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IONOSPHERIC EFFECTS OF SOLAR FLARES AND EARTHQUAKE ACCORDING TO DOPPLER FREQUENCY SHIFT ON AN INCLINED RADIO PATH

Abstract. The effects in the ionosphere and the fine structure of ionospheric response to the action of X-ray and ultraviolet radiation of C1.7 - M5.2 classes flares occurred during solar cycle 24 (2014–2016) have been studied. The study was carry out using method of Doppler sounding of the ionosphere on an inclined radio path with a high time resolution (sampling frequency 25 Hz), which is based on the principle of the phase locked loop (PLL). It was shown that the intensity of C3.0-class solar flares is a minimum threshold when the appearance of disturbances in the ionosphere could be detected by the Doppler frequency shift (DFS) method. Solar flares less than C3.0-class were not reflected in Doppler frequency variations. The most expressed ionospheric response, recorded in the Doppler frequencies, occurred to X-ray flares with a sharp onset, flares with a smooth increase intensity gave a much less response. An unusual effect of the appearance of high-frequency component in Doppler frequency records in the interference beat form has been detected, indicating the occurrence of ionized heterogeneities in the ionosphere during solar flares. The appearance of high frequency component on the Doppler frequency shift records was also registered during the M5.1 earthquake. The application of Doppler frequency shift method that use the PLL loop has greatly expanded the ability to record and analyze the mechanisms of appearance the ionospheric disturbances during solar flares and earthquakes.

Key words: Doppler frequency shift, ionosphere, solar flares, earthquake**.**

1. Introduction. Solar flares are manifested themselves by bursts of radiation flux in all ranges of the electromagnetic spectrum from radio waves to X-rays and is the pulse energy source causing short-term disturbances in the ionosphere. The main disturbance effect on the ionosphere in solar flares is X-ray and extreme ultraviolet radiation (EUV). The X-ray flux emitted during the flare can increase by several orders. The X-ray and EUV bursts lead to a marked increase in the electron concentration in the ionosphere, depending on the spectral distribution of energy, which eventually, is shown in variations of Doppler frequency at the respective frequencies in the region of radio wave reflection. Various methods and instruments are used to investigate ionospheric disturbances, including vertical sounding ionosondes, incoherent scatter radars, transionospheric sounding by GPS navigation satellite signals, etc. The most effective of the well-known ionosphere methods is Doppler shift sounding. This study uses the method of Doppler measurements developed at the Ionosphere Institute [1], which is based on the principle of the phase-locked loop (PLL). This method was used for remotely detect disturbances in the ionosphere during industrial and underground nuclear explosions [1-4], for registration of ionospheric signatures to launch vehicles [5] and study of lithospheric-atmospheric-ionospheric coupling in earthquakes [4]. The advantage of this method is high time resolution, high accuracy of Doppler frequency measurements under multipath signal conditions, possibility to organize round-the-clock continuous observations, which allows to detect short-term processes in the ionosphere with high time and frequency resolution [6-8]. The purpose of the study was to investigate the characteristics of ionospheric response to solar flares of different classes according to the data on Doppler sounding of ionosphere.

2. Methology. Continuous Doppler sounding of the ionosphere was performed during 38 solar flares that occurred during the period 2014-2016 of 24-th solar cycle. Doppler measurements of signals reflected from the ionosphere were carried out on a different inclined radio path (sampling frequency 25 Hz), using signals from radio transmitters located in China, Kyrgyzstan and Kuwait. Information about solar flares was obtained from the site (www.tesis.lebedev.ru). The intensity of X-ray flux in the energy range 0.5-10 keV (wavelength 0.5-8 Å) was analyzed according to the data of satellite GOES-13 (ftp:/ft/ftp.swpc.noaa.gov/pub); radio flux density at 27.8 cm (F27.8) and 10.7 cm (F10.7) - according to the Callisto solar radio spectrograph data (www.ionos.kz), which located on Radiopoligon Orbita; extreme solar ultraviolet (0.1-7 nm) - according to the data of extreme ultraviolet spectrophotometer ESP_QUAD of the NASA Solar Dynamics Observatory (SDO) satellite (http:/p.color.edu/eve/data). Extreme ultraviolet has the greatest effect on the F2 region of the ionosphere [9] and the lower layer of the ionosphere (D-region) is most affected by X-ray radiation. Ionospheric regions from altitudes of 110 km to 200 km respond to ionizing X-ray as well as ultraviolet radiation. The paper highlights the most characteristic Doppler frequency shift (DFH) records of X-ray solar flares. The work presents the most characteristic Doppler Frequency Shift (DSH) records during X-ray solar flares.

