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Optical Observations of Large-Scale Undulations in the 23rd Cycle of Solar Activity

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Abstract—A statistical analysis of observations of large-scale undulations during the 23rd cycle of solar activity was performed using optical data from two stations: Tixie (71.6°N, 128.9°E) and Zhigansk (66.8°N, 123.4°E). The total number of events recorded was 54 (43 events at Tixie and 11 at Zhigansk). The complete list of observed events is presented. The occurrence frequency of eveningside (17–23 LT) undulations during the solar activity growth (1999) and decline (2003–2005) phases tends to increase. Large-scale undulations were shown to be generated both on the equatorward boundary of the diffuse auroral zone and inside the diffuse zone, which does not necessarily occur during magnetic storms.

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1. INTRODUCTION

The first record of large-scale undulations on the equatorward boundary of diffuse auroras was performed by the DMSP satellite in the evening side near the peak of the ring current (Lui et al., 1982). These undulations were a diffuse "tongue" extended to the equator from the equatorward boundary of diffuse auroras with an amplitude of 40–400 km and a wavelength of ~200–900 km. Since that time, this rare phenomenon has attracted the attention of researchers. There was some evidence that wavelike structures are associated with geomagnetic storms (Lui et al., 1982; Kelley, 1986; Baishev et al., 1997, 2000a; Zhang et al. 2005; Baishev and Rich, 2006; Henderson et al., 2010); the main parameters of wavelike structures were obtained (Lui et al., 1982; Nishitani et al., 1994; Baishev et al., 1997, Henderson et al., 2010), and mechanisms were proposed to explain this phenomenon (Kelley, 1986; Yamamoto et al., 1993, 1994). Nishitani et al. (1994) and Baishev et al. (2000) used ground-based optical observations to reveal that undulations on the equatorward boundary of diffuse auroras propagate westward at a velocity of $V \sim 0.6$–0.7 km/s.

Most studies on large-scale undulations are based on single-satellite measurements (Lui et al., 1982; Kelley, 1986; Yamamoto et al., 1993, 1994; Zhang et al., 2005; Baishev and Rich, 2006; Henderson et al., 2010). With rare exceptions (Baishev et al., 2010), there has been no study with simultaneous use of satellite and ground-based observations. Finally, there a have been absolutely no statistical studies of large-scale undulation observations during a long period of time. We managed to fill this gap. Since 1994–1995, we have been constantly conducting optical observations of auroras at two stations on the 190° magnetic meridian (Tixie and Zhigansk) using all-sky TV cameras. A large amount of observational data has been gathered.

This paper presents a complete list of large-scale undulations recorded during the 23rd cycle of solar activity and the first statistical analysis results.

2. OBSERVATIONS

For analysis, we used all-sky TV observation data obtained from March 1994 at Tixie (71.6°N, 128.9°E) and from November 1995 at Zhigansk (66.8°N, 123.4°E). The auroras were recorded during moonless periods. A description of all-sky TV cameras with a temporal resolution of ~4 s can be found in (Shiokawa, et al., 1996).

The table presents a list of all large-scale undulations recorded from March 1994 to March 2008. This period covers 54 events (43 at Tixie and 11 at Zhigansk) with 393 diffuse tongues. Twenty-two events were recorded during magnetic storms and 32 events were recorded in the absence of magnetic storms; i.e., the magnetic-to-nonmagnetic ratio of undulation events was 2 : 3. It should be noted that the undulations at Zhigansk were mainly recorded during magnetic storms (eight events) or at $Kp > 3$ (three events).

