Amplitude variations of the reflected signal during vertical sounding of the ionosphere at mid-latitudes

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Annotation. In this paper, we discuss the main types of quasiperiodic variations in the amplitudes of the reflected signal during vertical sounding of the ionosphere at mid-latitudes. The initial experimental data are vertical sounding ionograms obtained by the Cyclone ionosonde. Ionosonde is located in Kazan (59 °, 49 °) and in standard mode allows to receive one ionogram per minute. In the analysis, methods are used to visualize a large flow of ionograms in the form of final summary maps of the state of the ionosphere (A-, H-, As-maps). In the work, typical examples of quasiperiodic variations in the amplitudes of the reflected signal in ionograms and on A-maps are given for various types of multipath beatings (polarization and in the case of scattering). The frequency properties of such beatings are used to estimate the difference in the virtual reflection heights between modes of different polarizations with high accuracy (up to ~ 90 m, then a height resolution of the ionosonde of ~ 2.5 km), which makes it possible to refine the form of the electron concentration profile of the lower part of the ionosphere. A phenomenon rare for the mid-latitude Es layer was detected, it is beatings of two O modes with different virtual reflection heights. The features of quasiperiodic variations in the amplitudes of the reflected signal on the traces of the transient Es (rEs) layer are also given. Possible causes of the appearance of such beatings are considered.

Keywords: ionosonde «Cyclone», ionogram, ionosphere, interference of reflected signals.

Introduction

Research on the sporadic E layer has been going on for many decades [Mathews, 1979, 1998, Budden, 1961, Whitehead, 1989, Haldoupis, 2003, 2011, Bakhmet'eva, 1999, 2005, Chkhetiani, 2013, Shalimov, 2014, etc.]. The sporadic E layer is distinguished by high intensity on the one hand (the electron concentration in the Es layer can be several times higher than the concentration of the surrounding regular layer E), and on the other hand, it is very thin (several km). In connection with these features, this layer has, different from other layers of the ionosphere, the dependence of the height and amplitude of reflections on frequency. Therefore, in the 70-80s of the 20th century, studies of the amplitude-frequency characteristics (AFC) of reflections from the Es layer during vertical sounding of the ionosphere were popular. Particular interest was in the pattern of quasiperiodic beatings on the frequency response, due to the interference or coupling of several magnetoionic modes. Such beatings are called polarizing fading. The main studies of polarization fading on the frequency response of the Es layer were performed in [Chessel, 1971a, 1971b, Turunen, 1980, Jalonen, 1981], and for reflections from the F layer it was performed in [Drobzhev, 1975]. In [Chessel, 1971a; 1971b], the semitransparent ranges of the sporadic Es layer are considered based on the coupling mechanisms of magnetoionic modes, and model calculations of the reflection, transmission, refraction coefficients and semithickness of the Es layer under various geophysical conditions are presented. [Jalonen, 1981] was analyzed vertical sounding ionograms and high-latitude stations and found experimental evidence of beatings on the frequency response of the E and Es layers, also it was noted a decrease in the step between successive interference minima. Such beatings interpreted in the framework of interference and coupling of two magnetoionic modes with ordinary polarization. At middle latitudes the Es traces are characterized by an increase in the steps between successive interference minima and fading is usually explained by the interference of the O and X modes [Yusupov, 2011, Akchurin, 2011]. Due to the very small thickness (few km) of the Es layer, it is extremely difficult to distinguish between the interference of the O and X modes from the interference of two O modes. The task is simplified if we draw an analogy with beatings on the traces of layer F, which were studied in detail in [Drobzhev, 1975]. This work is devoted to the study of beatings during reflections from the ionosphere at mid latitudes, both already described and previously undescribed, in order to generalize all types of "polarization beatings." Such a study was made possible thanks to the features of the Cyclone ionosonde control system.

1. Equipment and methods for visualization of vertical sounding data of the ionosphere

The initial experimental data are vertical sounding ionograms obtained by the Cyclone ionosonde (Kazan ~ 59 ° E, 49 ° N). To study the rapidly changing processes occurring in the ionosphere the ionosonde “Cyclone” control system was updated in February 2010 [Akchurin, 2010]. After modernization, the ionosonde has the following characteristics: 1) the peak power of the sounding signal is ~10 kW. 2) the duration of the sounding pulse is 70 μs. 3) the frequency range of sounding is 1-9 MHz. 3) sounding time 20 s. In standard mode, the Cyclone ionosonde receives one ionogram per minute. The ionosonde has a crossed delta antenna with a height of ~ 10 m (one arm of the antenna works for transition, and the other for receiving). The ionosonde does not have a system for separating polarization modes during receiving. On the one hand, it allows analyzing the amplitudes variations of the reflected signals during polarization fading, which describing in this paper. On the other hand, makes it difficult to automatically extract traces of reflections on the ionogram, which is necessary for reconstructing electron concentration profiles.

Currently, there are no reliable fully automatic methods (without operator) for obtaining height-electron concentration profiles from vertical sounding ionograms. Therefore, on the one hand, the high temporal resolution of the Cyclone ionosonde (1 ionogram per minute) makes it possible to obtain new data on the dynamics of the ionosphere; on the other hand, it is extremely difficult to provide manual processing of such a large amount of data. To solve this problem, Kazan Federal University developed algorithms for visualizing a large flow of ionograms in the form of summary maps of the state of the ionosphere (A-, H-, As-maps) [Yusupov, 2011, Akchurin, 2011].

A-map (amplitude map) is the time variations of the amplitude-frequency characteristics of the reflected signal, H-map (height map) is the time variations of the height-frequency characteristics of the reflected signal, As-map is the time variations of the summary amplitude (over all frequencies) of the reflected signal. The As-map is similar to the radar methods of observing the ionosphere and to the well-known forms of representations of the results of vertical sounding in the form of RTI-images [Haldoupis, 2006, Lynn, 2011, Harris, 2016]. Figure 1 illustrates the process of obtaining summary maps of the state of the ionosphere. Figure 1a shows an example of an ionogram. To obtain A-maps, maximum amplitudes for each frequency are searched (Figure 1b), to obtain H-maps, heights are searched for corresponding to maximum amplitudes (Figure 1d), and to obtain As-maps for each height, the total amplitude for all frequencies is found (Figure 1e).

