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Simultaneous Observations of the Natural Electromagnetic Emission in the ELF–VLF Range at Kamchatka and in Yakutia during the Solar Eclipse of August 1, 2008

G. I. Druzhin[a], V. N. Uvarov[a], V. A. Mullayarov[b], V. I. Kozlov[b], and A. A. Korsakov[b]

[a] *Institute of Cosmophysical Research and Radiowave Propagation, Far East Division, Russian Academy of Sciences, Mirnaya ul. 7, Paratunka, Elizovo raion, Kamchatka oblast, 684034 Russia*

[b] *Shafer) Institute of Cosmophysical Research and Aeronomy, Siberian Branch, Russian Academy of Sciences, pr. Lenina 31, Yakutsk, 677007 Russia*

e-mail: drug@ikir.kamchatka.ru

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Abstract—The effect of the solar eclipse that occurred on August 1, 2008, on the level of the natural electromagnetic emission signals in the ELF–VLF range, simultaneously observed at Kamchatka and in Yakutsk, and the variations in the amplitude and phase of signals from the ULF radiostations, registered in Yakutsk, has been considered. The ULF radiostations in Krasnodar, Novosibirsk, and Khabarovsk successively emitted signals at frequencies of 11 905, 12 649, and 14 880 kHz. Based on the observations of the signals from these radiostations, it has been established that the signal amplitudes and phases increased by 3–5% and 30°–45° when the signals crossed the lunar shadow region. The synchronous registration of the ELF–VLF noise emission indicated that a bay-like increase and the following decrease in the emission to the background level was observed at both receiving points during the eclipse from ~1000 to 1130 UT. This effect was registered at frequencies of 0.6–5.6 kHz in Yakutsk and at lower (30–200 Hz) and higher (2.5–11 kHz) frequencies at Kamchatka. In this case the noise emission intensity maximum was observed when the lunar shadow maximally approached the registration point. At higher frequencies, the emission maximum was observed simultaneously at both points (at 1100 UT) but with a delay relative to the maximum at lower frequencies. The possible causes of the appearance of the solar eclipse effects in the natural ELF–VLF emission are considered.

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1. INTRODUCTION

The ELF–VLF electromagnetic emission during the solar eclipses in northeastern Russia was previously observed in Yakutsk on March 9, 1997, and March 29, 2006. The region of the total lunar shadow during the eclipse of March 9, 1977, crossed the receiving point from west to east. Therefore, it was possible to observe the eclipse effect in the signals of the Omega system of ULF radiostations located in the eastern, southern, and western directions. The effects in the intensity of natural ELF–VLF emissions were simultaneously considered. During the passage of the lunar shadow, the radiostation signal phases increased by 30°–35°, and the signal amplitude increased by 15–30% relative to the daily variations. The eclipse effect in natural emissions, received from the western and southwestern directions, was observed as an increase in the intensity at frequencies of 0.47–8.7 kHz, but the enhancement of emissions was most intense (by a factor of 3–4 on average) at frequencies of 4–9 kHz [Mullayarov et al., 1999].

During the solar eclipse of March 29, 2006, the lunar shadow region successively covered the sunlit part of the radiosignal propagation path from the western coast of Africa to Altai. The main emission sources and the observation point were under daytime and nighttime conditions, respectively, in contrast to the opposite situation during the solar eclipse of 1997. In this case the effects observed previously were registered again in 2006 with certain differences. During the eclipse of March 29, 2006, the phase increased by 30°–40° on the Krasnodar–Yakutsk path and by 15° on the Novosibirsk–Yakutsk path at all registered frequencies (11 905, 12 649, and 14 880 kHz), and the signal amplitude simultaneously increased by approximately a factor of 1.2. In addition, the number of atmospherics received in Yakutsk from the west increased by a factor of 1.4 during the eclipse [Karimov et al., 2008].

The ionospheric effects during the eclipse of March 29, 2006, were also observed in Murmansk and Nizhni Novgorod. It was established that the 34% eclipse in the E and F_1 regions of the polar ionosphere causes a decrease in the electron density by 15–20%, and the delay time of this effect is 12–25 min [Belikovich et al., 2008].

