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Effect of the Total Solar Eclipse of March 20, 2015, on VLF/LF Propagation

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Abstract—The analyzed amplitude and phase variations in electromagnetic VLF and LF signals at 20–45 kHz, received in Moscow, Graz (Austria), and Sheffield (UK) during the total solar eclipse of March 20, 2015, are considered. The 22 analyzed paths have lengths of 200—6100 km, are differently oriented, and cross 40–100% occultation regions. Fifteen paths crossed the region where the occultation varied from 40 to 90%. Solar eclipse effects were found only on one of these paths in the signal phase (–50°). Four long paths crossed the 90–100% occultation region, and signal amplitude and phase anomalies were detected for all four paths. Negative phase anomalies varied from –75° to –90°, and the amplitude anomalies were both positive and negative and were not larger than 5 dB. It was shown that the effective height of the ionosphere varied from 6.5 to 11 km during the eclipse.

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1. INTRODUCTION

Solar eclipses represent the unique possibility of studying physical and chemical ionospheric processes in the situation when the solar radiation intensity rapidly changes. Gokov et al. (2008) indicated that a solar eclipse results in the following variations in the near-Earth environment: the atmospheric gas cools, a density shock is generated, the electron density decreases in the ionosphere, the electron and ion temperatures decrease in the outer ionosphere, the geomagnetic field varies, etc. Therefore, it is very interesting to study solar eclipse effects at altitudes of the lower ionosphere.

Ionospheric sounding by VLF/LF radiowaves is still the most sensitive method for detecting anomalous ionization and altitude variations of the *D* region that reflects these waves. Researchers started analyzing variations in the amplitude and phase of subionospheric signals at different frequencies (from 10 to 60 kHz) and receiver and transmitter positions relative to the occultation region during solar eclipses and at different times of day in the 1960s–1970s. The results of these analyses are numerous. The studies were performed for signals received on differently oriented paths with different lengths (e.g., (Crary and Schneible, 1965; Kaufmann and Schaal, 1968; Kamra and Varshneya, 1967; Hoy, 1969; Ricardo et al., 1970; Lynn, 1973)). Kaufmann and Schaal (1968) considered the effects during the total solar eclipse of November 12, 1966, on a long (13300 km) path. The path was largely under nighttime conditions, and the eclipse was observed in the sunlit path zone, as a result of which it was to a certain degree difficult to interpret the data. However, it was found that the phase pronouncedly (by about 20°) changed when the occultation was maximal. The signal amplitude changed quite insignificantly. Hoy (1969) studied the received signal on the Rugby (UK)–Canberra (Australia) very long path during the total eclipse of September 22, 1968. The results were similar to those achieved by Kaufmann and Schaal.

Crary and Schneible (1965), on the contrary, performed studies on short paths (shorter than 1000 km). They found that the amplitude increased by 2–3 dB and the phase decreased by 60–100° during the solar eclipse of July 20, 1963. The ionospheric height increased by 6–11 km.

The results generally indicated that signal daily variations are disturbed during solar eclipses. In this case it is most effective to measure the phase in order to observe variations in signal propagation parameters. An average increase in the signal amplitudes for the paths with lengths varying from 1000 to 10000 km was about 1 dB, whereas the phase changed by 40°. The ionospheric height of reflection was usually 3–8 km. Many researchers (Reeve and Rycroft, 1972; Sen Gupta et al., 1980; Lynn, 1981; Mendes Da Costa et al., 1995) concluded that the effects caused by a solar eclipse largely depend on the signal frequency and path length. Therefore, the researchers continued studying the ionospheric parameters during solar eclipses.