3. Results. Doppler measurements during the C3.0-class flare of May 12, 2015 were carried out on an inclined radio path between points Urumqi, China (44.133N 86.883E) - Radiopoligon Orbita, Kazakhstan (43.058N 76. 973E). A radio transmitter with a capacity of 100 kW (f=5960 kHz) of a radio broadcasting station located in Urumcius was used. The radio receiver of the Doppler measurements was located in Radiopoligon Orbita. A transmitter with a power of 100 kW (f = 5960 kHz) of a radio broadcasting station located in Urumqi (China) and a radio receiver located on the Radiopoligon Orbita (Kazakhstan), were used. The distance (D) between the radio transmitter and the radio receiver is 808.55 km. To determine the radio wave reflection height between Urumqi - Radiopoligon Orbita, an ionospheric electron concentration profile was used, which was calculated using a model IRI-2012 (figure 1). The reflection height of the radio wave for the common component, calculated taking into account the electron concentration profile and the data of model IGRF12, was 179.712 km. (Figure 1a).

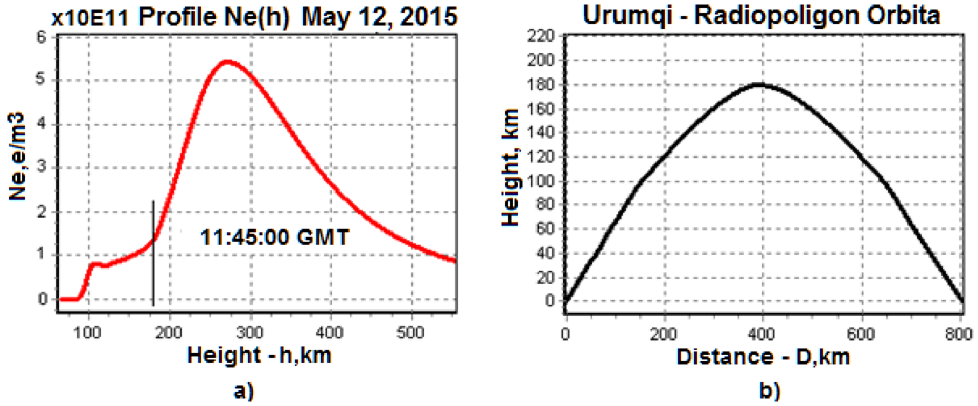

Figure 1 – Profile of electron concentration for time 11:45:00 (GMT) calculated according to model IRI-2012 (a) and trajectory of radio path of signal transmission (f = 5960 kHz) from Urumchi to Radiopoligon Orbita (b). The vertical line indicates a point on the curve where the ionosphere electron concentration corresponds to the reflection point of radio wave at height of 179.712 km, F1-region of ionosphere

Increase the intensity of X-ray and ultraviolet radiation lead to an increase the electron concentration in the ionosphere during the flare. It’s the rate of change in electron concentration that is being leaded the response Doppler shift during the flare. Figure 2 show graphs of X-ray, extreme ultraviolet and radio (right Y-axis), and Doppler frequency shift of ionospheric signal (left Y-axis) during the solar flare. The obtained data demonstrate the obvious relationship of Doppler frequency shift with dynamic of basic indicators of solar activity during C3.0-class flare. The graph shows that the maximum amplitude of Doppler shift (reflection height 179.7 km) corresponds to the initial step of increasing the rate of the ionizing EUV and X-ray flow. And as ultraviolet and X-ray intensity maximizes, Doppler frequency shift variations return to the background level. In contrast to X-ray and EUV, changes of radio flux (F10,7 and F27,8) during flare were more short-lived with the expressed exit to a maximum, just as in the Doppler shift.

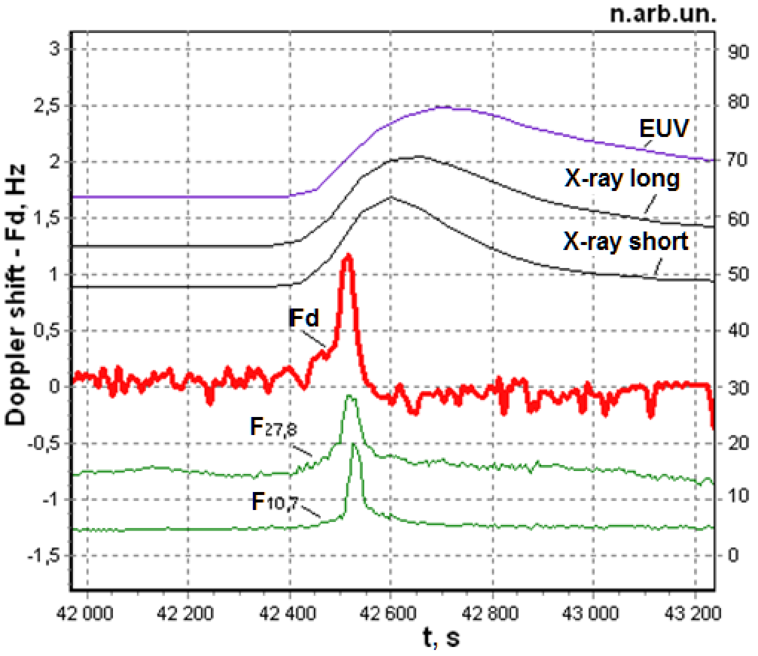

Figure 2 – Ionosphere response to C3.0-class flare in variations of Doppler frequency shift (Fd) on an inclined radio path Urumqi - Radiopoligon Orbita (left Y-axis) and EUV (right Y-axis); X-ray long (0.1 - 0.8 nm) and X-ray short (0.05 - 0.4 nm) and solar radiation flux density $F_{10,7}$ and $F_{27,8}$ (right Y-axis). X-axis – time in seconds from the beginning of the day May 12, 2015