During the solar eclipse of August 1, 2008, the observations were performed in Yakutsk (62° N,

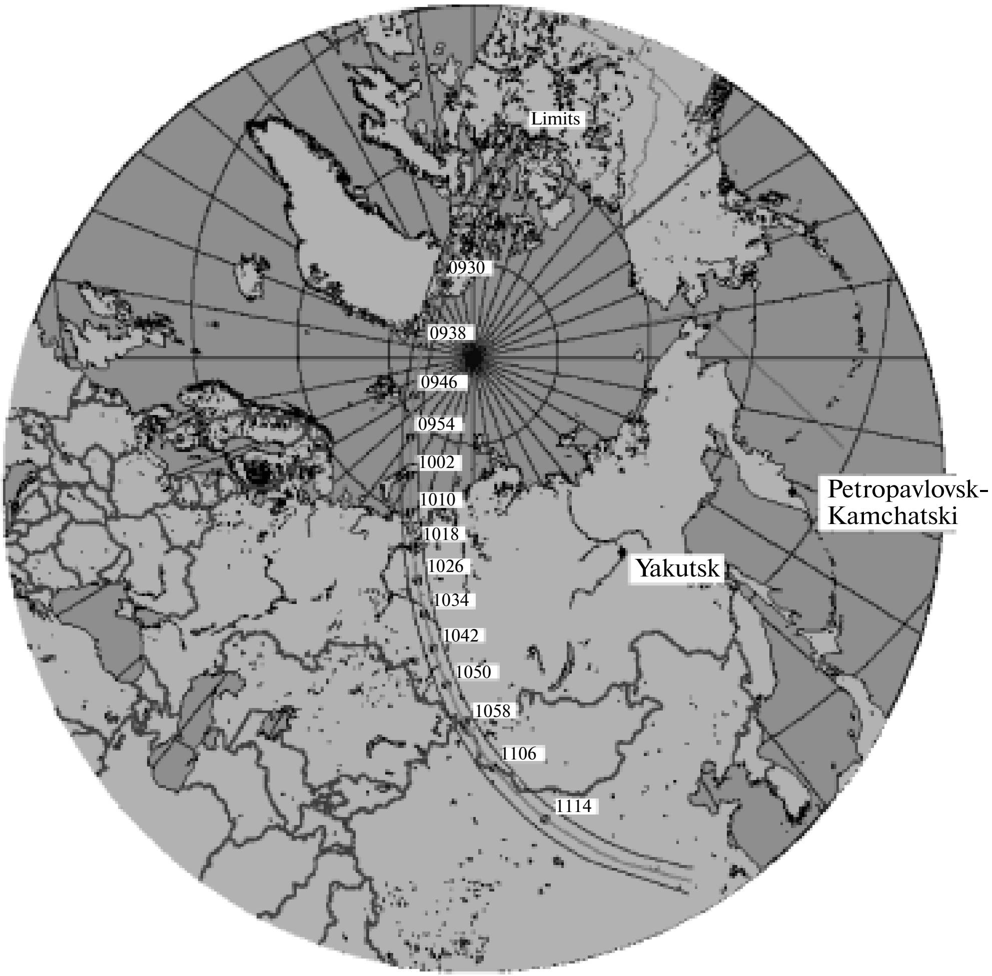

Fig. 1. The lunar shadow band on August 1, 2008 (UT) and the points of emission registration in Yakutsk and at Kamchatka.

129.7° E) and at Kamchatka (53° N, 158° E). Figure 1 presents the map of the Northern Hemisphere with the total lunar shadow band [http://www.hermit.org/Eclipse/2008-08-01] and the observation points. This eclipse started at 0920:57 UT, when the lunar shadow was in contact with the Earth in the northern dawn regions of Canada. Later, the lunar shadow passed over Greenland; crossed the Arctic Ocean, Western Siberia, and Altai; passed along the boundary between Mongolia and China; and left the Earth's surface in central China at 1121:21 UT, when the sunset was observed at that time. The shadow traveled a distance of more than 10.5×10^3 km during 2 h, moving at an average velocity of about 1.4 km/s. The eclipse duration was maximal (2 min 27 s) in the middle of this band (in the Nadym region), where the maximal shadow width and propagation velocity were 236.8 km and about 0.9 km/s, respectively [http://www.eclipse-2008.ru/eclipse.php].

It is known that the intensity of received emissions depends on the source power and signal propagation conditions. The performed studies indicated that the African and Australian (southeastern Asia and Australia) global thunderstorm centers [Druzhin et al., 1986], located outside the eclipse region on August 1, 2008, were the predominant sources of VLF emissions in northeastern Russia. The signal propagation paths crossed the eclipse region, which contributed to the intensity of received emissions. This work was performed in order to obtain new data on the effects observed when the ULF signals and natural ELF–VLF emissions crossed the lunar shadow region.