Clilverd et al. (2001) carried out the most detailed experimental and model studies during the total solar

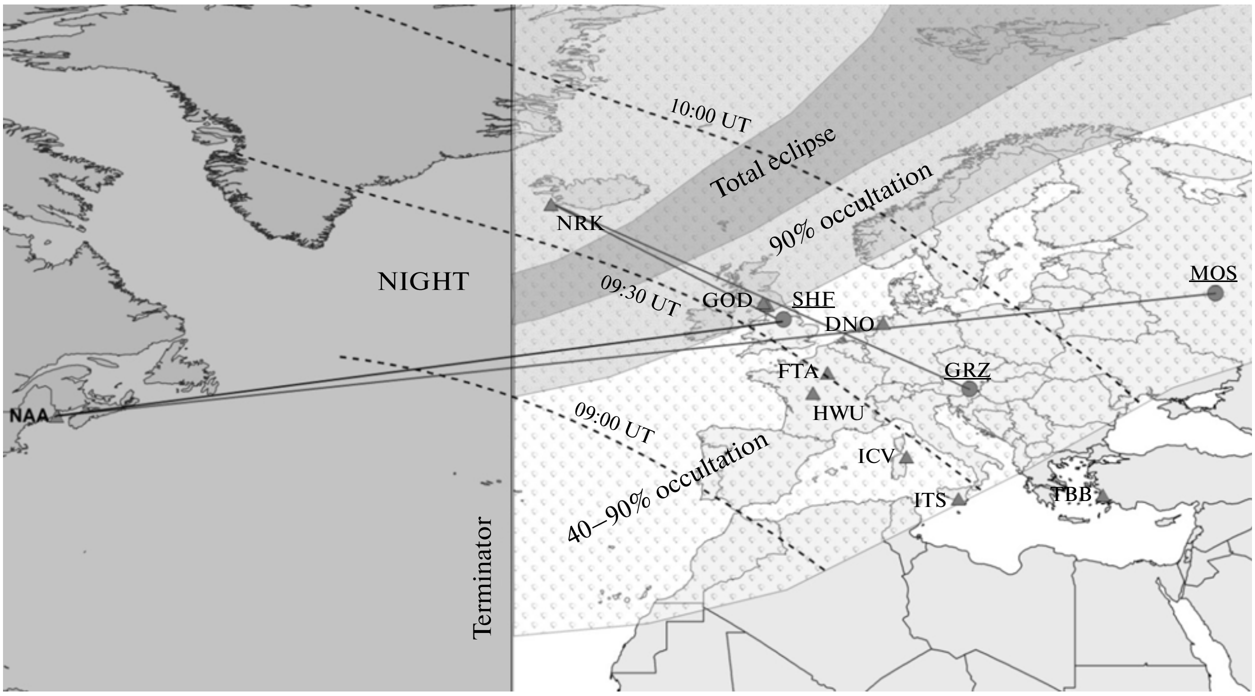

Fig. 1. System of VLF/LF observations in Europe and the occultation regions during the solar eclipse of March 20, 2015 (timeanddate.com). The positions of the sources at MOS, GRZ, and SHF are shown by circles. Triangles show the position of transmitters: NRK (37.5 kHz) in Iceland, GQD (22.1 kHz) in Great Britain, ICV (20.27 kHz) on Sardinia, ITS (45.9 kHz) on Sicily, TBB (26.7 kHz) in Turkey, DHO (23.4 kHz) in Germany, FTA (20.9 kHz) and HWU (21.75 kHz) in France, and NAA (24.0 kHz) in USA. Four long paths that crossed the 90–100% occultation region (NAA–MOS, NAA–SHF, NRK–SHF, and NRK–GRZ) are shown by straight lines. A vertical double line shows the position of the morning terminator at an altitude of 100 km calculated for 07 h 40 min UT.

eclipse observed on August 11, 1999, in Europe. The amplitude and phase of VLF/LF signals at 16–24 kHz were measured for 17 paths with different lengths (from 90 to 14500 km). All paths crossed the region with the occultation varying from 90 to 100%. Positive amplitude anomalies were observed during the total solar eclipse on the paths shorter than 2000 km, and negative amplitude variations were typical of the paths longer than 10000 km. Negative phase anomalies were found for most paths regardless of their length.

In particular, a positive phase anomaly of 40° was observed on the path of the signal that was transmitted from UK and was received in Budapest. Although the signal characteristics varied differently on different paths, the average amplitude and phase variations were about 3 dB and –50°, respectively. The experimental data were successfully modeled with regard to chemical processes in the lower ionosphere. It is customary to characterize variations in the ionospheric *D* region by two parameters: the effective height of the ionosphere (H', km) and a constant (β, km^{-1}) that characterizes the variation in conductivity in the lower ionosphere (Wait and Spies, 1964). It was found that the eclipse effects were maximal when H' was 79 km and $\beta = 0.5$ km^{-1} as compared to $H' = 72$ km and $\beta = 0.43$ km^{-1} for normal daytime conditions (Thomson, 1993). In this case the model sensitivity to an increase in the ionospheric height and to parameter β depended on the specific path and time of day.