Undulations were generated on the equatorward boundary of the diffuse zone in 35 (out of 54) events and inside this zone in 17 events. For two events, we did not manage to visually determine the undulation location. During magnetic storms, the ratio of events detected on the equatorward boundary of the diffuse

List of large-scale undulations according to all-sky TV camera observations at Tixie (March 1994–March 2008) and Zhigansk (November 1995–March 2008)

No.	Date	Observation time, UT	Observation station	Number of tongues	Transparency[1]	Position[2]	*Kp*	*Dst*	Note
1.	29.10.1994	0859–0914	TIX	4	1	?	6_0	–39	main phase of a storm
2.	14.01.1996	1055–1105	ZGN	2	1	E	5_0	–34	recovery phase of storm
3.		1302–1314	ZGN	2	1	E	4_+	–45	
4.	11.02.1996	1044–1110	TIX	5	2	E	4_+	–39	
5.	14.11.1996	1118–1135	ZGN	2	1	E	3_+	–47	
6.	01.03.1997	1055–1126	TIX	7	2	?	2_0	–33	recovery phase of storm
7.	02.03.1997	1214–1240	TIX	6	1	D	2_0	–24	main phase of a weak storm (?)
8.	24.10.1997	1010–1020	TIX	2	1	D	4_+	–34	main phase of a weak storm
9.	22.11.1997	1118–1141	ZGN	5	2	D	5_+	–22	main phase of a storm
10.	18.02.1998	1213–1226	TIX	5	1	D	3_0	–38	main phase of a weak storm
11.	22.02.1998	1127–1221	TIX	14	2/3	E	2_+	–7	
12.	20.03.1998	1334–1348	TIX	6	1	E	2_0	–11	
13.	09.11.1998	0957–1032	ZGN	5	1	E	6_+	–115	main phase of a storm
14.	23.11.1998	1235–1255	TIX	2	2	E	3_0	–1	
15.	11.12.1998	1240–1250	ZGN	4	3	E	4_0	–65	main phase of a storm
16.	08.01.1999	1209–1240	TIX	12	1	D	3_0	–1	
17.	14.01.1999	0923–1100	ZGN	16	1	E	5_+	–84	main phase of a weak storm
18.	09.03.1999	1125–1227	ZGN	18	2	D	3_+	–29	
19.	01.11.1999	1135–1211	TIX	13	1	E	4_-	–19	
20.	08.11.1999	0917–1030	TIX	14	2	D	4_-	–42	main phase of a storm
21.	13.12.1999	1100–1117	ZGN	3	1	E	4_0	–62	main phase of a weak storm
22.	03.12.2000	1035–1115	TIX	7	1/2	E	2_0	–4	
23.	23.12.2000	0800–0918	TIX	17	2	E	4_0	–49	recovery phase of a weak storm
24.	20.02.2001	1025–1039	TIX	3	1	D	1_+	–2	
25.		1208–1216	TIX	1	1	E	2_-	–7	
26.		1241–1333	TIX	12	1	E	2_-	–6	
27.	21.02.2001	1056–1112	TIX	2	1	E	2_-	–8	
28.		1200–1222	TIX	3	1	E	2_0	0	
29.	23.01.2002	1221–1337	TIX	12	1	E	2_-	–7	
30.	30.11.2002	1039–1052	TIX	5	2	E	3_0	–31	
31.	26.12.2002	0950–1004	TIX	5	2	E	3_0	–30	
32.		1134–1210	ZGN	6	3	D	3_0	–43	
33.	27.12.2002	0833–0852	TIX	6	2	D	5_-	–62	main phase of a storm
34.	07.02.2003	1200–1215	TIX	6	2	E	3_+	–35	
35.	03.03.2003	1053–1148	TIX	11	1	E	2_0	–16	
36.	07.03.2003	1107–1130	TIX	7	1	E	3_+	–31	
37.		1142–1200	TIX	3	1	E	3_+	–31	
38.		1254–1330	TIX	7	1	E	2_+	–28	
39.	21.12.2003	1031–1228	TIX	24	3	E	3_+	–17	
40.	19.01.2004	1251–1303	TIX	4	1	E	4_-	–12	
41.	11.02.2004	1044–1049	TIX	1	2	D	3_0	–2	initial phase of storm
42.		1106–1120	TIX	4	2	D	3_0	–11	main phase of a storm
43.		1325–1335	ZGN	3	1	D	5_-	–40	
44.	25.10.2004	1049–1120	TIX	6	1	E	3_+	–16	

Table. (Contd.)