2. SIGNALS OF ULF RADIOSTATIONS

During the solar eclipse of August 1, 2008, the ULF signals were registered only in Yakutsk. The radiostations in Krasnodar, Novosibirsk, and Khabarovsk were used. Each radiostation successively emitted signals at frequencies of 11 905, 12 649, and 14 880 kHz. Signals were registered using the hardware system including a receiving loop antenna oriented from east to west. A GPS receiver (GPS Trimble Thunderbolt) was used to

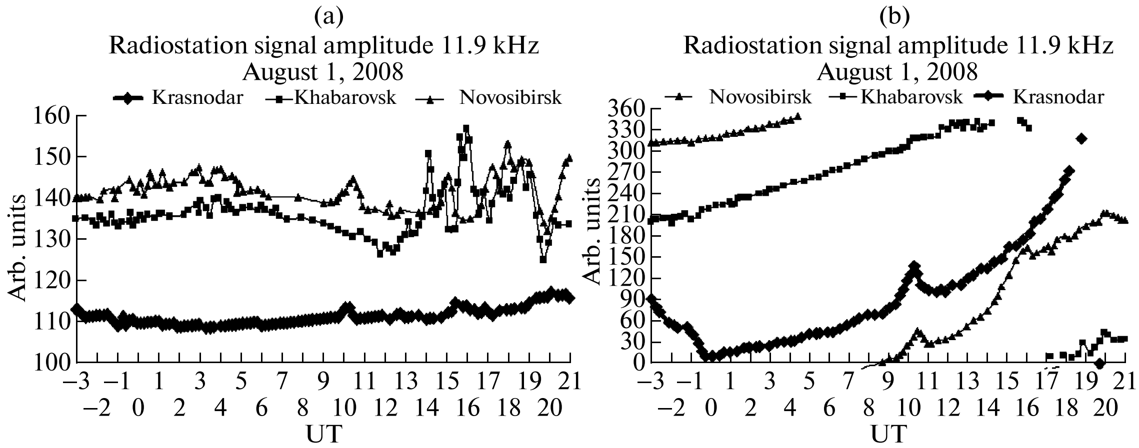

Fig. 2. The daily variations in the (a) amplitude and (b) phase of the signals registered in Yakutsk.

measure the signal phase; time signals were transmitted from this receiver to a computer through ADC. The signal propagation path from the Krasnodar station (the distance to Yakutsk is 5.7×10^3 km) passed through the eclipse region, the Novosibirsk station (2.6×10^3 km) was immediately in the eclipse region, and the station in Khabarovsk (1.4×10^3 km) was outside the lunar shadow region.

Figure 2 shows the daily variations in the amplitude and phase of the signals registered at a frequency of 11905 kHz. For signals from the Krasnodar station, the eclipse effect was registered at 1020 UT as increases in the amplitude and phase by 3% and 45°, respectively, relative to the preceding level. For signals from the Novosibirsk station, the amplitude and phase increased by 5% and 30°, respectively. The solar eclipse effect was almost absent in signals from the Khabarovsk station.

3. NATURAL ELF–VLF EMISSION

As before [Mullayarov et al., 1999; Karimov et al., 2008], during the solar eclipse the observations of the natural emission in Yakutsk were performed at the expedition point with a low level of industrial noise. A multichannel recorder with a magnetic antenna oriented from east to west was used in this case. A signal was recorded at fixed frequencies in the range from 0.47 to 5.6 kHz.

At Kamchatka, a multichannel ELF–VLF recorder at the Karymshina expedition point was used to register the natural electromagnetic emission. Two horizontal components of the magnetic field and one vertical component of the electric field were received. Figure 3 presents the record of the signals during the solar eclipse at both points, received from magnetic antennas the plane of which was oriented from east to west. It is evident that the eclipse effect in Yakutsk manifested itself in an intensification of emissions after 1000 UT at all registered frequencies, and the intensity was maximal from 1030 to 1100 UT and decreased after 1100 UT. The maximal intensity was observed at ~1030 UT at lower frequencies (470 and 610 Hz) and at about 1100 UT at higher frequencies (2.2, 3.1, and 5.6 kHz).

In the records at Kamchatka, the eclipse effect was also observed as a bay-like increase in the emission level. In the region of lower frequencies (30–60, 70–200, and 200–600 Hz), the intensity started increasing after 1000 UT, reached its maximum at 1015 UT, and subsequently gradually decreased. The emission intensity increased more than twice, less than twice, and by a factor of 1.3 in the bands 30–60, 70–200, and 200–600 Hz, respectively. The intensity increased by 20% at about 1100 UT in the frequency bands 2.5–6.5 and 7–11 kHz against a background of clearly defined daily variations.