The pulse effect of flare electromagnetic energy on the ionosphere allows determining inertia-time constant of the ionosphere at specific heights. The concept of inertia-time constant of ionosphere was first implemented by E.V. Appleton in 1953 [10]. A comparison the time of exit on a maximum of X-ray and EUV relative to the onset ionospheric response to the solar flare by Doppler data is presented in table 2.

Table 2 – Time of an exit to a maximum of Doppler frequency shift, intensity X-ray and EUV radiation from the beginning of ionospheric reaction to the solar flares

Doppler frequency shift Fd	X-ray short 0,05 - 0,4 nm	X-ray long 0,1 - 0,8 nm	EUV 0,1 - 7 nm
84s	166s	224s	277s

During the C3.0-class solar flare, which occurred on May 12, 2015, the ionosphere time constant for the height of 179 km, determined by the Doppler method, was 84 seconds, which is much in line with D. M. Baker, K. Davies calculations [11]. Analysis of the data (table 2) and the graphs (figure 2) showed that X-ray reached the maximum intensity more rapidly, than the output to the maximum of ultraviolet radiation. While the time of peak response in the Doppler shift was significantly less. Given that the Doppler shift changes proportional to the rate change of total electron content [9], it can be assumed that mainly X-ray short determines the ionospheric response in F1-region to a flare compared to the EUV, which has a predominant effect on the F2-region [12]. It is noted that the most expressed response of Doppler frequency shift occurs to X-ray flares with sharp start. In contrast, X-ray with a smooth escalating is accompanied by a significantly smaller response in the Doppler frequency shift.

In order to determine threshold sensitivity of Doppler method for detection of disturbances in ionosphere, Doppler frequency shift records were analyzed in case of weak solar flares of different intensity of C1.7-C3.0 class, which occurred sequentially within one day. Table 3 shows the main characteristics of the 4 solar flares on May 12, 2015 (tesis.lebedev.ru).

Table 3 – Characteristics of C1.7-C3.0-classes solar flares that occurred on May 12, 2015

Solar flare class	Active area	Beginning	Maximum	End
		GMT		
C2.6	2339	02:15:00	03:02:00	03:42:00
C2.2	2339	04:27:00	04:32:00	04:37:00
C1.7	2339	10:40:00	10:46:00	10:50:00
C3.0	2339	11:45:00	11:51:00	11:56:00

It has been established that flares of less than C3.0-class did not impinge on the Doppler frequency shift recordings. The ionospheric response was recorded only for C3.0-class flares, the intensity of which may be considered to be a threshold for such ionosphere condition, which is accompanied by Doppler frequency shift.

In order to determine the effects of the solar flares on the upper and lower layers of ionosphere, simultaneous of the Doppler measurements were made on the inclined radio path of Kuwait – Radiopoligon Orbita (f=15090 kHz, D=3007.211 km) and Urumchi – Radiopoligon Orbita (f=7260 kHz, D=808,546 km). The frequencies of the radio transmitters were specifically selected so that the radio wave reflected from the F2-region and the F1-region of ionosphere. The height of reflection of the radio wave was determined by the method described above. The radio frequency f=7260 kHz was reflected from the height 185.650 km. A radio signal from Kuwait came to the reception area in two hops, reflecting from 292 km of F2 region of the ionosphere. According to the GOES-13 and SDO satellite (NASA) data, during the C5.1-class flare on July 07, 2016, there were bursts in the X-ray and ultraviolet fluxes (Figure 3). The response of ionosphere to the flare was recorded on the DFS records at f=15090 kHz (duration of disturbance - 324s, Doppler shift amplitude - 1.302 Hz) and on the DFS records at f=7260 kHz (duration of disturbance - 750s, maximum Doppler shift amplitude reached 2.698 Hz).