In recent works (e.g., (Druzhinin et al., 2010; De, S.S. et al., 2009, 2011; De, K.S. et al., 2011)) devoted to the solar eclipses of August 1, 2008, and June 22, 2009, it was also noted that VLF/LF propagation is affected by the passage of the Moon's shadow during a solar eclipse, and the signal phase is the most sensitive characteristic. In these works studies were performed for different signals (Al'fa Russian transmitters (~12–15 kHz), an NWC Australian transmitter (19.8 kHz), Russian 25-kHz transmitters, and a Japan 40-kHz time service transmitter) registered in Yakutsk and India. It was found that the amplitude changed by 3–5% and the phase varied by 30°–45° when signals crossed the Moon's shadow region. The calculations indicated that the ionospheric height increased by 3–4 km during the eclipse. Guha et al. (2010) observed the amplitude and phase characteristics during the solar eclipse of July 22, 2009, on the 2200 km path. The occultation was maximal during the morning terminator, i.e., during the transition from the nighttime to daytime ionosphere. The eclipse resulted in a change in the signal's usual form during the terminator, and the amplitude decreased by 3.2 dB in this case.

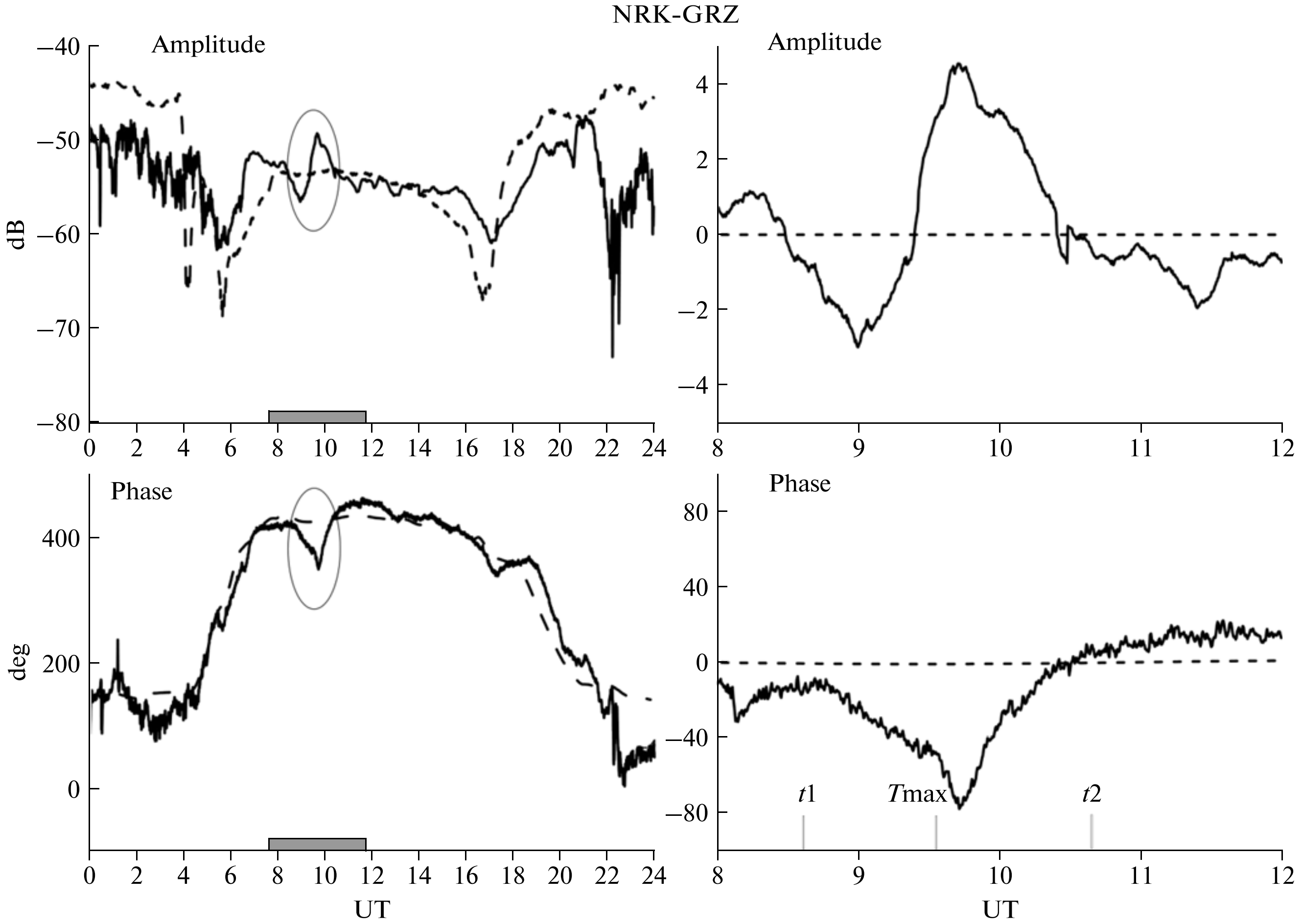

Fig. 2. Amplitude (the upper plots) and phase (the lower plots) variations in the NRK (37.5 kHz) signal registered on March 20, 2015, at GRZ. On the right-hand plots, the current signal and the signal averaged for several undisturbed days of months are shown by solid and dotted lines, respectively. The left-hand plots represent the signal daily variations; the right-hand plots show the difference between real signal variations during the eclipse and variations in the averaged undisturbed signal. The eclipse period is shown by a gray triangle on the *X* axis of the left-hand plots. Amplitude and phase anomalies caused by the eclipse are shown by ellipses on the left-hand plots. The times of the first and last contacts in Reykjavik (Iceland), where a transmitter is located, are marked by *t*1 and *t*2 on the *X* axis of the lower right-hand plot. The instant of the eclipse maximum phase (97% in this region) is marked by *T*max.