At Kamchatka, it was possible to compare the time variations in the vertical electric *Ez* and horizontal magnetic *Hx* (the east–west frame plane) and *Hy* (north–south plane) components of the emission received during the eclipse in different frequency ranges (Fig. 4). It is clear that the effect in the form of a bay-like increase in the intensity at frequencies of 70–200 Hz was observed only in the *Hx* component. At frequencies of 7–11 kHz, the eclipse effect manifested itself in the form of an insignificant increase in the intensity in the *Ez* and *Hx* components, the effect in the *Hy* component being absent.

4. DISCUSSION OF RESULTS

The amplitude and phase of the ULF signals measured in Yakutsk during the solar eclipse of August 1, 2008, confirmed the conclusions drawn previously during the eclipses of March 9, 1997, and March 29, 2006. The signal amplitude and phase increased in all cases. On the path outside the lunar shadow (e.g., for the signals from the Khabarovsk radiostation), considerable changes in the amplitude and phase were not observed. In Yakutsk and at Kamchatka, the noise emission background on August 1, 2008, increased due to the effects originating when signals from remote thunderstorms propagated through the lunar shadow band. The lunar shadow leads to a decrease in the electron density [Belikovich et al., 2008] and effective collision frequency in the ionospheric *D* region and to an increase in the height of the Earth–ionosphere waveguide. During the eclipse, the emission intensity maximum in the region of lower frequencies was observed at ~1015 UT at Kamchatka and at ~1030 UT in Yakutsk. Assuming that signals from an emission source propagate in the Earth–ionosphere waveguide through the lunar shadow region, we calculate the distances from the observation points to the lunar shadow, the lunar shadow azimuths, the distance between the observation points, the distance to the possible source, and the position of this source (see Fig. 5). In this case we select the signal propagation paths so that they would cross the lunar shadow center during the observation of the maximal signal amplitudes.

Considering spherical triangles presented in Fig. 5, we determine the distances from the observation points to the lunar shadow, the lunar shadow azimuths, the distance between the observation points, the distances to the source, and the source position. The known values are the latitudes, and the longitudes of the observation points and lunar shadow: 62° N, 129.7° E (Yakutsk); 53° N, 158° E (Kamchatka); 62° N, 75° E (point *N*); and 67° N, 69° E (point *M*).

From triangle *PKJ*, we determine the distance from Kamchatka to Yakutsk, i.e., the side

$$KJ = \arccos(\cos(PK)\cos(PJ) + \sin(PK)\sin(PJ)\cos(L_k - L_j)),$$

where *PK* and *PJ* are the distances from the pole to Kamchatka and Yakutsk, and $(L_k - L_j)$ is the longitudinal difference.

The triangle angles are

$$PJK = \arccos\left(\frac{\cos(PK) - \cos(KJ)\cos(PJ)}{\sin(KJ)\sin(PJ)}\right),$$

$$PKJ = \arccos\left(\frac{\cos(PJ) - \cos(KJ)\cos(PK)}{\sin(KJ)\sin(PK)}\right).$$

The azimuth of Yakutsk from Kamchatka is $AzJK = 2\pi - PKJ$.

The azimuth of Kamchatka from Yakutsk is $AzKJ = PJK$.

From triangle *PKM* with the known sides *PM* and *PK* and angle $MPK = L_k - L_m$, equal to a difference between the longitudes of Kamchatka and the lunar shadow center at a given instant, we determine side *KM* and angle *PKM*.

The distance from Kamchatka to the lunar shadow is

$$KM = \arccos(\cos(PK)\cos(PM) + \sin(PK)\sin(PM)\cos(L_k - L_m)).$$

Angle *PKM* is

$$PKM = \arccos\left(\frac{\cos(PM) - \cos(KM)\cos(PK)}{\sin(KM)\sin(PK)}\right).$$

The azimuth of the lunar shadow from Kamchatka is $AzKM = 2\pi - PKM$.

In a similar way, we determine side *JN* and angle *PJN* from triangle *PJN*, taking into consideration that angle $MPK = L_j - L_n$ is determined as a difference in longitudes between Yakutsk and the lunar shadow center.

The distance from Yakutsk to the lunar shadow is

$$JN = \arccos(\cos(PJ)\cos(PN) + \sin(PJ)\sin(PN)\cos(L_j - L_n)).$$

Angle *PJN* is

$$PJN = \arccos\left(\frac{\cos(PN) - \cos(JN)\cos(PJ)}{\sin(JN)\sin(PJ)}\right)$$

The azimuth of the lunar shadow from Yakutsk is $AzJN = 2\pi - PJN$.