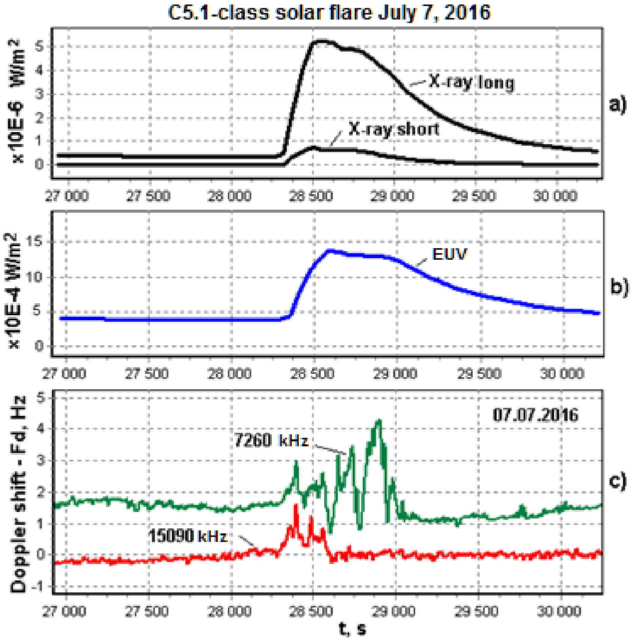

Figure 3 – Ionosphere response to C5.1-class solar flare in variations of Doppler frequency shift:
a) – X-ray long (0.1 - 0.8 nm) and X-ray short (0.05 - 0.4 nm); b) – EUV (0,1 - 7 nm); c) – variations of Doppler frequency shift on an inclined radio path Urumqi - Radiopoligon Orbita (7260 kHz) and Kuwait - Radiopoligon Orbita (15090 kHz).
X-axis – time in seconds from the beginning of day July 7, 2016

Figure 3c shows a significant difference in the duration of DFS perturbations on different radio paths, as well as appearance of a distinct zug with oscillations with periods from 179s to 240s (f=7260 kHz). Comparison of DFS variation records at two different frequencies suggests that the F1-region of the ionosphere is more sensitive to X-ray and ultraviolet radiation than the F2-region. Noted, that there are no periods in X-ray and EUV fluxes that could correlate with periods that had arisen in the zugs of Doppler frequency variations (figure 3). This suggests that the appearance of a clear zug of oscillations in DFS may be due to the passage of acoustic gravity waves (AGW) at the heights of radio wave reflection at a moment of X-ray and ultraviolet effects on the ionosphere.

Analysis of monitoring results of DFS at radio path Urumqi - Radiopoligon Orbita (860 km) and Red River - Radiopoligon Orbita (164 km) revealed the appearance of high-frequency component in the interference beat form on the Doppler records during two solar flares. The characteristics of solar flares are shown in table 3.

Table 3 - Characteristics of solar flares March 9, 2015 and May 8, 2014

Date dd, mm, yy	Solar flare class	Active area	Beginning	Maximum	End
			по времени GMT		
09.03. 2015	C4.0	2297	10:02:00	10:08:00	10:16:00
05,08. 2014	M5.2	2056	10:59:00	10:07:00	10:18:00

Data processing allowed us to identify the appearance a high-frequency component on the DFS records about 2.5 minutes before the main ionospheric response to C4.0-class flare and after it (figure 4a).The calculation of amplitude dynamic spectrum of the high-frequency component revealed Doppler frequencies in the range of 0.66 Hz to 12.5 Hz. (figure 4b).

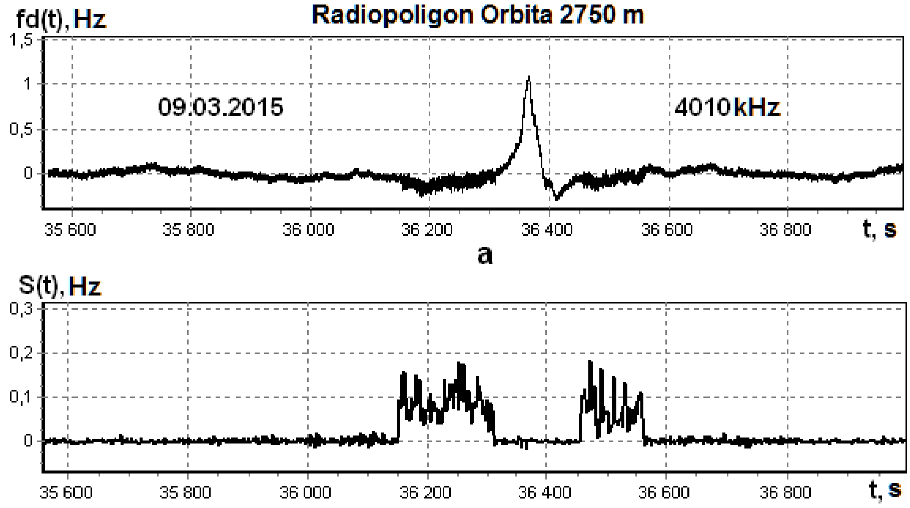

Figure 4 – Ionosphere response to C4.0-class solar flare March 9, 2015: Doppler frequency shift (a) on an inclined radio path Red River – Radiopoligon Orbita and (b) dynamic spectrum of DFS amplitude in the range of 0,66 -12,5 Hz. X-axis – time in seconds past 00 hour (GMT)

The appearance of high frequency component in DFS variations was also recorded during M5.2-class flare August 5, 2014 (figure 5). Comparison of figures 4 and 5 shows the dependence of the expression and duration of these effects on the intensity of the solar flares. In a case of C4.0-class flare the duration of a high frequency disturbance in ionosphere was approximately 400 seconds, DFS amplitude reached 1Hz, and for the M5.2-class flare with perturbation duration of more than 1,000 seconds, the DFS reached magnitude of 3Hz. The appearance of high-frequency variations in DFS during solar flares of the C4.0 and M5.2 classes is quite a rare effect, significantly different from our previous observations, as well as those described in the literature.