Thus, the solar eclipse effects registered in the amplitude and phase of subionospheric radio signals are different and substantially depend on not only the signal path length and frequency but also on the time of day and occultation degree. Therefore, each solar eclipse is unique, and studying the related effects makes it possible to improve our knowledge of the ionospheric *D* region behavior.

The present work is devoted to studying the effect of the total solar eclipse of March 20, 2015, on VLF/LF propagation at the European stations.

2. OBSERVATION SYSTEM

The work is based on the registration of VLF/LF signals (~20–45 kHz) received at the European network of stations located in Moscow (MOS), Graz (GRZ, Austria), and Sheffield (SHF, UK). The receiving stations simultaneously measure the amplitude and the MSK (minimum shift keying) phase of modulated signals from several (10–12) receivers at an interval of 20 s. An UltraMSK receiver (http://ultramsk.com/) designed in New Zeeland is used to receive signals. The reception is performed with an electric spike antenna in a narrow frequency band (±100 Hz relative to the fundamental frequency). The relative position of receivers and some transmitters is shown in Fig. 1.

The solar eclipse of March 20, 2015, was a total solar eclipse of 120 saros (a period equal to 18 years 11.3 days). The eclipse could be observed in the northern Atlantic Ocean and Arctic Regions. The eclipse partial phases were observed in Europe, western Russia, Central Asia, the Middle East, and North Africa (Fig. 1). The eclipse had a magnitude of 1.045 and gamma of 0.9454. This means that the Moon's shadow simply slipped over the Earth's surface at northern lat-