No.	Date	Observation time, UT	Observation station	Number of tongues	Transparency[1]	Position[2]	*Kp*	*Dst*	Note
45.	17.11.2004	0919–0928	TIX	3	1	E	3_0	–49	main phase of weak storm
46.		1119–1155	TIX	7	1	E	2_+	–54	
47.	12.12.2004	0912–1000	TIX	8	2	D	4_0	–38	
48.	12.01.2005	1208–1217	TIX	6	1	D	5_-	–48	main phase of weak storm
49.	09.02.2005	0937–0950	TIX	4	2	D	4_0	–39	
50.	16.02.2005	1143–1222	TIX	15	2	E	3_+	1	initial phase of a weak storm
51.	25.12.2005	0948–1205	TIX	23	1	E	2_-	–14	
52.	28.10.2006	1023–1038	TIX	5	1	E	3_-	–10	
53.	15.01.2007	0950–1043	TIX	6	1	D	3_0	1	
54.	10.12.2007	1220–1349	TIX	14	1	E	2_0	–3	

[1] Classification of transparency:
1 – good (many stars can be seen);
2 – fair (only bright stars can be seen);
3 – bad (no stars can be seen).

[2] Position of large-scale undulations:
E – on the equatorward boundary of the diffuse zone;
D – within the diffuse zone;
? – undefined.

auroras and inside this zone was 1 : 1 (10 : 10); in the absence of magnetic storms, this ratio was roughly 3 : 1 (25 : 7).

Undulations were mainly observed at 09–13 UT (18–22 LT). The duration of these events ranged from a few minutes to two hours.

Figure 1a shows (top to bottom) the number of sunspots averaged over a month (thin line) and year (bold line), Fig. 1b shows histograms of the frequency of undulations, and Fig. 1c shows the total number of days when all-sky TV cameras were operated occurrence at Tixie (shaded rectangle) and Zhigansk (light rectangle) during the 23rd cycle of solar activity. The data on the number of sunspots were taken from the website ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/.

Because the recordings in each year were fixed for January–March and October–December, we took the total number of days in these two periods. The frequency of undulations was defined as a ratio of the number of events to the total number of observation occurrence days. Figure 1b shows the distribution of undulation events over seasons (histograms) and years (solid line). The small amount of data gives no way of revealing statistically significant regularities; however, one can notice a slight increase in the frequency of undulations during the growth (1999) and decline (2003–2005) phases of solar activity occurrence.

Figure 2 shows a histogram of the number of undulation events depending on their duration (left) and on the number of recorded tongues (right). It can be seen that the duration of undulation events is mostly less than 40 minutes and ~1–8 diffuse tongues are often observed, which is consistent with the results obtained in (Lui et al., 1982; Nishitani et al., 1994; Henderson et al., 2010). For example, the analysis of sequential satellite images in (Lui et al., 1982) indicates that the duration of undulation events was 0.5–3.5 h. Nishitani et al. (1994) used ground-based observation data to show that four diffuse tongues were recorded during 22 min, and the four giant tongues described in (Henderson et al., 2010) according to the IMAGE satellite data lasted ~2 hours.

According to (Lui et al., 1982; Zhang et al., 2005; Henderson et al., 2010), which are based on satellite data, undulations were recorded on the equatorward boundary of the diffuse auroral zone. Baishev et al. (2010) described a case study when undulations were observed inside the diffuse zone. The present paper a used statistical data obtained for the 23rd cycle of solar activity to confirm that undulations can indeed be generated inside the diffuse zone. Out of the 54 undulation events, 17 were recorded inside the diffuse zone.

Figure 3 shows an example of synchronous recording of undulations observed inside the diffuse zone by the DMSP F14 satellite and an all-sky TV-camera at Zhigansk on March 9, 1999. The magnetic activity was moderate ($Kp = 4+$). Figure 3a shows an image from the DMSP F14 satellite obtained in the time range from 1219:41 to 1232:25 UT. The circle indicates the