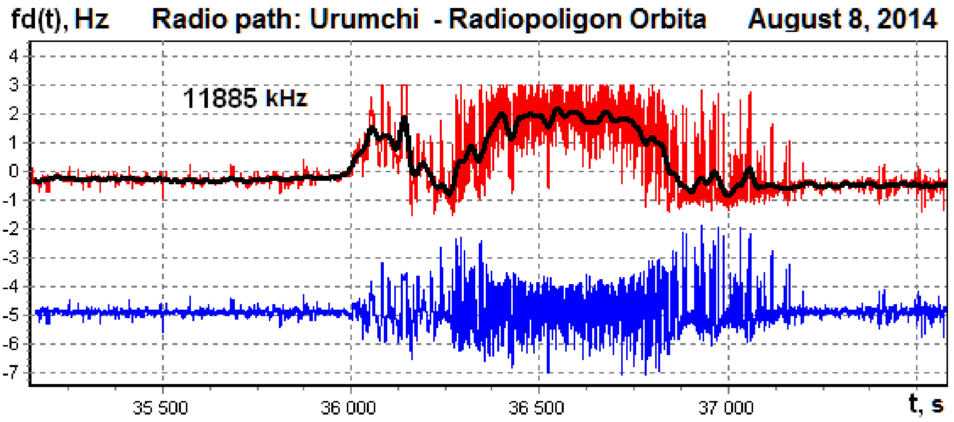

Figure 5 – Ionosphere response to M5.2-class solar flare May 8, 2014 in variations of Doppler frequency shift on Urumchi - Radiopoligon Orbita radio path. The upper graph (red) is variations of DFS and its low frequency component (black line). The lower graph (blue) is a high frequency component in variations of DFS. For ease of analysis, the lower chart is shifted along the Y axis. X-axis – time in seconds past 00 hour (GMT)

The appearance of high frequency variations in Doppler frequencies of ionospheric signal was also recorded during the earthquake. For an example we will consider the results of Doppler frequency shift registration during the earthquake occurred on March 15, 2015 at 14:01:01 by GMT, m_b=5.1 Epicenter coordinates: 42.92N and 76.89E. The earthquake occurred 30 km south from Almaty town and felt in Almaty town with intensity 4 by MSK-64 scale (www.kndc.kz). Figure 6 shows the epicenter location relative to the radio path Red River - Radiopoligon Orbita. Design azimuth in direction from transmitter to receiver was 72,144 °, distance from transmitter to receiver - 204 km. Calculation of the trajectory of radio waves for frequency f=4010 kHz was carried out by the computer program according to the IGRF12 model for the common component taking into account the magnetic field (calculation of radio path was performed by V.M.Krasnov).

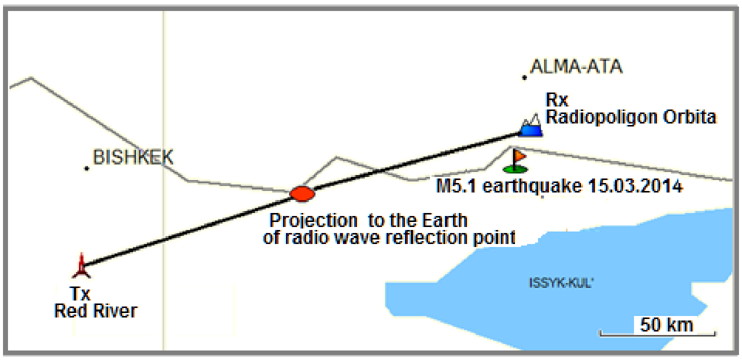

Figure 6 - Layout of radio path Red River (Tx) – Radiopoligon Orbita (Rx) relative to the earthquake epicenter March 15, 2015

The following parameters of the radio track were determined by calculation: height of reflection of radio waves (182.26 km), distance from the reflection point of the transmitter (110.43 km), distance from the epicenter of the earthquake to the projection of the reflection point of radio waves to the Earth (93.7 km), azimuth (262°), distance from the epicenter to Radiopoligon Orbita (16.8 km), azimuth (23.7°), distance from the epicenter to the point of radio waves reflection (84.22 km), azimuth (264 748°). This location of the epicenter relative to the radio path makes it possible to detect disturbances from the different ionospheric layers: from F2-region (estimated height 182.26 km) and the lower ionosphere layers. Analysis of the Doppler measurements showed that 5 minutes after earthquake, high frequency variations appeared on the records of the Doppler frequency shift as the outcome of additional beams arrival, which formed interference beat with a large amplitude beam at the input of Doppler radio receiver (figure 7a). Calculations demonstrated a marked increase in the Doppler dynamic power spectrum in the range of 5-12 Hz in 4 min 51s after mainshock (figure 7b). Note that this time is quite sufficient to propagate the perturbation from the lithosphere to the heights of the ionosphere.

