailed information on the lower ionosphere.

2. Equipment and software for Tweek registration

A hardware-software complex was created for recording atmospherics [Shvets et al., 2016]. The complex includes sensors of three components of the electromagnetic field, an analog part, an analog-to-digital converter (ADC) and software for signal pre-processing and recording. As sensors, two air frame magnetic loops are used to receive two horizontal mutually orthogonal magnetic components and a rod capacitive antenna for receiving the vertical electric component. Magnetic antennas are oriented in the geographic south-north and west-east directions. The analog part includes antenna preamplifiers that provide a flat frequency response in the frequency band from 300 Hz to 20 kHz, as well as main amplifiers designed to detect the signals from the outputs of the preamplifiers and connecting cable of 30m length to the inputs of the ADC. A four-channel sound card MAYA44 is used as an ADC. It operates at a sampling frequency of 48 kHz, and it has a built-in digital low-pass filter designed to eliminate the effect of frequency aliasing when digitizing signals.

The data acquisition software is built on the basis of the MATLAB package using the “ASIO” driver and the “Playrec” library [http://www.playrec.co.uk/], that provide operation of multi-channel sound cards in the environment of Windows operating system.

The algorithm of the program is as follows. The time realizations of the three field components come from the ADC into a buffer #1 in continuous mode. Simultaneously, the buffer #2 previously filled is analyzed to detect an atmospheric with its electric component exceeding a specified threshold value. The buffer #3 recorded before the buffer #2 is used to keep the initial part and the prehistory of the atmospheric in the case that its duration did not fit completely into the buffer #2. After filling buffer #1 the numeration of buffers is cyclically changed.

If an atmospheric was detected, its three field components, each of total length of 40 ms including a prehistory of 2.56 ms, are added in the data file that is accumulated during one hour. The header of the file contains information on the coordinates of the observation point, sampling frequency, the number of channels, the length of recorded atmospherics, and the data format identifier. Each atmospheric in the file is accompanied by a packet of information containing the absolute start time, the length of the recording, and the absolute calibration coefficients.

The receiving antennas were installed on the roof of the laboratory building on the territory of the Institute of Radiophysics and Electronics in Kharkov (50.046300° N, 36.290668° E). Measurements were carried out around the clock and an ensemble of three-component records of atmospherics was accumulated.

3. Algorithm for identification and analysis of Tweeks

Determining the time dependence of the instant frequency in a tweek harmonic allows for estimating the distance to lightning discharge and corresponding mode cutoff frequency [e.g. Ohya et al., 2008] by least square two-dimensional fitting with the theoretical dependence for the *n*-th order mode, which is determined as follows for a model of the flat waveguide with perfectly conducting boundaries:

$$f_n(\tau) = \frac{f_{cn}}{\sqrt{1 - \left(\frac{\rho}{\rho + c\tau}\right)^2}}, \tag{1}$$

Where, n is the waveguide mode order, f_{cn} is the cutoff frequency, ρ is the distance to the lightning, and τ is the time relative to the start of the tweek.

This method was modified in Shvets et al. [2014] whereby inverting Eq.(1) relative to f_{cn} the dispersion of instant frequencies is compensated by fitting the only one parameter, the distance, and estimations of the cutoff frequencies from all detected harmonics are obtained simultaneously. In this study we develop an automatic algorithm based on this method.

3.1. Determination of peaks in dynamic spectrum of tweeks

To extract any tweek harmonics we calculate a dynamic amplitude spectrum with a moving Gaussian window of about 5 ms length and with time step of 0.6 ms and from the current spectra we determine positions of spectral peaks, which satisfy the following conditions. First, they must be smooth enough, namely: maximum amplitude is greater than the two neighbor points and each neighbor point is higher than their neighbors to the left and to the right respectively. Second, they must exceed the noise level at a corresponding frequency. To find the noise level we calculate the amplitude spectrum of the prehistory portion of a recorded signal and apply 7-point smoothing.