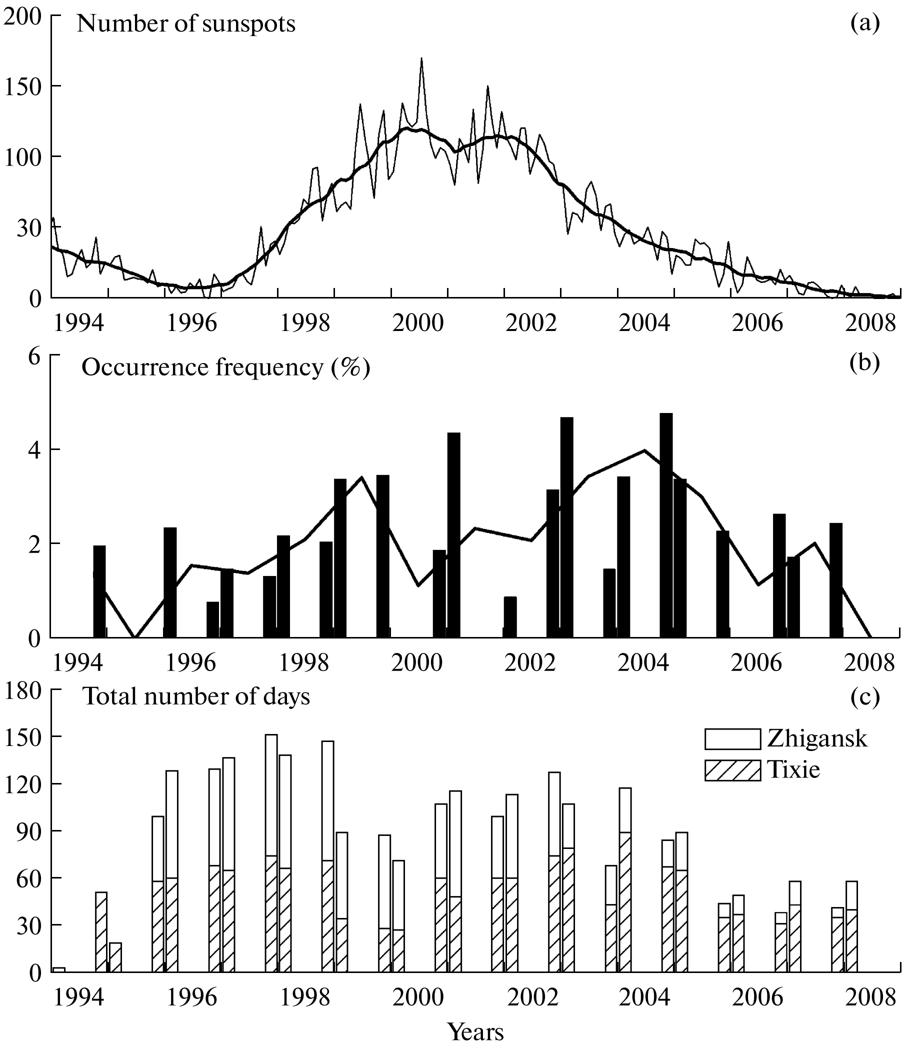

Fig. 1. Top to bottom: the number of sunspots, averaged over a month (thin line) and year (bold line) (a), histograms of the frequency of undulations (b), and the total number of days of all-sky TV cameras at Tixie (shaded rectangle) and Zhigansk (light occurrence rectangle) (c) for the 23rd cycle of solar activity.

field of view of the TV-camera at Zhigansk with a radius of 400 km. Figure 3b shows schematically undulations observed in the field of view of the TVcamera (Fig. 3a). For comparison with the satellite observations, Figs. 3c–3e show the TV frames for 1222, 1223, and 1224 UT, respectively, when the satellite was flying near Zhigansk. The TV frames near the zenith of the Zhigansk station indicate four diffuse tongues (numbered from *1* to *4*). The southern edge of the sky has a clearly traced equatorward boundary of diffuse auroras, and the northern edge involves a discrete arc. Thus, using optical and satellite data, we identified three major diffuse tongues (numbers *1*, *2*, and *4*) with an amplitude of ~90–100 km and a wavelength of ~150–200 km. The third tongue with an amplitude of ~70 km and a wavelength of ~90 km can only be identified on TV frames. Using TV camera data (Figs. 3c–3e), we estimated that the undulations propagated westward at a velocity of 1 km/s.