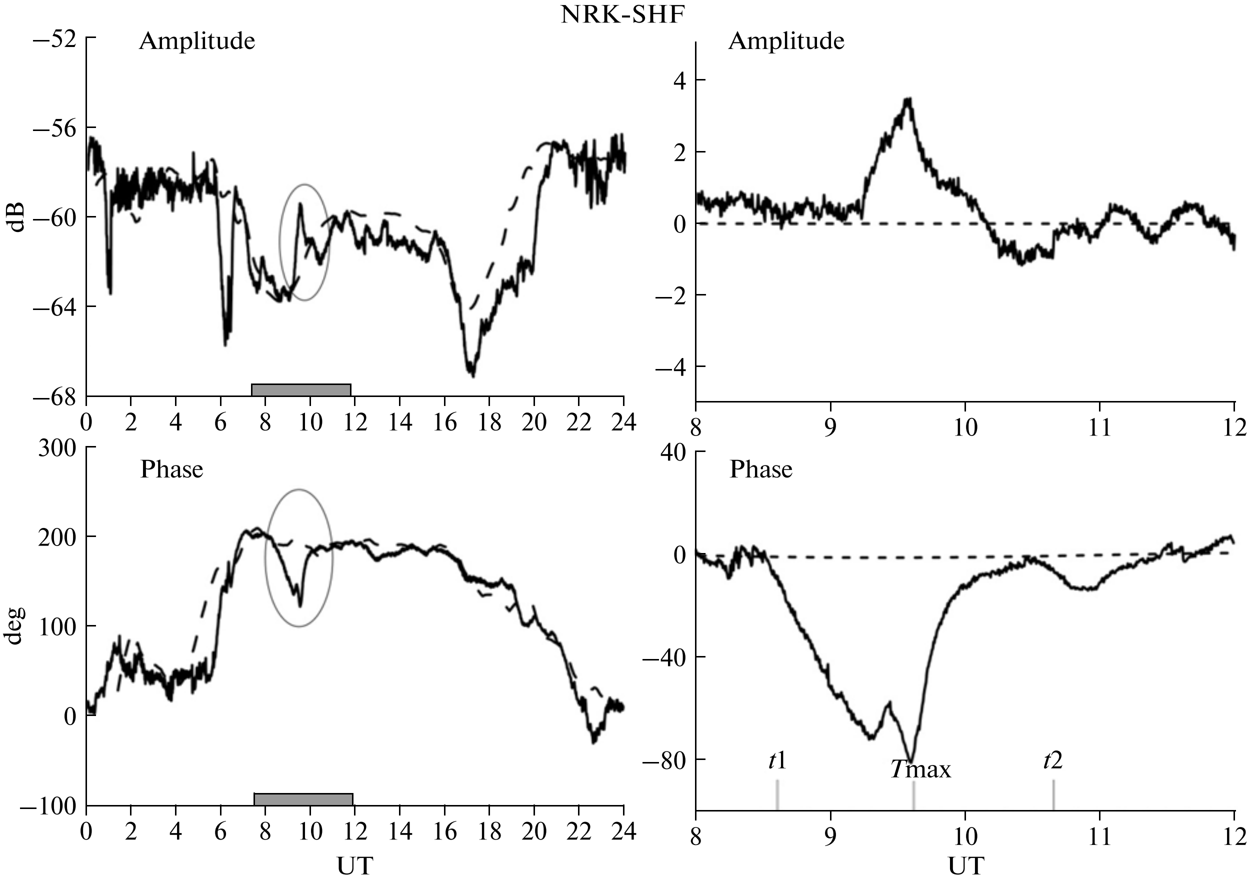

Fig. 3. The same as in Fig. 2 but for the signal registered at SHF (UK).

itudes, where the Earth rotation contributes to the shadow-passage duration less significantly than it does near the equator. Therefore, the total eclipse maximal time on the Moon's shadow path was less than 3 min. The total eclipse maximal duration was 2 min 47 s at 9:45 UT near the Faeroes coast. The total eclipse was observed in a wide band (about 460 km) in northern Europe. The eclipse passed over the Atlantic Ocean between 07:40 and 11:50 UT; i.e., its duration was about 4 h. The eclipse started in northwestern Europe and moved eastward, passing between Iceland and Great Britain, toward Faeroes and islands in northern Norway.

We analyzed 22 paths in Europe. The region of 90–100% occultation was crossed by four long paths with lengths of 1600 km (NRK–SHF) to 6100 km (NAA–MOS) (Fig. 1). It was impossible to analyze signal records on the NRK–MOS path, which also crossed the total eclipse region, owing to considerable leakage, which was probably caused by the receiver position in central Moscow, where the electromagnetic environment is rather noisy. Below, the variations in the signal amplitudes and phases on different paths during the eclipse are analyzed in detail.