Shown in Figure1 are an example of the waveform (a) and spectrogram (b) of the transverse magnetic component of a tweek received on August 18, 2014 at 21:03:27.734 UT, while distributions of the spectral peaks found in the dynamic spectrum without any noise threshold are given in Figure1(c), and those with account of the noise threshold in Figure1(d). It can be seen that the peaks are grouped into the frequency-decreasing harmonics of tweeks. There are observed that the number of peaks corresponding to the noise component in the signal, which were not filtered out by applying the initial selection criteria, were essentially reduced.

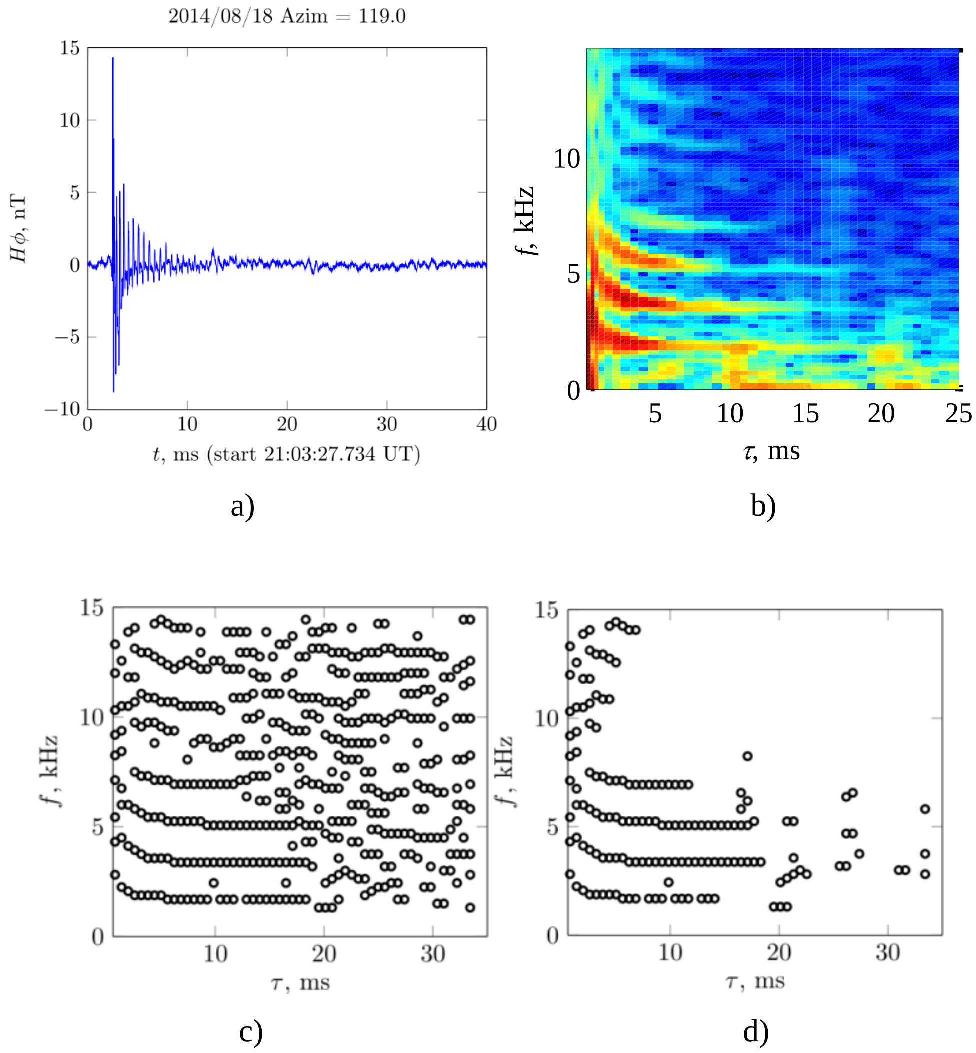


Figure 1: Waveform (a) and spectrogram (b) of a tweek, and spectral peaks detected without any noise threshold (c); with the threshold value of signal to noise ratio 0 dB (d).