We determine the distance to the emission source. For this purpose, we consider triangle *IKJ*, where angle $KJI = PJN + PJK$, angle $IKJ = PKJ - PKM$, and angle *KIJ* is

$$KIJ = \arccos(-\cos(IKJ)\cos(KJI) + \sin(IKJ)\sin(KJI)\cos(KJ)).$$

The distance from the emission source to Kamchatka is

$$IK = \arccos\left(\frac{\cos(KJI) + \cos(IKJ)\cos(KIJ)}{\sin(IKJ)\sin(KIJ)}\right),$$

and the distance from the source to Yakutsk is

$$IJ = \arccos\left(\frac{\cos(IKJ) + \cos(KJI)\cos(KIJ)}{\sin(KJI)\sin(KIJ)}\right).$$

We determine the latitude and longitude of the emission source and triangle *PKI*, taking into account that angle $PKI = PKM$.

The emission source latitude is

$$Fi = \arccos(\cos(PK)\cos(IK) + \sin(PK)\sin(IK)\cos(PKI)).$$

Angle *IPK* is

$$IPK = \arccos\left(\frac{\cos(IK) - \cos(PI)\cos(PK)}{\sin(PI)\sin(PK)}\right).$$

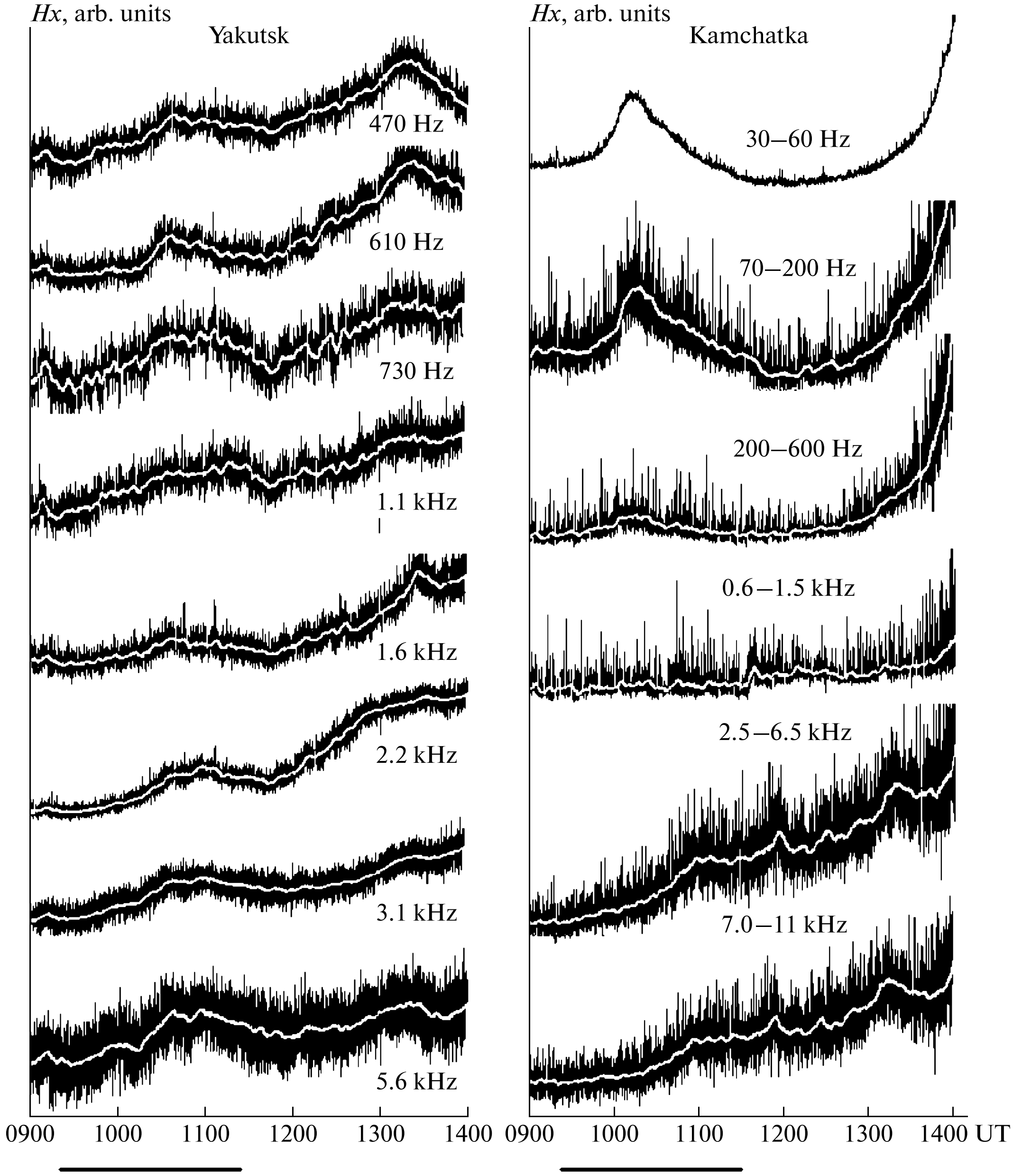

Fig. 3. The fragment of the record of the ELF–VLF signals in different frequency ranges in Yakutsk and at Kamchatka during the solar eclipse of August 1, 2008. The bottom horizontal line shows the time interval during which the lunar shadow was on the Earth's surface.