3. RESULTS OF ANALYSIS

The signal analysis was to a certain degree complicated by geomagnetic conditions. A strong magnetic storm with *Dst* about –230 nT occurred at night (according to UT) on March 17–18, 2015 (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index/html). A proton flare registered with the GOES-15 geostationary satellite was observed for two days before this storm. The storm recovery phase continued for more than a week, and an intense flux of relativistic electrons was registered during that period. Although geomagnetic activity affects only the behavior of a nighttime signal on mid-latitude paths (e.g., (Rozhnoi et al., 2014)) and the eclipse was observed during the daytime, this made it difficult to select quiet undisturbed days as a control for the observations.

Fifteen of the 22 paths crossed the region where the occultation was 40–90%. Solar eclipse effects were found only on the signal phase on the ICV–GRZ path. The minimal deviation of the signal phase from the normal monthly average value was 50° on this path. The signal minimum was observed at about 09:40 UT, when the partial eclipse reached approximately the path midpoint. No effect on the signal amplitude was found for this path. However, we should note that a

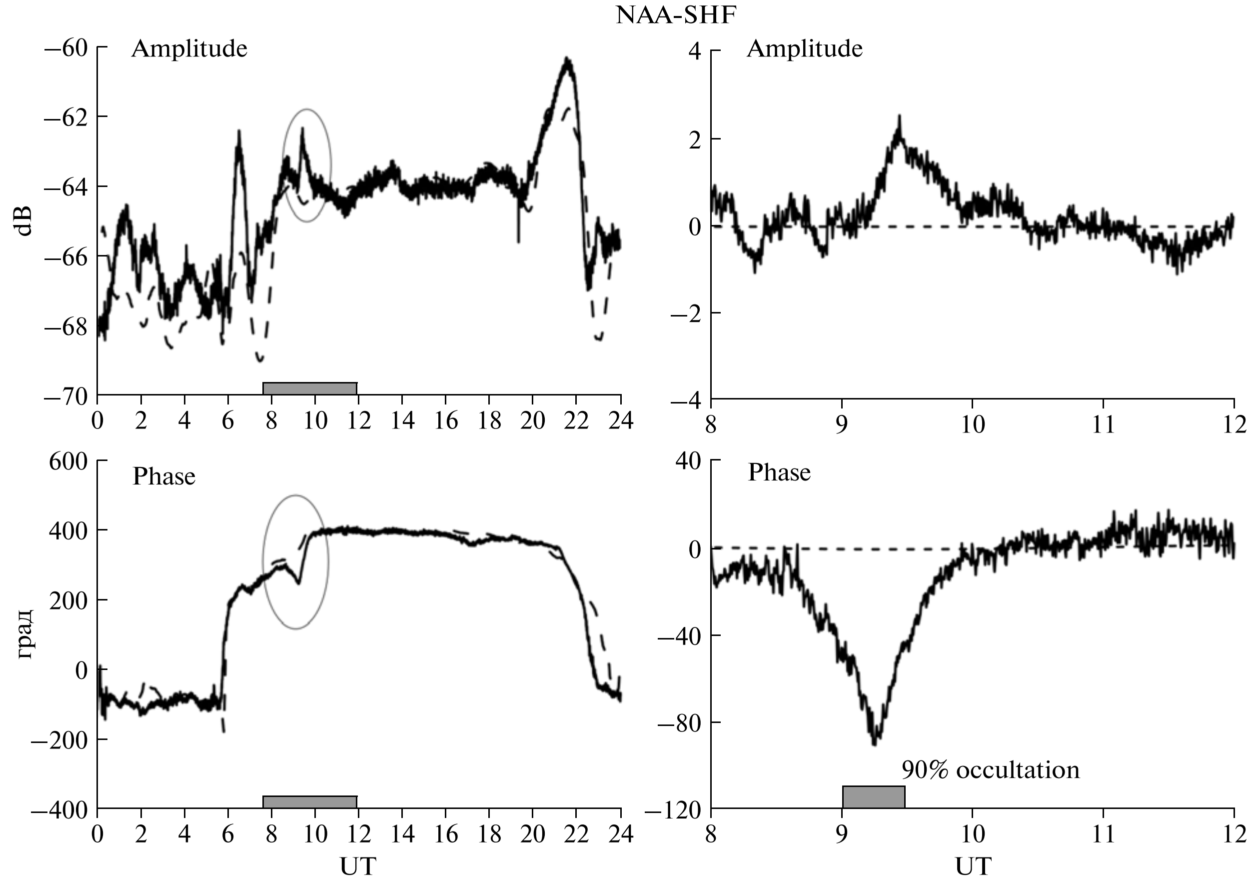

Fig. 4. The same as in Fig. 3 but for the NAA (24 kHz) signal. The period during which the signal propagated along the path through the eclipse maximum zone is shown on the *X* axis of the lower right-hand plot.

sufficiently stable phase is not received from all transmitters.