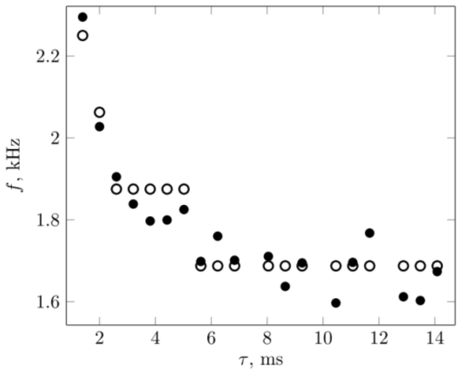
3.2. Frequency interpolation

Obviously, due to the finite width of the time window, the accuracy of determining the instantaneous frequency will be limited by the spectral frequency resolution $\Delta f = 1/T$, where T is duration of the elementary interval of realization over which the current spectrum is calculated. To improve estimates of the peak frequencies we calculate corrections by three-point parabolic interpolation, including the maximum and two surrounding points, in accordance with the well-known formula:

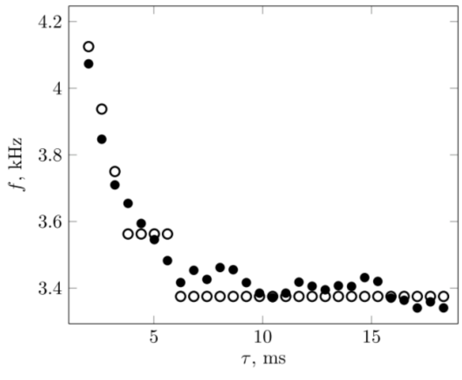
$$f = f_k + \delta f ; \delta f = \Delta f \left[\frac{S_{k+1} - S_{k-1}}{2(2S_k - S_{k-1} - S_{k+1})} \right], \tag{2}$$

where k, f_k, and S_k are the point number, frequency and amplitude of the peak maximum in the discrete spectrum, and Δf is the spectral frequency resolution.

As a result, we obtain smoothed dependence of the instantaneous frequency of tweek harmonics. Figures 2a and 2b illustrate the initial (circles) and interpolated (fatty points) positions of the peak frequencies in the first and second harmonic picked up from Figure 1(d).



(a)



(b)

Figure 2: Result of frequency interpolation in the first two tweek harmonics.

3.3. Initial estimation of the source distance

The final goal of the analysis is estimating the distance to a source and effective waveguide heights for each observed harmonic of a tweek, that makes it possible to estimate the parameters of the conductivity profile of the lower ionosphere [Maurya et al., 2012; Shvets et al., 2014; Tan et al., 2015]. In this study we use the method based on the transformation of instantaneous frequencies [Shvets et al., 2014], which will simplify automation of the procedure for separating individual harmonics.

Having coordinates of peaks on the frequency-time (f-t) plane $f(\tau)$ we recalculate their positions by inverting equation (1) relative to $f_c(\tau)$:

$$f_c(\tau) = f(\tau)\sqrt{1-\left(\frac{\rho}{\rho+c\tau}\right)^2}\,. \tag{3}$$

Obviously, if the distance ρ in Eq. (3) is close to its true value, the recalculated peak frequencies $f_c(\tau)$, corresponding to tweek harmonics, will be grouped in the vicinity of the waveguide cutoff frequencies along the horizontal lines on the f-t plane.

For automate finding of the distance ρ, we employ the "cumulative" effect by maximizing the "power" of the histogram of the distribution of peak frequencies transformed by Eq. (3) when those are concentrated around the cutoff frequencies:

$$F_h = \sum_{i=1}^{M} s_i^2\,, \tag{4}$$

where M is the number of cells in the histogram, and s_i is the height of the i-th histogram bar. The result of such transformation of spectral peaks positions in Figure 1(d), when the functional (4) reaches a maximum at distance ρ = 750 km, is shown in Figure 3.