The source longitude is $L_i = L_k - IPK$.

As a result of the calculations, performed using the above formulas, we found that the Kamchatka–Yakutsk distance is KJ = 1980 km, the azimuth of Yakutsk from Kamchatka is $AzJK = 312°$, and the azimuth of Kamchatka from Yakutsk is $AzKJ = 107°$. The distances from the emission source to Yakutsk and Kamchatka were IJ = 15 800 km and IK = 17 800 km, respectively; the source coordinates were Fi = 35° S and L_i = 8° W. The directions toward the emission source from Yakutsk and Kamchatka are 294° and 324°, respectively; angle $KIJ = 6°$.

The performed calculations indicated that the emission source was located far from the receiving points, the propagation paths (the source–Yakutsk and the source–Kamchatka) were close to each other and passed through central Africa, and the Kamchatka–source–Yakutsk angle (KIJ) was small (KIJ = 6°). Analyzing the calculation results, we can consider that the signal propagation paths were approximately in line with each other. In this case we can only state

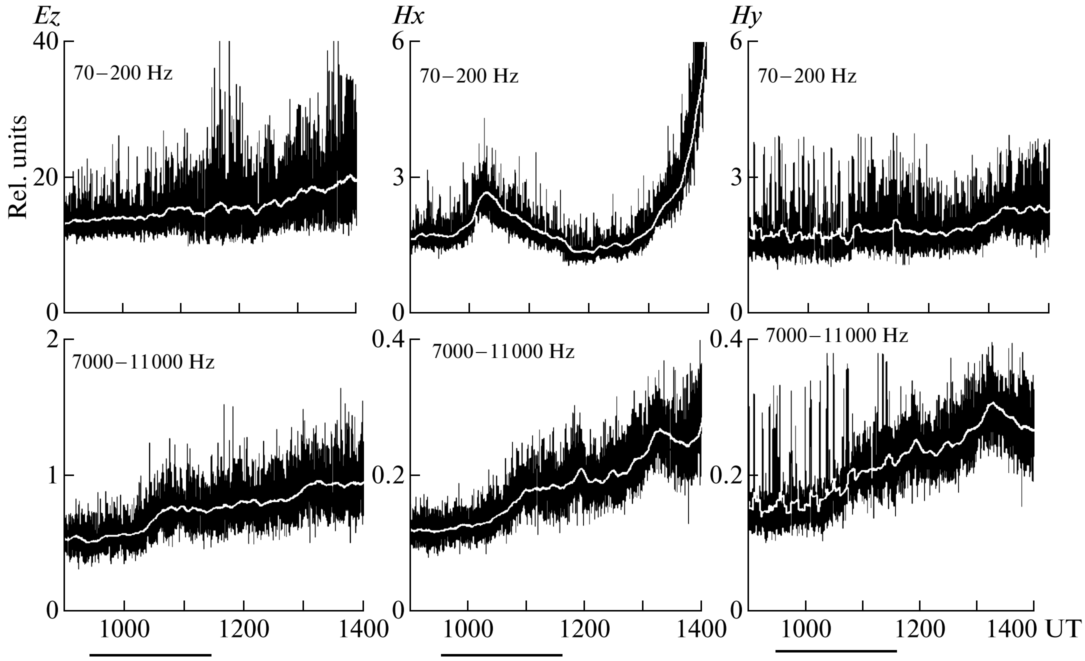

Fig. 4. The variations in different electromagnetic field components at Kamchatka during the solar eclipse of August 1, 2008. Horizontal lines mark the time of the lunar shadow.

that the signal from the emission source comes to Kamchatka and Yakutsk from northwest along the great circle arc, crossing the lunar shadow region.

Based on the calculations, we also found that the emission maximum in Yakutsk and at Kamchatka at approximately the same frequencies (0.61, 5.6 kHz and 0.2–0.6 kHz, respectively) was observed when the lunar shadow maximally approached the registration point (Fig. 6). At Kamchatka, this effect was observed only when the lunar shadow passed in the region of high latitudes.