To reveal the differences in the spatial scales of wavelike structures observed inside the diffuse zone for each of the 17 events, we took the most distinct diffuse tongue and determined its length and amplitude. Figure 4 shows the calculation results of the spatial parameters of diffuse tongues (wavelength and amplitude). The projection of the TV-frames onto the Earth's surface was calculated taking into account the auroral height at 110 km. The measurement error was ~10 km.

It can be seen that the amplitude of wavelike structures ranged from ~50 to ~150 km, and the wavelength was from 100 to 300 km; i.e., the spatial parameters of the tongues generated inside the diffuse zone are several times smaller than those of the tongue recorded on the equatorward boundary of the diffuse auroral

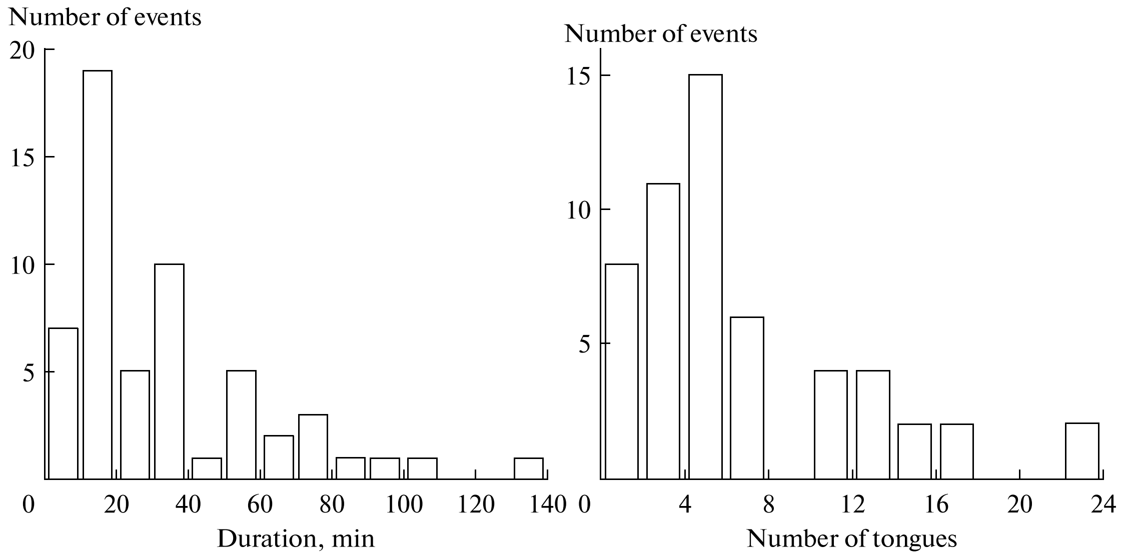

Fig. 2. Histogram of the number of undulation events depending on their duration (left) and the number of registered tongues (right).

zone (Lui et al., 1982; Baishev et al., 2000; Zhang et al., 2005; Henderson et al., 2010).

3. DISCUSSION

A total of 54 undulation events have been recorded during nearly 15 years of optical measurements at Tixie and Zhigansk. Even if we take into account the weather conditions and absence of observations because of technical reasons, we can conclude that undulations are a rather rare phenomenon. The small amount of events did not give an opportunity to identify statistically significant regularities between the frequency of undulations and the solar activity cycle. One can only speak about a small increase in the frequency occurrence of undulation occurrence during the growth (1999) and decline (2003—2005) phases of solar activity. The increase in the frequency of undulations during the decline phase of solar activity can be attributed to the well-known fact occurrence of increased geomagnetic activity delayed by 2—3 years relative to the maximum of solar activity (see, for example, Fig. 1d in (Baishev et al., 2010b)), while the small increase in the growth phase is difficult to explain. One can only suppose that the generation of undulations is not always associated with magnetic storms and can be caused by some processes in the inner magnetosphere. It is noteworthy that 1999 was characterized by three events observed during magnetic storms and three events observed in the absence of magnetic storms.