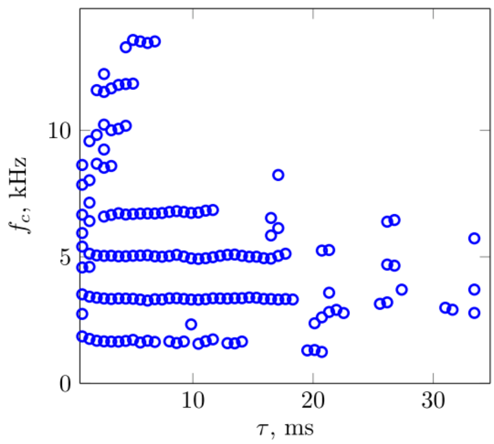


Figure 3: Spectral peaks in the dynamic spectrum of the tweek after compensation of the waveguide frequency dispersion.

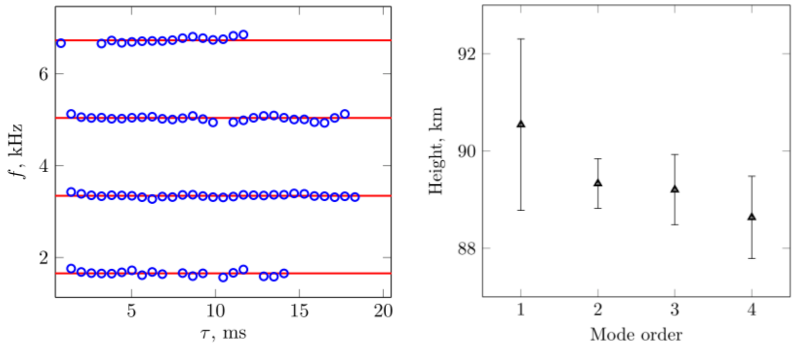
3.4. Selecting tweek harmonics

Now we should select separate tweek harmonics from the distribution of transformed peak frequencies distribution that are seen as horizontally arranged sequences of points in Figure 3.

We form the pulse wave function with the pulse width of 100 Hz. The positions of rectangular pulses on the frequency axis are multiples of the frequency of the expected first order cutoff, which is varied from 1.4 to 2.7 kHz. Calculating a convolution between the pulse wave and the histogram of frequency distribution of the allocated spectral peaks (see Figure3) we find the frequency at which the convolution reaches a maximum. This frequency and its multiples are adopted as the initial estimates of the cutoff frequencies of the fundamental and higher order modes. Such a procedure allows us to estimate the cutoff frequencies, even if the first order harmonic in the dynamic spectrum is lost.

To identify and select separate harmonics we choose peaks within a corridor of 200 Hz width around initially estimated cutoffs. We remove also peaks after a gap more than 2 ms from the spectral peak successions allocated at the beginning of the dynamic spectrum. We identify a tweek harmonic if a corridor picks up more than 7 points (the length of a harmonic should be more than 5 ms).

Finally, we adjust the distance value to minimize a functional represented as a sum of standard deviations for all the selected harmonics. For the adjusted distance, which appeared equal to the initial estimation 750 km for the tweek example above, we determine median values of the transformed peak frequencies for each harmonic and corresponding standard deviation. Shown in Figure 4(a) circles are the identified selected harmonics and the straight horizontal lines represent the median frequencies of the transformed harmonics that designate the cutoff frequencies for the first and three higher order waveguide modes. The corresponding effective waveguide heights defined as $h = nc/2f_c$, with the error bars are shown in Figure 4(b) by triangles.



a) b)

Figure 4: Selected harmonics (a) and corresponding effective waveguide heights for the first four modes (b) revealed with application of the developed automatic procedure of tweek analysis.