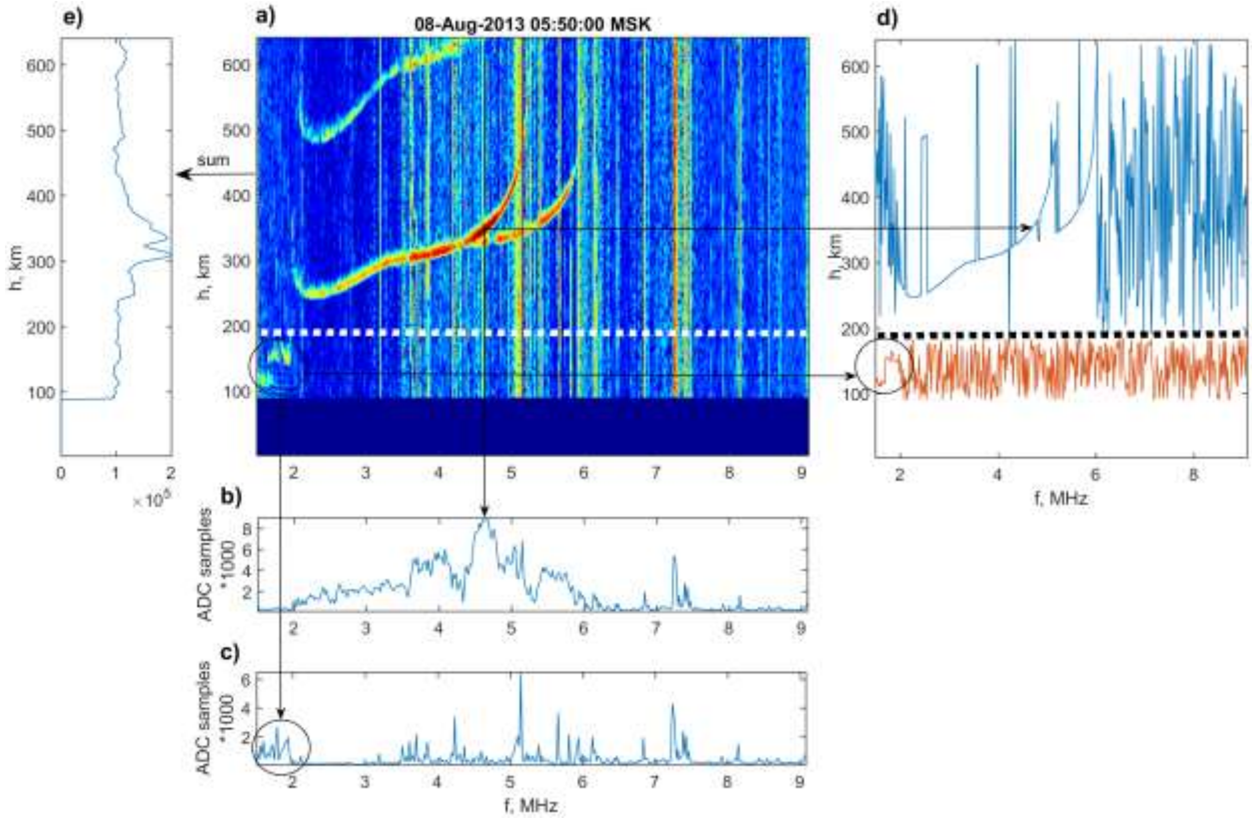

Figure 1. Diagram of the algorithm for obtaining summary maps of the state of the ionosphere. a) Ionogram; b) frequency response of layer F; c) frequency response of layer E; d) height-frequency plot of layers F and E; e) Height histogram obtained by summing all the amplitudes of the ionogram along the frequency axis.

Further, for each moment of time (for the corresponding ionogram), such procedure is repeated. When constructing A- and H-maps separately for the E- and F-regions, the ionogram is divided into two altitude intervals of 1-200 km and 200-600 km, respectively. Figure 2 shows summary maps of the state of the ionosphere for August 22, 2013.

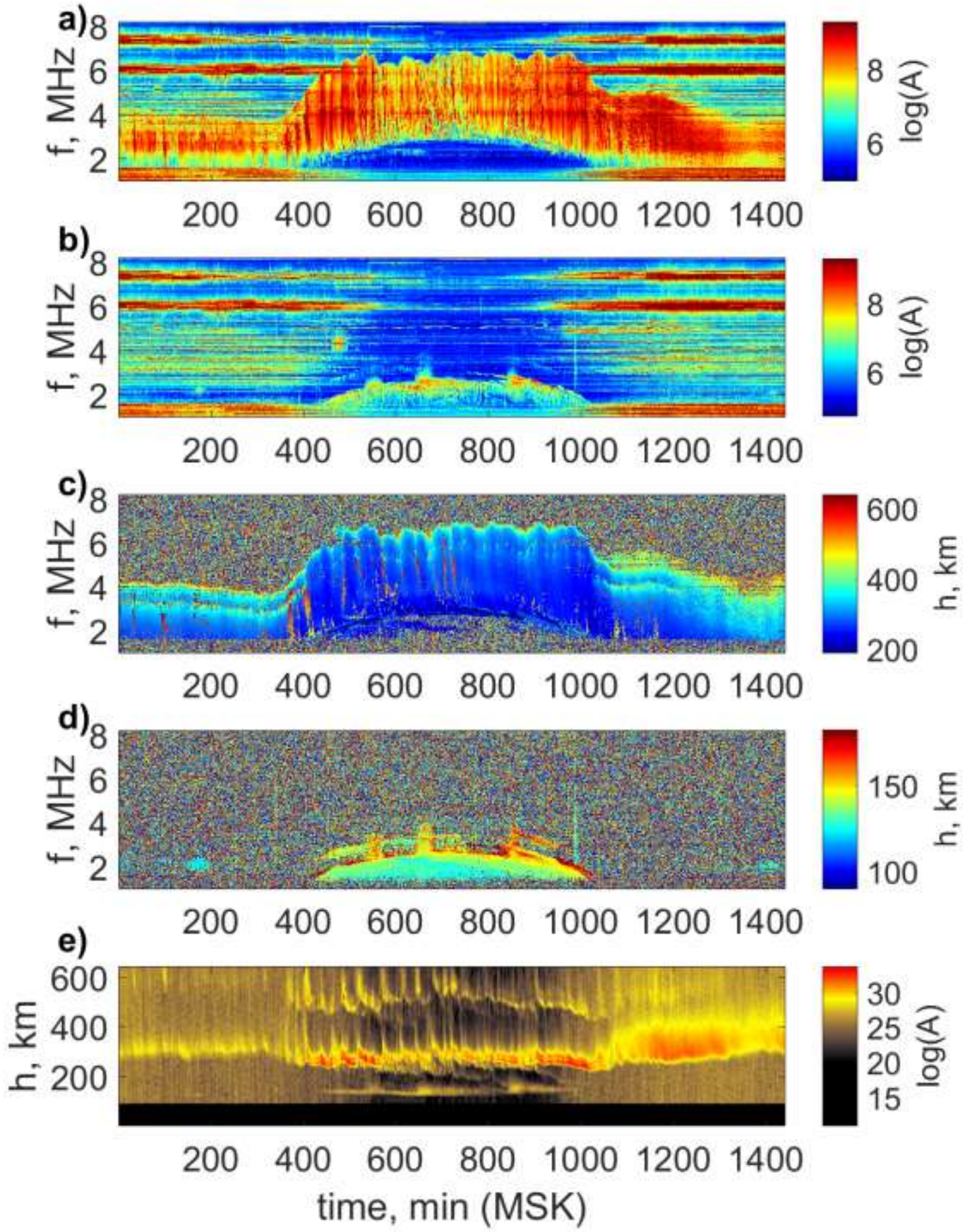

Figure 2. a) A-map of the F-region; b) A-map of the E-region; c) H-map of the F-region; d) H-map of the E-region; e) As-map.

Figure 2 shows that summary maps of the state of the ionosphere, which clearly illustrate variations in the amplitude of the reflected signal, variations in the height of the reflected signal, and variations in the virtual heights of the layers of the ionosphere. Using summary maps, it can easily analyze variations in the critical frequencies of the layers of the ionosphere. In this paper, summary maps of the state of the ionosphere are used to study beatings on ionospheric traces in vertical sounding. two examples of important results that are made accessible via this presentation mode

2.1. Variations of amplitudes of signals reflected from layer F

In [Drobzhev, 1975], beatings (polarizing fading) during signal reflection from layer F were studied in detail and it was shown that beatings can serve as an additional source of information on the background concentration of the lower part of the ionosphere. Also in this work, variations of the zero beating point studied (sounding frequency, where the difference in the virtual heights of the O and X modes tends to zero). Unfortunately, these works were carried out using analogue technology. The data was not stored on a digital medium devices, but was analyzed using photos of oscillograms.

That O/X interference (beatings) occurs indicates that the respective E-fields at the antenna are of similar magnitude, that the phase paths are well defined, and that the Fresnel reflection areas are well defined. In this case, as the O/X pulses begin to overlap at the antenna, the coherent combination of the 2 signals occurs. As this is a function of frequency, the interference pattern occurs with, apparently, full or fullest overlap at f*. In Figure 3, the full overlap results in the smallest E-field at the receiver. This is by hypothesis an "accident". Figure 3a shows an example of an ionogram of the Cyclone ionosonde with beatings when a signal is reflected from layer F (according to the type of O and X modes). In Fig.3b, the height-frequency characteristics for the O and X modes, and in Fig.3c, the frequency response of the F layer. Per Fig.3c, the "beatings" seen clearly and demonstrate that the O/X-mode reflections are coherent. That is, each signal at each frequency has a well defined phase center leading to the positive/negative reenforcement of the two in the received signal. In the figures, the point of zero beatings f* is marked. A characteristic feature of the AFC variations in reflection from the F layer is the presence of two intervals with different properties. In the first interval (before the point of zero beating), a sequential increase in the frequency difference between the minima is observed, and in the second (after the point of zero beatings) a sequential decrease in the frequency difference between the minima is observed.