In earlier studies (Lui et al., 1982; Nishitani et al., 1994; Baishev et al., 1997, 2000; Zhang et al., 2005; Baishev and Rich, 2006; Henderson et al., 2010), undulations in the evening side were recorded during magnetic storms. Only two events (November 4, 2000, with $Kp = 5$ (Henderson et al., 2010) and December 12, 2004, with $Kp = 4$ (Baishev et al., 2010a)) were observed in the absence of magnetic storms.

Our a statistical analysis for the 23rd cycle of solar activity revealed that only 22 events were recorded during magnetic storms and 32 events were recorded in the absence of storms (the ratio of undulation events is 2 : 3). The reason for this ratio requires further investigations.

The most likely mechanism for the generation of undulations on the equatorward boundary of diffuse auroras is the Kelvin—Helmholtz instability, which arises with a strong shear flow of plasma near the plasmapause (Kelley, 1986). Currently, strong shear flows near the plasmapause are associated with the formation of fast subauroral polarization streams (SAPS's) (Foster and Burke, 2002). Foster and Vo (2002) performed a statistical analysis of SAPS's using incoherent scatter data from the Millstone Hill station ($L \sim 3$) for two solar cycles (1979—2000). The maximum SAPS velocity of above 1000 m/s was recorded in the range from ~18 to ~21 MLT at $Kp = 6$. With decreasing magnetic activity, the SAPS velocity in the evening—midnight side decreases too, constituting ~400 m/s with $Kp = 2$.

Wang et al. (2008) divided the SAPS events derived from 2002—2003 measurements with the DMSP series satellites into two groups: $Kp < 3$ (calm conditions) and $Kp \geq 3$ (disturbed conditions). Although the flights of the DMSP satellites were limited to 15—22 MLT covering the most probable SAPS position (Foster and Vo, 2002), the largest number of SAPS events were recorded for ~19—20 MLT for both groups. The ratio of events was approximately 1 : 3 (depending on the conditions).

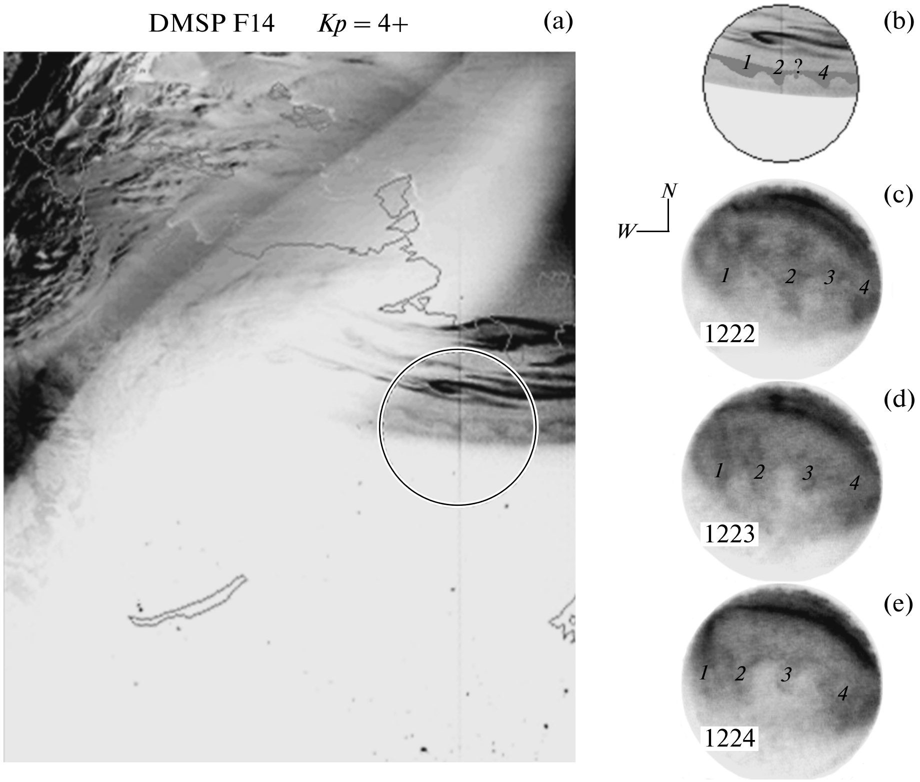

Fig. 3. Example of undulations recorded simultaneously by the DMSP satellite (a, b) and an all-sky TV camera at Zhigansk (c–e) on March 9, 1999. The auroral image taken in the time range from 1219:41 to 1232:25 UT and TV frames taken at 1222, 1223, and 1224 UT are presented in the negative. On the TV frames, north is upward and west is leftward. The circle is the view field of the all-sky TV camera at Zhigansk with a radius of 400 km. The four diffuse tongues are numbered from *1* to *4*.