4. Location of Thunderstrom cells and Ionosphere height variations

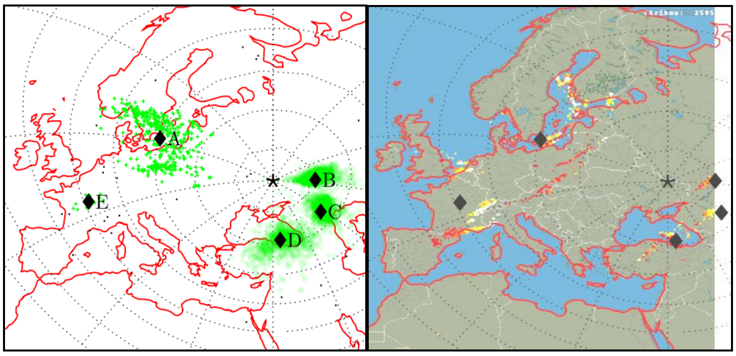
The proposed automatic method is demonstrated on the real data obtained during a night of 18 –19 August 2014 with high thunderstorm activity in Europe. We choose the period from local sunset to sunrise at the observation point, approximately from 17 till 2 hours of UT. To determine geographical coordinates of lightning strikes we combine the distance and direction finding techniques, the latter one being based on the Poynting vector calculation [Nickolaenko et al., 1994].

Positions of strokes determined by registered tweeks are plotted on the map in Figure5a by points. The observatory place in Kharkov is marked by a star, the azimuthal grid with step 30° and the distance grids with step 500 km centered at the observation point are shown by dotted lines.

A density-based clustering algorithm DBSCAN [Ester et al., 1996] was applied to isolate different thunderstorm cells by results of lightning location by tweeks. The result of clustering is shown in Figure5a where the foci of the outlined clusters are designated by rhombs and marked by letters. The total numbers of tweeks registered from these clusters are A – 379, B – 2035, C – 1053, D – 1105, E – 10.

To estimate the location accuracy by tweeks we compare our results with the lightning distribution map for the corresponding period of time available on the website of the “Worldwide, real time, community collaborative lightning location network Blitzortung.org” [http://ru.blitzortung.org/archive_data.php]. The geographical map in the Miller projection (the same as for Figure5a) with lightning locations determined by the Blitzortung network, designated by the colored in the dark red – white colormap points, are shown in Figure5b. The bold rhombs designate positions of the “centers of gravity”, determined by tweeks, as shown in Figure5a.

We observe the most active regions from Iberian Peninsula to Baltic Sea. Most of them are widely extended in the South-West to North-East direction in the Blitzortung’s map in Figure5b that is rather connected with the weather fronts in Europe. Less intensive thunderstorms are extended from Anatolian peninsula to North-East of Azov Sea.



a) b)

Figure 5: Lightning strokes determined by tweeks (a) and provided by the Blitzortung.org lightning location network (b) during the night of 18 – 19 August, 2014. The bold rhombs designate the “centers of gravity” of lightning clusters

It is seen that the active areas A and E determined by tweeks only partly overlap with strikes on the Blitzortung map in the West Europe. The most distant active areas at Iberian Peninsula are almost not detected by tweeks. This is probably due to relatively high noise level at the observation place for magnetic field components especially that limits the distance of lightning detection. Much better correspondence is observed for three active regions B, C, and D located to East, South-East and South of the observation point. These three clusters are located much closer to the observation point and thus we observe much stronger intensity for them in comparison with the results of Blitzortung network whose stations are situated mostly in West Europe.

By using these three clusters, we made a comparison between Figure 5(a) and Figure 5(b), which indicate that we can roughly estimate the distance estimation offset to be less than 100 km. Figure5a enabled us to roughly estimate the random error to be of the order of 200 km from the radial dispersion of the strokes positions for the distances approximately from 400 to 1400 km.

The height variations determined for clusters A – D in Figure 5a are shown in Figure 6a – Figure6d respectively. The scatter plots and hourly medians of height with the error bars are given in each graph. The letter designations of the graphs correspond to those of the thunderstorm foci in Figure 5(a).