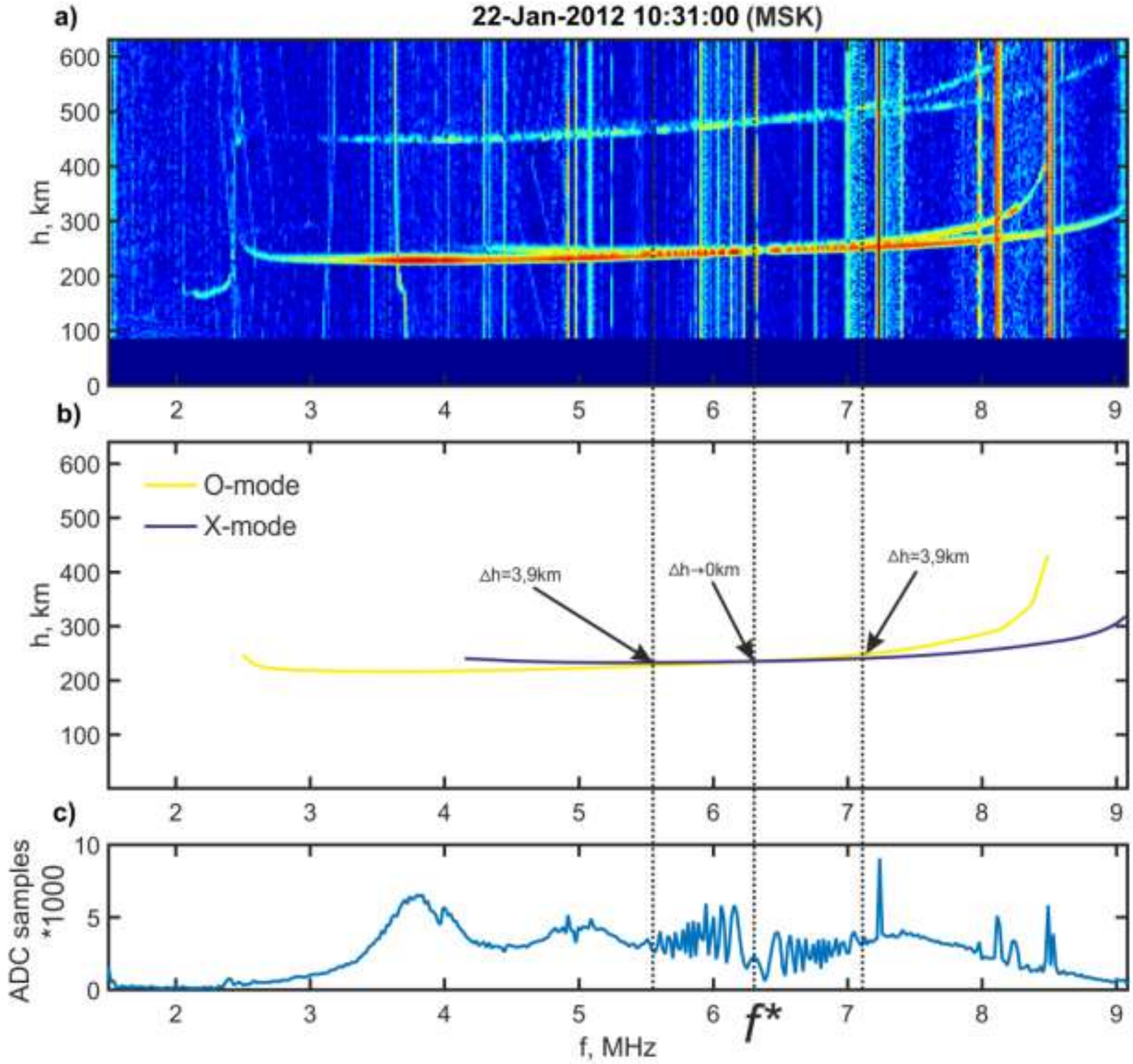

Figure 3. a) An example of an ionogram with beatings of the type O- and X-modes on the traces of layer F; b) the height-frequency characteristics of the O- and X-modes of the traces of layer F; c) frequency response of the F layer for a given ionogram showing a picture of polarization fading. Symbol f* is marks the frequency of zero beatings.

The zero beatings point itself is either a minimum or a maximum, and a pattern in the form of a ring is formed on the A-map (an example in Fig. 4.a). When the F layer layered into F1 and F2, it is possible to observe beatings both when the signal is reflected from the F1 layer and when reflected from the F2 layer (an example in Fig. 4.b). When the signal is reflected from the F layer, one can also observe the beatings of the O- and Z-modes (when the trace of the extraordinary Z-mode is located in the lower frequency region relative to the O-mode), but for middle latitudes this is an extremely rare phenomenon, it is more typical for polar latitudes. The frequency distance between the minima at which the quasiperiodic variations begin is ~ 38 kHz, the application of the formula $\Delta h = c / (2\Delta f)$ gives a difference of the virtual reflection heights of ~ 3.9 km between the ordinary and extraordinary modes. Thus, the beatings begin (end) when the traces of different polarization moving closer each other (moving away) by ~ 3.9 km then a sounding pulse duration is 70 μs. In addition to high-frequency variations in the amplitudes of the reflected signal associated with the coupling of O- and X-modes, low-frequency variations of the frequency response during the passage of moving ionospheric disturbances (TID) are clearly visible on the A-maps of layer F. These variations in frequency response are associated with an increase in the amplitude of the signal reflected from the maxima of the electron concentration formed during the passage of the TID. In Fig. 4, low-frequency variations in frequency response (associated with TID) are indicated by gray arrows. In As-maps, the traces of the passage of TIDs can also be seen in the form of inclined strips (for example, Fig. 2e).