Taking into account a relatively small distance between the receiving points (as compared to the distance from the assumed source of ELF–VLF noise) and the results achieved in [Druzhin and Kozlov, 1988; Murzaeva et al., 2001], we can assume that the effect of the solar eclipse was observed in signals from one predominant emission source, namely: the African center of global thunderstorm activity.

The presence of a considerable increase in the noise signal at 1015 UT at lower frequencies in the Kamchatka record and the absence of this increase at higher frequencies at that time can be explained as follows. Assume that a bay-like increase in a signal at receiving points is caused by the effects of signal propagation from thunderstorm discharges, originating at large distances from the observation points (several thousand kilometers), through the lunar shadow region. In such a case, the field strength (E) at a receiving point decreases with increasing frequency (f) in the range from several tens of hertz to ~2 kHz ($E \sim 1/f$) because a decay is insignificant at lower frequencies and is considerable at higher ones [Al'pert, 1972]. At frequencies higher than 2 kHz, the field strength increases but a signal decay can exceed a decay at lower frequencies. Consequently, the effect is not observed because of a considerable decay at higher frequencies. In Yakutsk the distance to the lunar shadow is smaller; therefore, a signal decay at higher frequencies is smaller, and the eclipse effect was observed at all frequencies.

We now consider why a bay-like enhancement of the signal at lower frequencies at Kamchatka appeared only in the *Hx* component and was absent in the *Hy* and *Ez* components. Figure 4 indicates that the median values of the noise constituent of the *Hx* and *Hy* components in the frequency range 70–200 Hz are approximately identical, and a bay-like disturbance was observed only in the *Hx* component during the eclipse. This means that a disturbance mostly came to the receiving point only from the east–west direction. It is also clear that the signal amplitude in the *Ez* component was much larger than in the *Hx* and *Hy* components. This could take place if an additional emission source in the near zone substantially contributed to the amplitude of the *Ez* field component and masked a signal that came from the far reception zone.

When signals propagate, the lunar shadow can have a focusing impact due to an increase in the altitude of the ionosphere in the lunar shadow region. At the same time, it is not improbable that not only thunderstorms but also ionospheric–magnetospheric sources

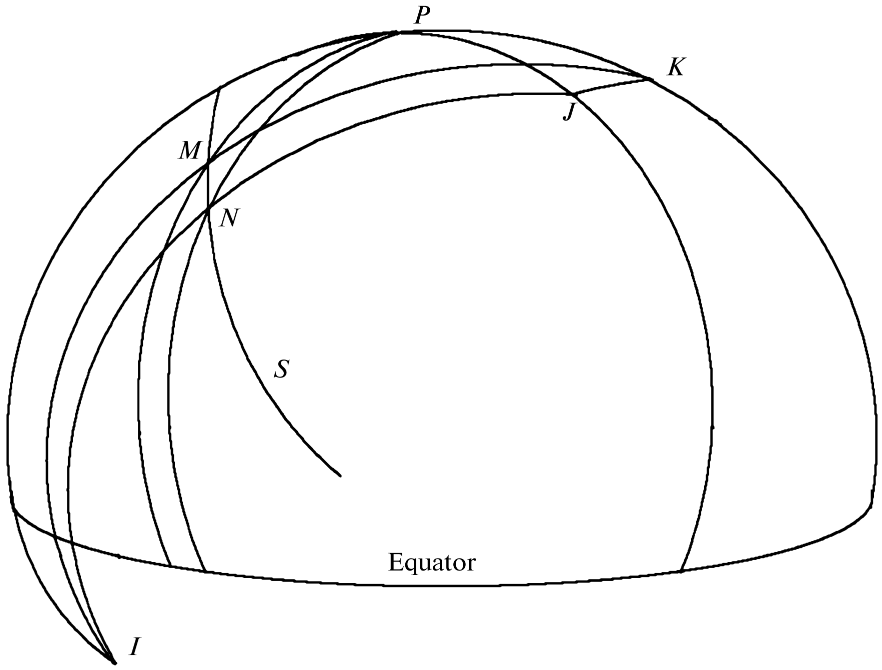

Fig. 5. The location of the Yakutsk (*J*), Kamchatka (*K*), pole (*P*), and lunar shadow observation points when the signal maximum was received in Yakutsk (*N*) and at Kamchatka (*M*); the assumed emission source (*I*); and the lunar shadow trajectory (*S*).