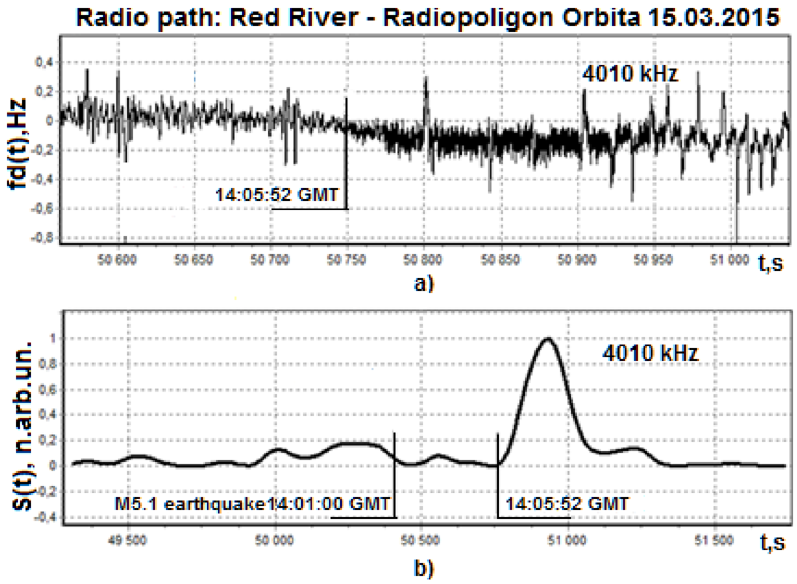

Figure 7 – Ionospheric response to M5.1 earthquake in variations of Doppler frequency shift
a) - high frequency variations of Doppler frequency shift (dark plot section);
b) - dynamic power spectrum of Doppler frequency shift variations (f=5-12 Hz).
X-axis – time from the beginning of the day March 15, 2015

The reflection of smaller-amplitude radio wave appears to have occurred when the radio signal passing above the earthquake epicenter. According to [13], additional ionized layers may be formed in the lower ionosphere at heights of 40-80 km above the earthquake preparation zone, which is in the opinion of by pulling the metal ions from the troposphere into the upper atmosphere by means of an anomalous electric field. There were no disturbances in the Doppler frequency shift associated with the earthquake preparation on March 15, 2015. In particular, this can be explained by the fact that the projection on Earth of the radio wave reflection point was not under the earthquake epicenter, but at a distance of 93.7 km in the north-east direction along the radio path Red River - Radiopoligon Orbita.

4. Resume. The effects in the ionosphere and the fine structure of ionospheric response to the action of X-ray and ultraviolet radiation of C1.7 - M5.2 classes flares occurred during solar cycle 24 (2014–2016) have been studied. The study was carry out using method of Doppler sounding of the ionosphere on an inclined radio path with a high time resolution (sampling frequency 25 Hz), which is based on the principle of the phase locked loop (PLL). It was shown that the intensity of C3.0-class solar flares is a minimum threshold when the appearance of disturbances in the ionosphere could be detected by the Doppler frequency shift (DFS) method. Solar flares less then C3.0-class were not reflected in Doppler frequency variations. The most expressed ionospheric response, recorded in the Doppler frequencies, occurred to X-ray flares with a sharp onset, flares with a smooth increase intensity gave a much less response. Against the background of disturbances in the ionosphere in solar flares, the appearance of zugs was recorded, which are detected during the passage of acoustic-gravitational waves (AGV) in the ionosphere. An unusual effect of the appearance of high-frequency component in Doppler frequency records in the interference beat form has been detected, indicating the occurrence of ionized heterogeneities in the ionosphere during solar flares. The appearance of high frequency component on the DFS records was also registered during the M5.1 earthquake, though the mechanisms of the occurrence of additional ionized regions in the lower ionosphere in earthquake and solar flares are different. The application of Doppler frequency shift method that use the PLL loop has greatly expanded the ability to record and analyze the mechanisms of appearance the ionospheric disturbances during solar flares and earthquakes.

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КӨЛБЕУ РАДИОТРАССАДА ЖИІЛІКТІҢ ДОПЛЕРЛІК ЖЫЛЖУ ДЕРЕКТЕРІ БОЙЫНША КҮН ЖАРҚЫЛДАРЫ МЕН ЖЕР СІЛКІНІСТЕРІНІҢ ИОНОСФЕРАЛЫҚ ӘСЕРЛЕРІ