Baishev et al. (2010b) similarly divided the 54 undulation events into groups with respect to geomagnetic activity and showed that the majority of events (both SAPS's recorded by the DMSP satellites (Wang et al., 2008) and undulations) were observed when $Kp \geq 3$. However, undulation events were observed at $Kp < 3$, which has not been found earlier in the literature. In addition, this behavior of both phenomena with a maximum of ~18–20 MLT allows us to suppose that these phenomena are causally related.

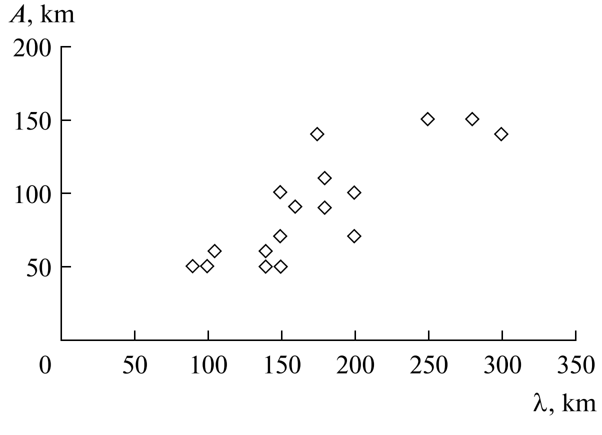

Fig. 4. Calculation of the wavelength and amplitude for the most clear diffuse tongue in each of the 17 undulation events observed within the diffuse zone.

Several cases of large-scale wavelike structures on the equatorward boundary of diffuse proton zone were studied using optical data from the Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) satellite in the range of ultraviolet wavelengths (Zhang et al., 2005). Synchronous measurements by the DMSP satellites during periods when diffuse wavelike structures were recorded indicated that the generation of large-scale wavelike structures requires large ion drift velocity (>1000 m/s) and their strong latitudinal gradient (>0.1 s^{-1}) recorded within the diffuse auroral oval.

Baishev et al. (2010a) for the first time revealed large-scale undulations inside the diffuse zone under the conditions described in (Zhang et al., 2005), i.e., large drift velocity Vy ~ 850 m/s and strong gradient ~0.08 s^{-1}. It can be assumed that, for all undulation events recorded in the diffuse zone, these conditions have been met. According to our data, the average westward propagation velocity of undulations inside the diffuse zone was ~800–900 m/s. The fact that the undulations in the diffuse zone have small scales (Fig. 4) compared to the ones observed on the boundary is probably due to the narrower band of the shear flow (Kelley, 1986).

4. CONCLUSIONS

Based on optical observation data at Tixie and Zhigansk, we for the first time present a detailed list of undulations observed during the 23rd cycle of solar activity. From March 1994 to March 2008, a total of 54 undulations events (43 at Tixie and 11 at Zhigansk) were recorded.

A statistical analysis of the observations of large-scale undulations has revealed the following:

(1) No statistically significant regularities between the generation of undulations and the solar activity cycle were detected, but the frequency of eveningside (17–23 LT) undulations during the solar activity growth (1999) and decline occurrence (2003–2005) phases tends to increase.

(2) Undulations are generated both during magnetic storms (22 events) and in the absence of magnetic storms (32 events).

(3) The finding obtained earlier by Baishev et al. (2010a) that a undulation can be generated inside the diffuse zone (17 events) was statistically confirmed.

The data need to be further analyzed to understand the physical processes in the magnetosphere–ionosphere system during the generation of undulations both in the absence of magnetic storms and in their presence. These problems can be solved by using simultaneous ground-based and satellite (for example, THEMIS, Cluster, and other projects) measurements.

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