The GQD–SHF path, with a length of about 200 km, was completely within the region with the 90% occultation. The signal propagation on such a short path is multimodal, which probably caused the magnetic storm (the post-storm effect) to have a considerable influence on the signal behavior. The normal daily variations in the signal amplitude and phase were strongly distorted for a week after the magnetic storm, especially during terminators. It was impossible to detect any eclipse effects against such a background. Although the signal amplitude and phase slightly increased and decreased (by 0.5 dB and −3.5°, respectively) at 09:40 UT (i.e., when the occultation was maximal on this path), the values of these characteristics were not larger than rms deviations.

On the GQD–MOS path, the transmitter and receiver were in the 90 and 65% occultation regions, respectively. For this path, no changes in the signal amplitude were found, and insignificant positive variations (the maximal values of which were only 15° at 10:30 UT, i.e., 10 min before the maximal eclipse in Moscow) were observed in the signal phase.

As was mentioned above, four long paths crossed the 90–100% occultation region. The analysis of the amplitudes and phases of the VLF/LF signals on these paths is illustrated in Figs. 2–5. Figures 2–5 show the variations in the signal phase and amplitude for the entire day on March 20 (left) and the difference between the actual signal variations during the eclipse (from 8 to 12 UT) and the variations in the averaged undisturbed signal.

Figures 2 and 3 show variations in the signal (37.5 kHz) transmitted from NRK near Reykjavik (Iceland) and received in Graz (Austria) and Sheffield (UK). Both paths pass near Faeroes, where the totality was most prolonged. They are the highest-latitude paths considered; the nighttime signal disturbances on the longer path and an anomalous terminator shift on the shorter path (the post-storm effect of the magnetic storm that occurred on March 17–18) were pronounced in the records for March 20. The effects caused by the eclipse are specific on both paths. On the NRK–GRZ path (Fig. 2), the amplitude first (after the first contact) starts decreasing (the maximal decrease is 3 dB relative to the normal level) and then rapidly increases and surpasses than the normal values by 4.5 dB approximately 2 min after the eclipse maxi-