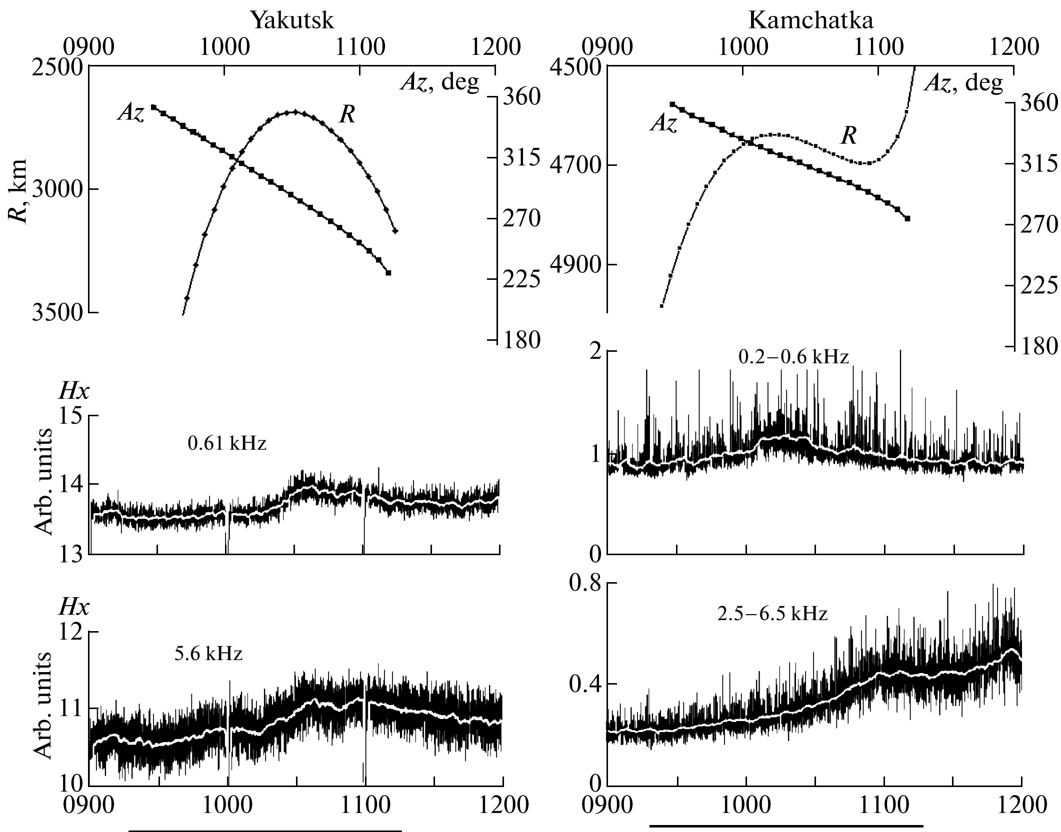

Fig. 6. The time variations in the distance (*R*) from the lunar shadow to Yakutsk and Kamchatka, in the azimuth (*Az*) of the direction of the lunar shadow center from the same observation points, and in the signal.

can make a certain contribution to the emission. The following studies can indicate what mechanism is predominant. The noise daily variations during this season are similar to the variations presented in [Druzhin and Shapaev, 1988; Druzhin and Kozlov, 1994; Murzaeva et al., 2001; Mikhailov et al., 2004].

5. CONCLUSIONS

(1) Using the signals from the ULF radiostations (which are located in Krasnodar, Novosibirsk, and Khabarovsk and emit at frequencies of 11 905, 12 649, and 14 880 kHz, respectively) observed on August 1, 2008, in Yakutsk, we considered the solar eclipse effects on the propagation radiowaves. We indicated that the signal amplitude and phase increase by 3–5% and 30°–45° relative to the background level when the propagation path crosses the lunar shadow region. Similar effects were not found out on the control path in Khabarovsk, which was located outside the lunar shadow.

(2) The natural electromagnetic ELF–VLF noise emission was for the first time synchronously registered in Yakutsk and at Kamchatka during the solar eclipse. When the lunar shadow passed from ~1000 to 1130 UT on August 1, 2008, a bay-like increase in the emission intensity with the following decrease in this intensity to the initial level was registered at both points. This effect was observed at frequencies of 0.6–5.6 and 2.5–11 kHz in Yakutsk and at Kamchatka, respectively. The time of formation of the intensity maximum depended on frequency, and the intensification was maximal (twofold as compared to the background level) at lower registered frequencies. In this case the noise signal intensity maximum at these frequencies was observed when the lunar shadow maximally approached the observation point. The intensity maximum at higher frequencies was observed at approximately the same time (1100 UT) at both registration points with a delay relative to the maximums at lower frequencies.

(3) An intensification of the natural ELF–VLF emission at Kamchatka and in Yakutsk during the solar eclipse of August 1, 2008, could be caused by the processes related to the propagation of the signal from the African center of global thunderstorm activity through the lunar shadow region.

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