Аннотация. Ионосферадағы әсерлесілер және Күн белсенділігінің 24 циклі (2014-2016 жж.) ішінде болған C1.7 - M5.2 класты күн тұтану кезінде рентген және ультракүлгін сәулеленудің әсерінен жұқа құрылымыды тербелістер зерттелді. Жұмыста Ионосфера институтында әзірленген доплерлік өлшеу әдісі қолданылды, оның негізінде жиілікті фазалық автоподстройкасының ілгегіні (ЖФАР) ң жұмыс принципі жатыр. Бұл әдіс өнеркәсіптік және жер асты ядролық жарылыстарды жүргізу кезінде ионосферадағы наразылықтарды қашықтықтан анықтау үшін, зымыран тасығыштарды ұшыру кезінде ионосфераның үнін тіркеу үшін және жер сілкінісі кезінде литосфералық-атмосфералық-ионосфералық байланыстарды зерттеу кезінде қолданылды. Әдістің артықшылығы жоғары уақытша рұқсат (25 Гц дискреттеу жиілігі), көп сәулелік сигнал жағдайында доплерлік жиіліктерді өлшеудің жоғары дәлдігі, тәулік бойы үздіксіз бақылауды ұйымдастыру мүмкіндігі болып табылады. Доплерлік өлшеулер Қытай, Қырғызстан және Кувейт орналасқан радиохабар таратқыштарының сигналдарын пайдалана отырып, түрлі көлбеу радиотрассаларда жүргізілді.

Ионосферадағы ауытқуларды анықтау үшін доплерлік әдістің шекті сезімталдығын анықтау мақсатында C1.7-C3.0 класының әр түрлі қарқындылығы әлсіз Күн жарқылы кезінде жиіліктің доплерлік ығысуы жазбаларына талдау жасалды, бір күн ішінде ретімен орын алды. C3.0 класындағы күн жарқылының қарқындылығы ионосферада ауытқулардың пайда болуы жиіліктің доплерлік жылжу әдісімен тіркеуге болатын ең аз шекті болып табылады. Тұтану класына аз-3.0 емес тигізді жазбаларында доплеровского ығысуы жиілікті ионосферного сигнал.

Доплерлік жиіліктің жылжуында тіркелген ионосфераның ең айқын көрінісі күрт басталуы бар күн рентгендік жарқылға айналды, қарқынды баяу өршу айтарлықтай аз үн берді.

Ионосфераның жоғарғы және төменгі қабаттарына күн тұтану әсерінің ерекшеліктерін анықтау үшін Кувейт - орбитаның радиополигоны (f=15090 кГц, D=3007,211 км) және Урумчи - орбитаның радиополигоны (f=7260 кГц, D=808,546 км). Көлбеу радиотрассаларында жиіліктің доплерлік жылжуын бір мезгілде өлшеу жүргізілді. Радиотаратқыштардың жиіліктері радиотолқындар ионосфераның F2 және F1-аймағынан көрінетіндей арнайы таңдалған. Кувейттен (f=15090 кГц) Радиосигнал қабылдау пунктіне ионосфераның 292 км F2 биіктігінен көріне отырып, екі секіру арқылы келді. Әр түрлі радиотрассаларда ЖДЖ қозу ұзақтығындағы елеулі айырмашылық, сондай-ақ f=7260 кГц жиілігінде 179с-тан 240с-қа дейінгі өзгермелі кезеңмен тербелістердің айқын цуг пайда болуы белгіленді.

Рентген және ультракүлгін сәулеленуде доплерлік жиіліктің цугында пайда болған кезеңдер жоқ. Бұл ЖДЖ нұсқаларында тербелістердің нақты цугасының пайда болуы Күн жарқылы рентген және ультракүлгін сәулеленудің ионосферасына әсер ету сәтінде радиотолқынның шағылысу биіктігінде акустико-гравитациялық толқындардың (АГТ) өтуіне байланысты болуы мүмкін. Екі түрлі жиіліктегі доплерлік ауысудың вариация жазбаларын салыстыру F1-ионосфера аймағы F2 аймағына қарағанда рентгендік және ультракүлгін сәулеленудің әсеріне аса сезімтал деп пайымдауға негіз береді.

Интерференциялы соқтығыстар түріндегі доплерлік жиіліктердің уақытша вариацияларының жазбаларында жоғары жиілікті құраушының пайда болуының ерекше әсері анықталды, ол ионосферада күн жарқылдары кезінде иондалған біртектіліктің пайда болуын куәландырады.

C4.0 және M5.2 класстағы күн тұтану кезінде ионосфералық сигналдың жиілігінің доплерлік ығысу вариацияларында жоғары жиілікті құрамдауыштың пайда болуы бұл біздің алдыңғы бақылаулардан, сондай-ақ әдебиетте сипатталған айтарлықтай ерекшеленетін өте сирек әсер. Ионосфералық сигналдың ЖДЖ жазбаларында жоғары жиілікті құраушының пайда болуы, сондай-ақ жер сілкінісі кезінде mb=5.1 магнитудасы тіркелген, бірақ төменгі ионосферада күн жарқылдары және жер сілкінісі кезінде қосымша иондалған облыстардың пайда болу механизмдері әртүрлі екенің көрсетеді

ЖФАР ілмегін пайдалана отырып, жиіліктің допплерлік жылжуын тіркеу әдісін қолдану, күн жарқылдары және жер сілкінісі кезінде ионосферада ұйытқулардың пайда болу механизмдерін талдау мүмкіндігін едәуір кеңейтеді.

Түйін сөздер: доплерлік жиілік ығысуы, ионосфера, күн жарқылдары, жер сілкінісі.