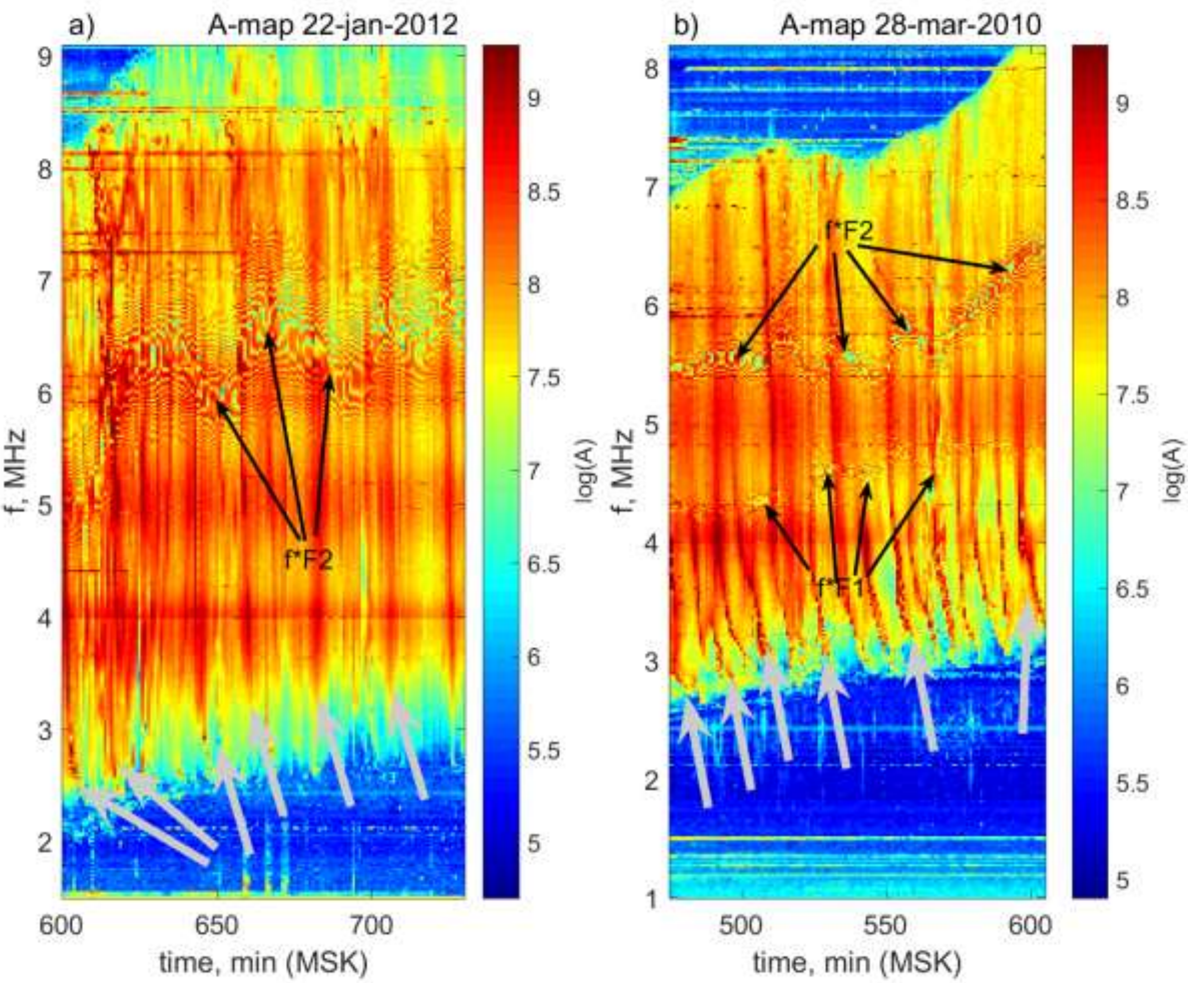

Figure 4. Pictures of the polarization fading of O- and X modes on A-maps for layer F2 (a) and simultaneously for F1 and F2 (b). For clarity, the black arrows indicate the frequency variations of the zero beating point, and the gray arrows indicate the increase in amplitude due to the passage of the TID.

2.2. Variations of signal amplitudes during reflection from the Es layer (O and X modes)

Variations in the amplitudes during beatings of O and X can also be observed when the signal is reflected from the sporadic layer Es, provided that the plasma frequency of the layer exceeds the reflection frequency of an ordinary wave by half the electron gyrofrequency [Yusupov, 2011]. The ionogram traces of Es at mid-latitudes are almost strictly horizontal. The dispersion inclination or cusp is observed only in the daytime at the low-frequency end of the Es layer trace, both for the O and X modes. The cusp of the unusual trace Es at the high-frequency end of the trace is in most cases not visible on the ionograms of vertical sounding due to blanketing by the trace of the ordinary component. Therefore, during signal reflections from the Es layer, beatings will usually be observed only up to the sounding frequency, where the difference in the virtual heights of the O and X modes tends to zero (points of zero beatings). Thus, in most cases, there will be a sequential increase in the frequency difference between the minima (in contrast to reflections from the F layer). An example of such beatings when reflected from Es is shown in Fig. 5. As can be seen from Fig. 5, the beatings are start at ~ 4.5 MHz (corresponds to a difference in effective heights between traces of ~ 5 km) and end ~ 6.2 MHz (corresponds to a difference in effective heights between traces of ~ 0.6 km). Fig. 6a shows an A-map corresponding to the beatings shown in Fig. 5.

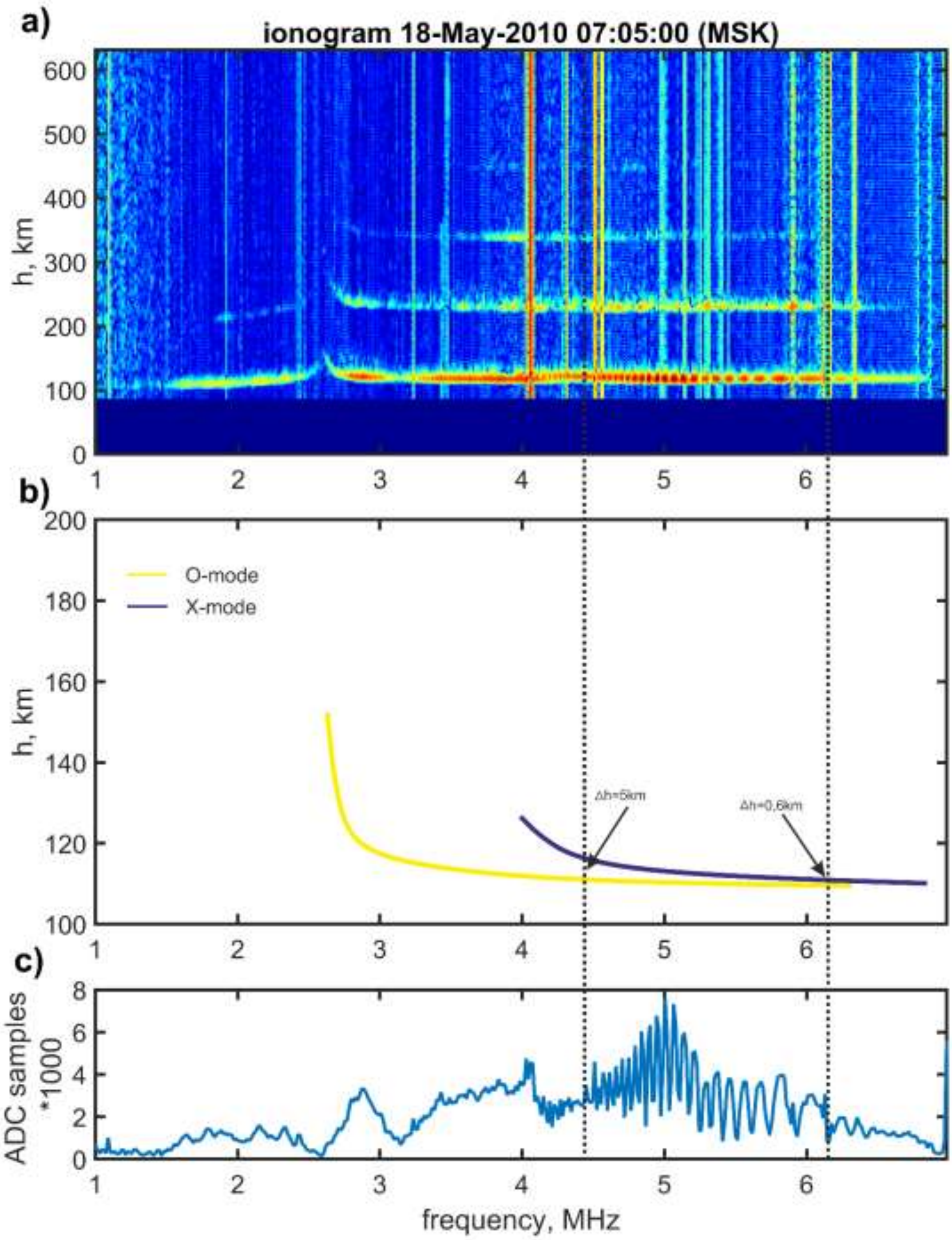

Figure 5. a) An example of an ionogram with variations in amplitudes during beatings according to the type of O- and X-modes on the traces of the Es layer; b) the height-frequency characteristics of the O- and X-modes of the traces of the Es layer (for clarity, the height axis is enlarged comparing with the ionogram); c) frequency response of the Es layer for a given ionogram showing a picture of polarization fading. Dotted lines mark the start and end frequency boundaries of the beating range. The arrows indicate the difference in the effective heights between the O and X modes at the boundaries of the beating range.