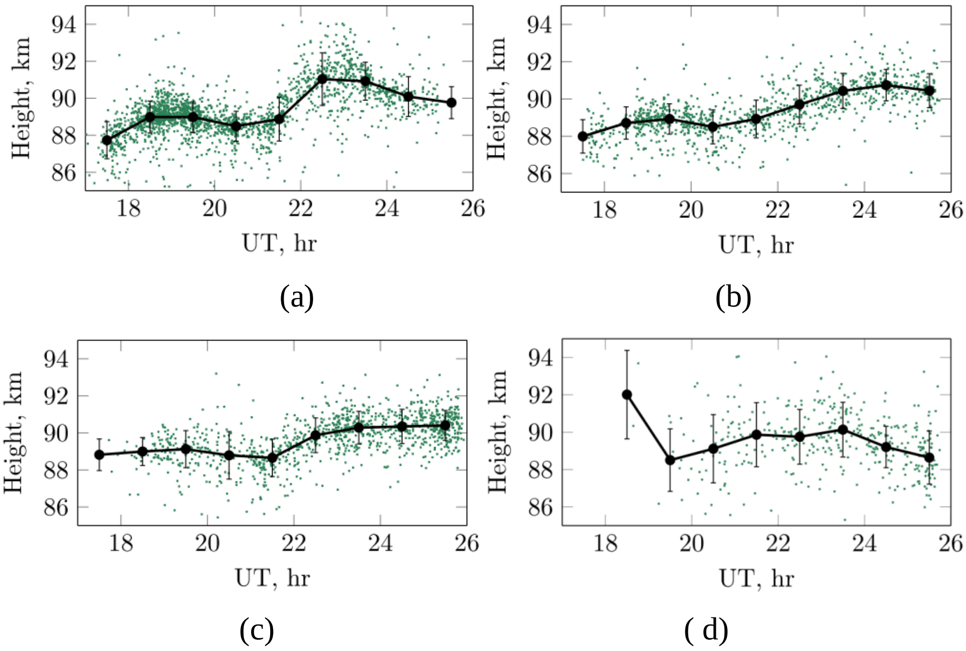


Figure 6: Ionosphere height variations determined by tweeks received from clusters A – D shown in Figure 5.

From these graphs we can see a step-like increase of the height by about 1 – 2 km approximately at the local midnight (21 UT) and the variation patterns slightly change for the closest clusters B, C, D. The height variation along the path to the cluster A demonstrates quite different behavior, because it has a wide maximum around local midnight. The difference found in the height variations patterns is probably connected with the dynamics of local ionospheric irregularities.

5. Conclusion

In this paper we have proposed a new technique for automatic identification of tweek atmospherics and finding the distance to lightning stroke and effective heights of the lower ionosphere along a propagation path for the fundamental and higher order modes of the Earth-ionosphere waveguide.

Effectiveness of the technique was demonstrated with experimental records of atmospherics accumulated during 9 hours of one night of 18 – 19 August, 2014. The total number of registered atmospherics was about 35400, one atmospheric per second on average. Among them about 5200 atmospherics were identified as tweeks and their geographical coordinates and corresponding effective ionosphere heights were determined. The total time of processing this 9-hour data ensemble took 622 seconds on a standard laptop with two-core 2GHz processor and 4 gigabyte memory that demonstrates an opportunity to use the developed automatic technique in a real-time system for monitoring the lower ionosphere.

Application of the clustering algorithm allowed us to automatically outline compact thunderstorm areas and to determine changes in the effective height of the lower ionosphere along different propagations paths that would be useful for studying the dynamics of ionospheric irregularities in time and space.

The distance finding accuracy of our tweek method was roughly estimated by a comparison with independent lightning location data from the Blitzortung.org lightning location network to be less than 100 km with standard deviation less than 200 km in the range of distances from 500 to 1400 km. These estimations essentially exceed those predicted by numerical modeling results for the applied distance finding technique [Krivonos and Shvets, 2016], but we should note the presence of rather strong manmade interferences at the observation site placed in urban environment.

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