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ИОНОСФЕРНЫЕ ЭФФЕКТЫ СОЛНЕЧНЫХ ВСПЫШЕК И ЗЕМЛЕТРЯСЕНИЙ ПО ДАННЫМ ДОПЛЕРОВСКОГО СДВИГА ЧАСТОТЫ НА НАКЛОННОЙ РАДИОТРАССЕ

Аннотация. Исследованы эффекты в ионосфере и тонкая структура отклика ионосферы на воздействие рентгеновского и ультрафиолетового излучений во время солнечных вспышек класса С1.7 - М5.2, произошедших за период 2014–2016 гг. в течение 24 цикла солнечной активности. В работе использовали метод доплеровских измерений, разработанный в Институте ионосферы, в основе которого лежит принцип работы петли фазовой автоподстройки частоты (ФАПЧ). Этот метод применялся для дистанционного обнаружения возмущений в ионосфере при проведении промышленных и подземных ядерных взрывов, для регистрации отклика ионосферы при запусках ракетоносителей и при исследовании литосферно-атмосферно-ионосферных связей при землетрясениях. Преимуществом метода является высокое временное разрешение (частота дискретизации 25 Гц), высокая точность измерения доплеровских частот в условиях многолучевого сигнала, возможность организации круглосуточных непрерывных наблюдений. Доплеровские измерения проводили на разных наклонных радиотрассах, используя сигналы радиовещательных передатчиков, находящихся в Китае, Кыргызстане и Кувейте.

С целью определения пороговой чувствительности доплеровского метода для выявления возмущений в ионосфере был выполнен анализ записей доплеровского сдвига частоты при слабых солнечных вспышках разной интенсивности класса С1.7-С3.0, последовательно произошедших в течение одного дня. Показано, что интенсивность солнечных вспышек класса С3.0 является минимальным порогом, когда появление возмущений в ионосфере можно зарегистрировать методом доплеровского сдвига частоты. Вспышки классом меньше С3.0 никак не отразились на записях доплеровского сдвига частоты ионосферного сигнала.

Наиболее выраженный отклик ионосферы, зарегистрированный в доплеровском сдвиге частоты, происходил на солнечные рентгеновские вспышки с резким началом, вспышки с плавным нарастанием интенсивности давали значительно меньший отклик.

Для выяснения особенностей воздействия солнечной вспышки на верхние и нижние слои ионосферы были проведены одновременные измерения доплеровского сдвига частоты на наклонных радиотрассах Кувейт - Радиополигон Орбита (f=15090 кГц, D=3007,211 км) и Урумчи - Радиополигон Орбита (f=7260 кГц, D=808,546 км). Частоты радиопередатчиков были специально выбраны так, чтобы радиоволны отражались от F2 и F1-области ионосферы. Радиочастота f=7260 кГц отражалась от высоты 185,650 км. Радиосигнал из Кувейта (f=15090 кГц) приходил в пункт приема двумя скачками, отражаясь от высоты 292 км F2-области ионосферы. Установлена существенная разница в длительности возмущений ДСЧ на разных радиотрассах, а также появление отчетливого цуга колебаний с изменяющимся периодом от 179с до 240с на частоте f=7260 кГц. Отмечено, что в рентгеновском и ультрафиолетовом излучении отсутствуют периоды, которые возникли в цугах вариаций доплеровской частоты. Это позволяет предположить, что появление четкого цуга колебаний в вариациях ДСЧ может быть связано с прохождением акустико-гравитационных волн (АГВ) на высотах отражения радиоволны в момент воздействия на ионосферу энергии рентгеновского и ультрафиолетового излучений солнечной вспышки. Сравнение записей вариаций доплеровского сдвига частоты на двух разных частотах дает основание полагать, что F1-область ионосферы более чувствительна к воздействию рентгеновского и ультрафиолетового излучения, чем область F2.

Обнаружен необычный эффект появления высокочастотной составляющей на записях временных вариаций доплеровских частот в виде интерференционных биений, который свидетельствует о возникновении ионизированных неоднородностей в ионосфере при солнечных вспышках. Появление высокочастотной составляющей в вариациях доплеровского сдвига частоты ионосферного сигнала во время солнечных вспышек С4.0 и М5.2 класса – это довольно редкий эффект, существенно отличающийся от предыдущих наших наблюдений, а также описанных в литературе. Появление высокочастотной составляющей на записях доплеровского сдвига частоты ионосферного сигнала было зарегистрировано также во время землетрясения магнитудой m_b=5.1, хотя механизмы возникновения дополнительных ионизированных областей в нижней ионосфере при землетрясении и солнечных вспышках различны.

Применение метода доплеровского сдвига частоты на наклонной радиотрассе, в основе которого лежит принцип работы петли ФАПЧ, существенно расширило возможности регистрации и анализа механизмов появления возмущений в ионосфере при солнечных вспышках и землетрясениях.

Ключевые слова: доплеровский сдвиг частоты, ионосфера, солнечные вспышки, землетрясение.

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