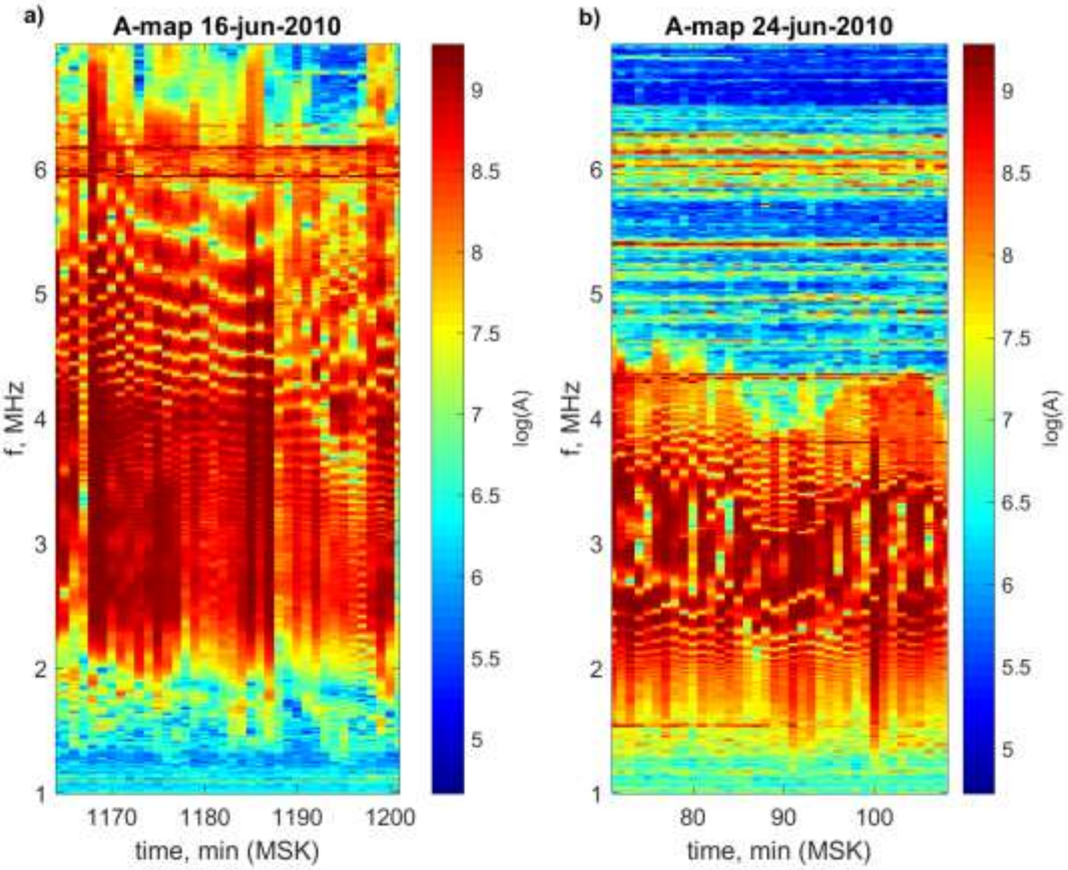

Figure 6. Pictures of the polarization fading of O- and X modes on A-maps for the Es layer. a) Increase in step between successive minima; (b) - the presence and increase and decrease of the step, and the frequency interval between the two types of beatings corresponds to the point of zero beatings point and forms a pattern in the form of a “ring”, similar to the pattern on the F-traces.

Figure 6b shows a very rare case of beatings in the Es layer traces, which are observed both before and after the point of zero beatings. When the X-trace moves closer to the O-trace, an increase in the frequency difference between the minima is observed. When the X-trace moves away from the O-trace, a decrease in the frequency difference between the minima is observed. In the region of zero beatings, a characteristic pattern in the form of successive “rings” is observed. For such case, it is possible to determine with high accuracy the point of zero beatings (and, therefore, the minimum distance between O- and X-traces). The middle of the frequency interval between the last minimum of the "step increasing range" and the first minimum of the "step decreasing range" is the point of zero beatings. As mentioned above, such a pattern of fading of Es traces is extremely rarely observed at mid latitudes and will be more characteristic of equatorial latitudes (due to the higher electron concentration in the Es layer). In addition, at mid-latitudes, the observation and analysis of such pattern of beatings is difficult due to technical limitations. It can be seen from Fig. 6b that the polarization fading pattern changes very quickly; therefore, we cannot reduce the ionogram repetition rate. On the other hand, a small step between the sounding frequencies and at the same time a wide sounding frequency range (for example, ~ 1-30 MHz) are required, which requires a rather complicated ionosonde control system and leads to a decrease in the ionogram repetition rate.

2.3. Variations in the amplitudes of signals reflected from the Es layer (two O modes)

Quasiperiodic variations in the frequency response of E and Es layers by the type of coupling of two O modes at polar latitudes were studied in [Jalonen, 1981], and attempts to find such beatings were made in [Sherstyukov, 1989]. These works were based on the theory described in [Chessel, 1971a, 1971b], where the appearance of the second O mode is explained as part of the mode coupling process. For oblique magnetic field lines and a steep gradient of the electron concentration of E and/or Es layers the part of reflection energy of the O-mode is transformed into the X-mode, which is reflected at a slightly higher height. In the back way, this transformed X-mode goes through the reflection level of the O-mode, and again turns into the O-mode. At polar latitudes, in [Jalonen, 1981], the frequency responce properties were established with a characteristic decrease in the frequency difference between successive minima. On ionograms of the Cyclone ionosonde, sometimes there are two very deep minima (each of which has a small frequency extension) or one deep minimum (with a large frequency extension) in the frequency range below the beatings region of the O and X modes. An example of the observation of such beatings is shown in Fig. 7 (arrows indicate two minima of the frequency response).

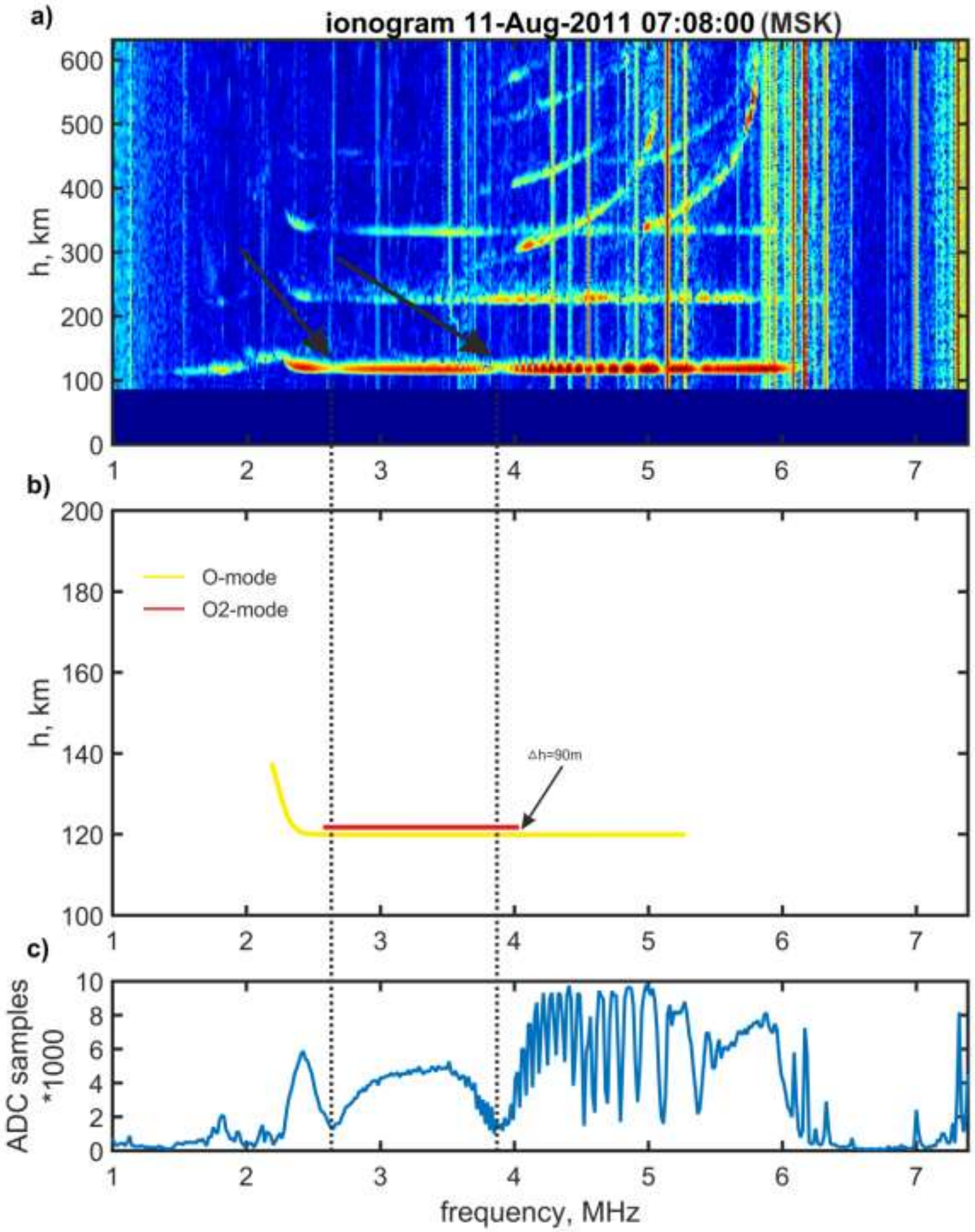

Figure 7. a) An example of an ionogram with beatings according to the type of two O-modes on the traces of the Es layer; b) the height-frequency characteristics of two traces of the O-modes of the Es layer (for clarity, the height axis is enlarged comparing with ionogram); c) Frequency response of the Es layer for a given ionogram showing a picture of polarization fading. The arrows indicate the minima of the beatings according to the type of two O-modes.

The A-map of the Es layer (Fig. 8) shows the time-frequency variations of the minima noted in Fig. 7, it can be seen that the variations of these minima form a “ring” pattern, which is similar to the variations of the zero beating point described in sections 2.1 and 2.2. If the rings in Fig. 8 are variations of the zero beating point, then most likely the reason for these variations is the change in the two reflection levels of the ordinary O mode and the transformed O mode, as shown in Fig. 7b and described in [Chessel, 1971a, 1971b, Jalonen , 1981].

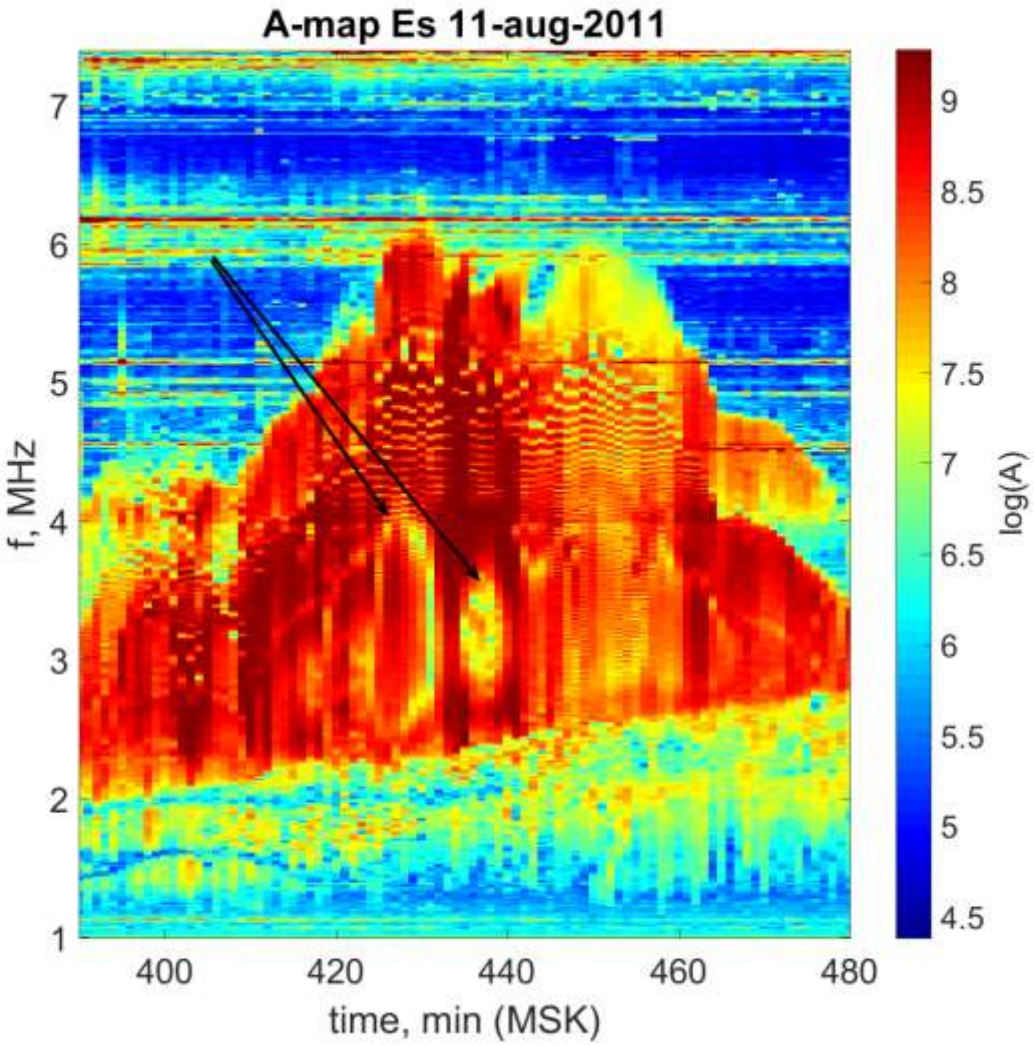

Figure 8. A-map of the Es layer showing the patterns of the polarization fading as two O-modes in the form of “rings”.

As can be seen from Figure 8, the pattern in the form of “rings” is brighter for the beatings of two O-modes (that is, the amplitude of the “rings” often drops to zero) compared to the beatings of the O- and X-modes (Fig. 6). The frequency difference between the boundaries of the “ring” shows variations in the distance between two O-traces. These variations are due to changes in the background electron concentration of the E layer, as well as due to changes in the form of the Es electron density profile. In the time interval 423-427 minutes, the “rings” expanded and the diameter of the “ring” changed from ~ 500 kHz to 1.6 MHz, which corresponds to a change in the difference in effective heights from ~ 300 m to ~ 90 m in 3 minutes. Further, in the time interval 427-432 minutes, the “ring” was compressed due to the moving away of the second O-mode of the trace from the main one. Variations in the “ring diameter” usually correlate with variations in the critical frequency of the Es layer. Thus, beatings can be used to obtain additional information about the background concentration of the lower part of the ionosphere. After calculating the virtual reflection heights of the O-mode of the Es layer and finding the characteristic points of the polarization fading, using machine learning, the form of the electron concentration profile of the lower part of the E layer can be calculated.

2.4. Signal beatings during reflection from the transient Es layer

The transient sporadic layer is a poorly known phenomenon. It is distinguished from the usual Es layer: 1) instantaneous appearance with a high limiting frequency (sometimes up to 25 MHz or more) 2) a flat trace shape (without a cusp even in the daytime) 3) low amplitude of the reflected signal (often not much higher than the noise level ionograms). The lifetime of the transient Es layer varies from ~ 1 to ~ 30 minutes, and the intensity only decreases. The causes of the appearance of the transient layer are associated with meteors [Maruyama, 2003, 2008, Yusupov, 2017, Kozlovsky, 2018]. An example of an ionogram with transient Es is shown in Fig. 9a.

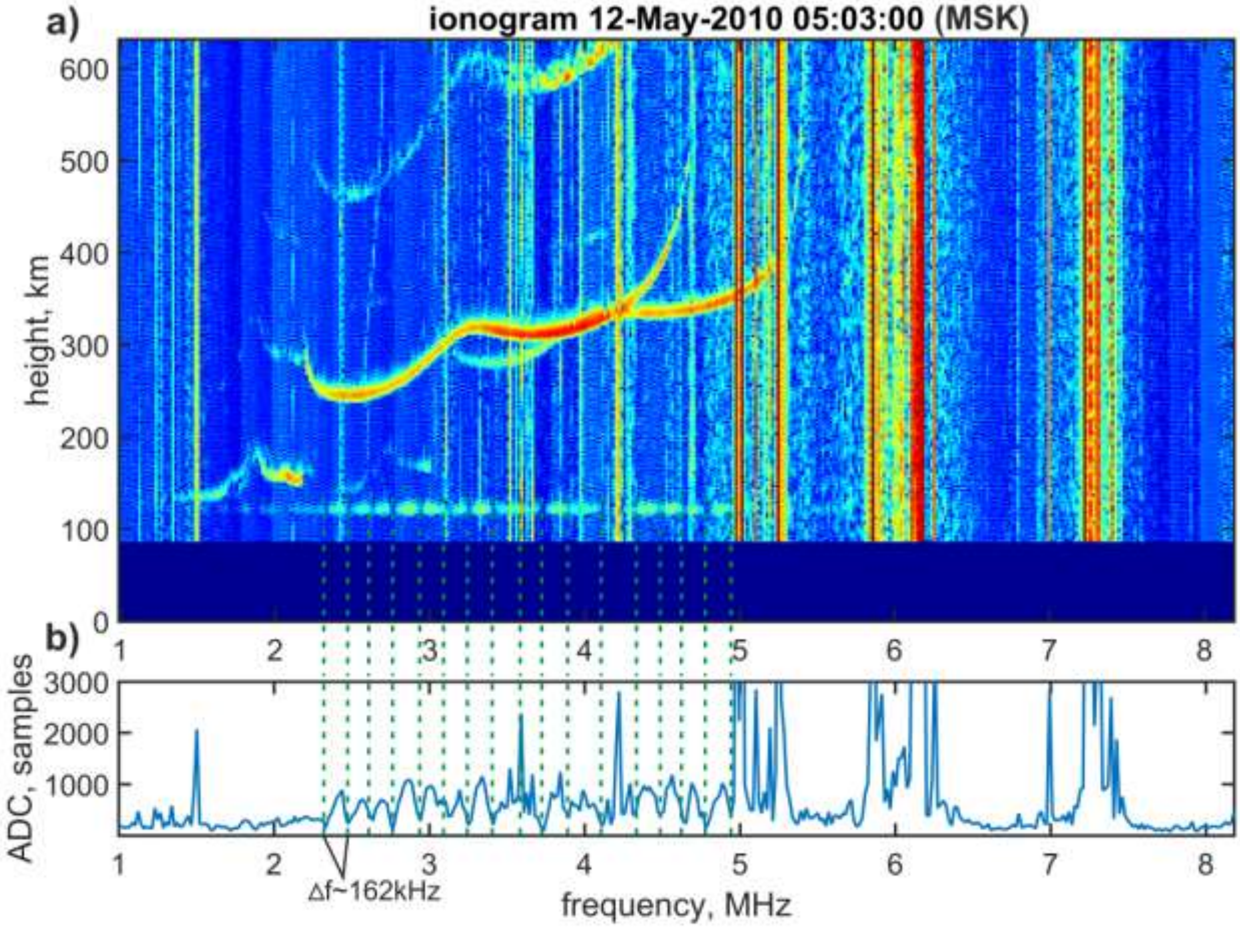

Figure 9. An example of an ionogram with a transient Es trace

Beatings with approximately equal frequency differences between the minima are clearly visible on the ionogram. Figure 9b shows the frequency responce of the reflected signal, the dotted lines indicate the frequencies of the minima. The difference between neighboring minima is Δf ~ 162KHz. As for other types of beatings, it is possible to obtain a difference in virtual heights Δh ~ 925m. However, what kind of signals will reflected at different heights? To split the signal into magnetoionic components, it is necessary sufficient layer thickness for appearing of anisotropy. In this case variations in frequency response will be similar to properties of beatings described in Section 2.2. However, as a rule, the thickness of this transient Es is insufficient for splitting the signal into magnetoionic components and the cause of such beatings as in Fig. 9 may be the separation of the meteor into fragments [Mathews, 2010]. Each meteor fragment forms a transient layer, and Δh (~ 925m) in this case shows the distance between the fragments. These layers cannot be separated on the ionogram, and they can be detected only by beatings.

2.5. Variations in the amplitudes of the reflected signals in scattering by layers E, Es, and F

It should be noted variations in frequency response arising from the scattering of signals. During scattering, the reflected signal becomes diffuse, has a duration longer than the sounding pulse, and it can also extend into the frequency region above the critical one. Scattering during vertical sounding is associated with the multipath reflection of the sounding signal from the ionosphere by random irregularities of plasma concentration, when several signals are return to the source through different paths and, therefore, they are associated with different group delays [Tolstikov, 2004]. The first studies of F-scattering were described in [Booker and Wells, 1938], then many works on this topic were performed, for example [Antonov, 1987, Gershman, 1963, Vybornoe, 1997, Muradov, 1982, Bowman, 1982, Renau, 1960, Booker, 1986]. The relationship between F and Es scattering was analyzed in [Mathews, 2001, Haldoupis 2011]. Frequency response during scattering looks chaotic and have very small frequency distances between minima/maxima, which is associated with multiple reflection of the sounding signals from various types of irregularities. An example of an ionogram with such variations in frequency response is shown in Fig. 10.

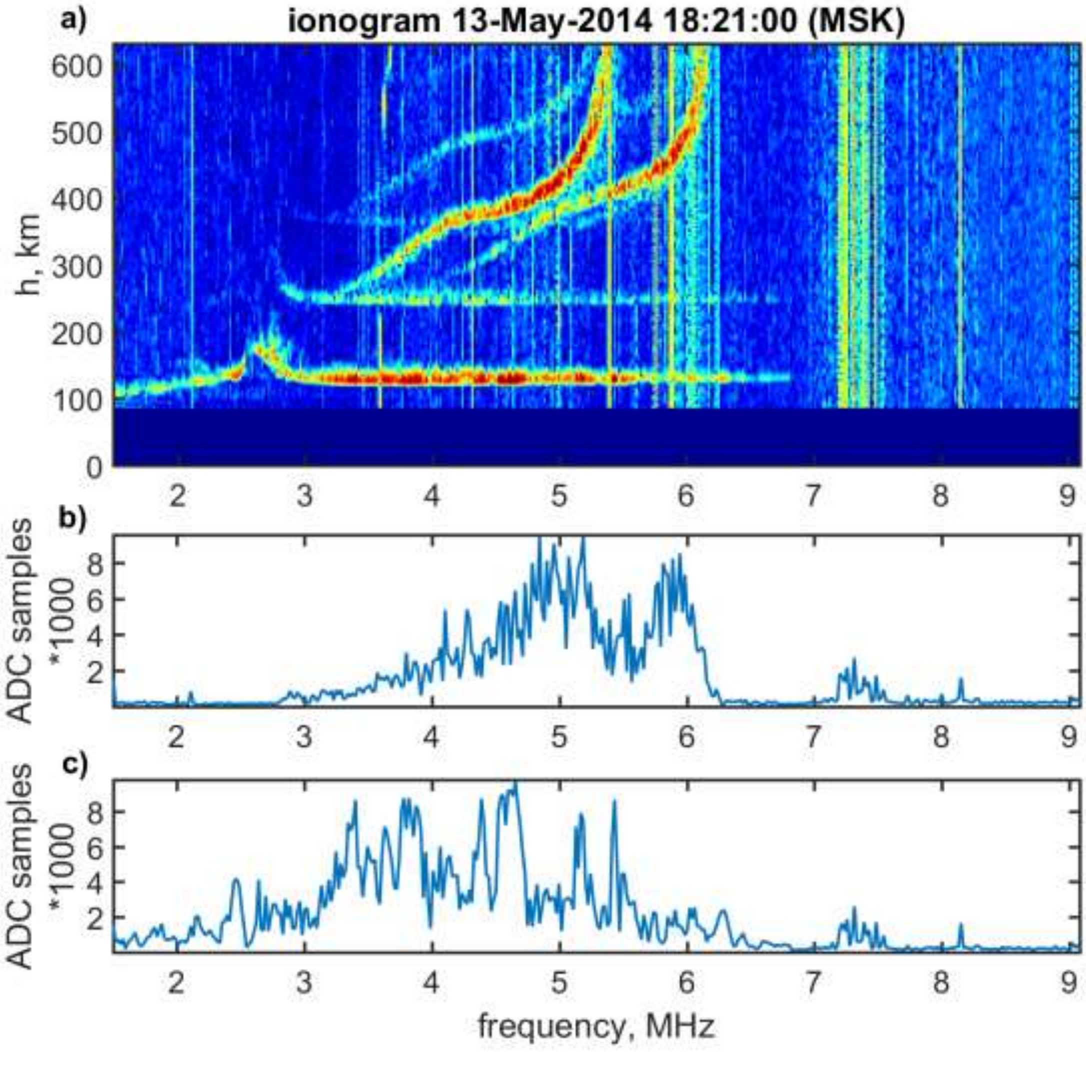

Figure 10. a) An example of an ionogram showing traces of F and Es layers with a scattering structure; b) Frequency response of the F layer; c) Frequency response of the Es layer. These frequency response clearly show the chaotic nature of the amplitude variations.

Using A-maps, it is easy to determine the periods of appearance of scattering for both E/Es traces (Fig. 11a) and for F-traces (Fig. 11b). In Fig. 11, the time range when scattering was observed is indicated by vertical dashed lines. It is seen that at ~ 970 minutes an Es layer appeared with scattering properties, and scattering appeared at the F layer after ~ 15 minutes. At ~ 1023 minutes, reflections from this Es layer began to disappear, and at the same time, scattering on the F trace stopped.

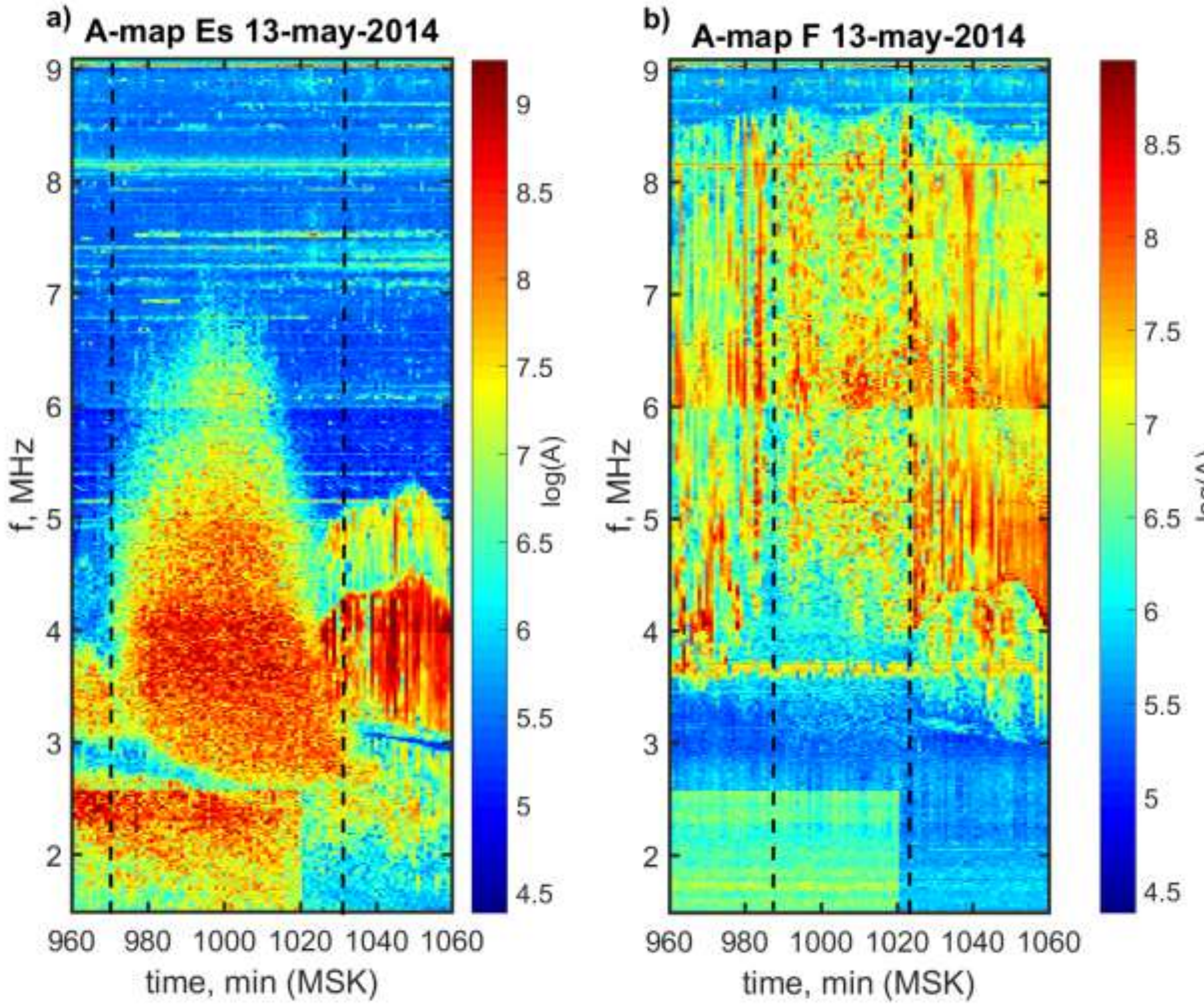

Fig. 11. An example of A-maps showing the variations in frequency response for the scattering phenomenon for layers E/Es (a) and F (b). The vertical dashed lines indicate the time interval of scattering phenomenon appearance.

Conclusion

The paper describes in detail the algorithm for constructing summary maps of the state of the ionosphere, considers and illustrates (with ionograms of the ionosonde Cyclone) all previously known beatings during vertical sounding of the ionosphere at mid-latitudes. Including interference beatings, rare for the mid-latitude Es layer, according to the type of two O modes. Examples of beatings during reflection of a signal from a transient Es layer are given and a hypothesis is proposed that explains the reasons for their appearance. The meteor is divided into fragments, each of which forms a transient Es layer. These layers cannot be separated on the ionogram, and they can be detected only by beatings. It was shown that at mid latitudes: 1) O- and X-mode beatings upon reflection from layer F are observed both before and after the point of zero beatings point. 2) The beating of the O and X modes in reflection from the Es layer in most cases is observed only before the point of zero beatings. 3) Beatings of two O-modes in reflection from the Es layer in most cases are observed only around the point of zero beatings. An analysis of the patterns of such a polarization fading makes it possible to determine with high accuracy the difference in the virtual heights between the ionogram traces of different polarizations. This information can be used to improve the accuracy of reconstructing the electron concentration profile of the lower part of the ionosphere. Typical examples of frequency response in the case of E/Es and F scattering are presented.

Acknowledgments

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