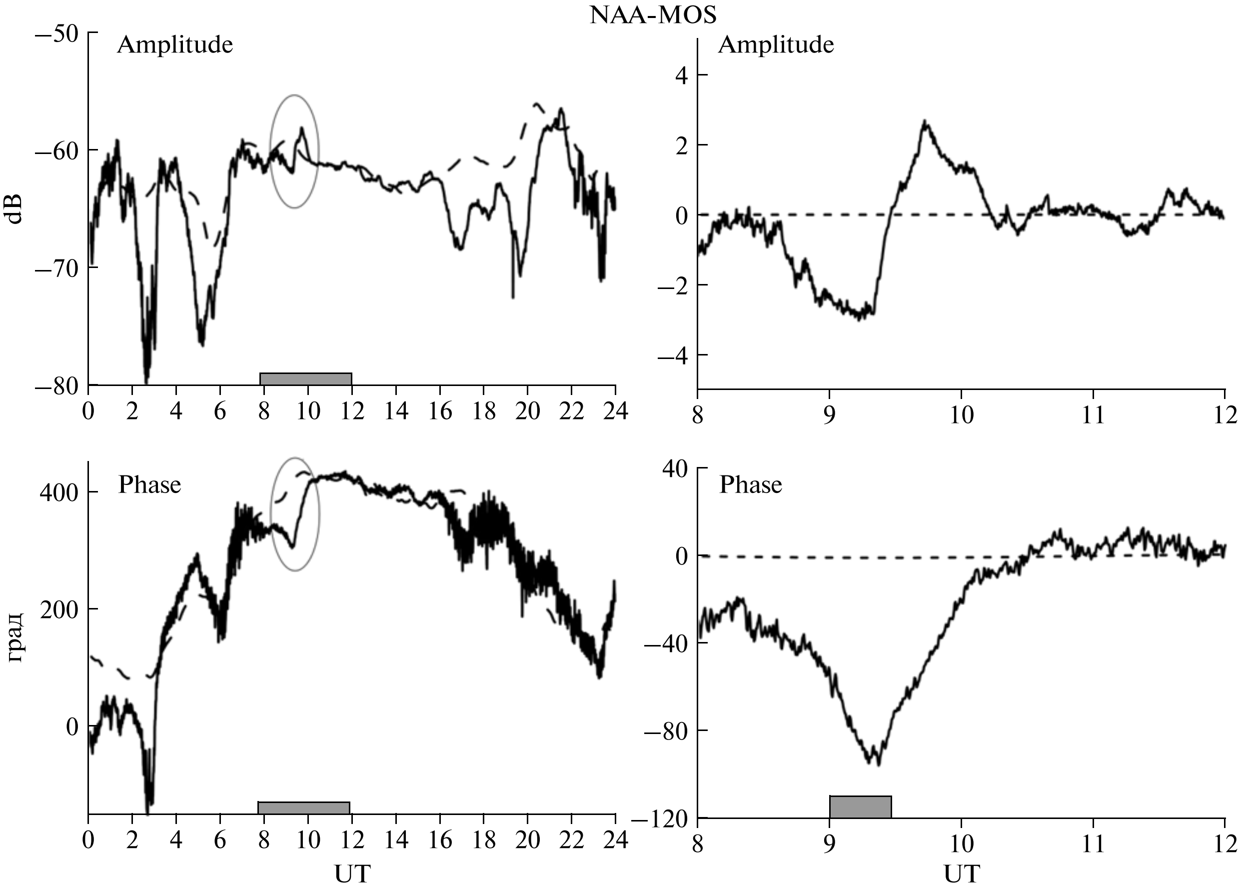

Fig. 5. The same as in Fig. 4 but for the signal registered at MOS.

mum phase in Reykjavik. In 40 min, the amplitude returns to its normal level (15 min before the last contact). The signal phase starts decreasing immediately after the first contact, and the anomaly value reaches −75° simultaneously with the amplitude minimum. The signal phase returns to its normal level also simultaneously with the amplitude recovery. On the NRK–SHF path (Fig. 3), the amplitude sharply increases 35 min after first contact and reaches maximal values (+3.5 dB) relative to the normal level 10 min before the eclipse maximum phase in the transmitter region. The amplitude subsequently abruptly decreases and returns to its usual level in approximately 30 min. The signal phase starts decreasing when the first contact is registered. The phase anomaly has a double peak. The first minimum (−65° relative to the normal level) is observed approximately 20 min before the maximal occultation in Reykjavik. The second anomaly peak (−80°) coincides with the maximal occultation in the transmitter region. The phase recovers simultaneously with the signal amplitude. Double peaks in the LF signal phase anomaly were also observed during previous eclipses on some paths (e.g., (Clilverd et al., 2001; De, K.S. et al., 2011).

Figures 4 and 5 show variations in the signal (24.0 kHz) transmitted from NAA (Maine, USA) and received at SHF and MOS. On these paths the period of the solar eclipse coincided with the end of the morning terminator. The signal paths were in the zone of maximal occultation (90–95%) from 09:00 to 09:30 UT. The signal phase negative deviation from the normal level (−90° and −85° on the NAA-SHF and NAA–MOS paths, respectively) was minimal at that time. The positive amplitude anomaly maximum (2.5 dB) on the NAA–SHF path (Fig. 4) was observed approximately 10 min after the signal phase minimal value. The signal behavior at MOS is more complex (Fig. 5). The amplitude first decreases synchronously with the signal phase, and the minimal negative anomaly reaches 3 dB simultaneously with the signal phase. Then, the amplitude starts increasing and surpasses than the normal value by approximately 2.5 dB in 25 min. The signal amplitude and phase return to their normal values at 10:10 UT, i.e., later than on the NAA–SHF path by 20 min.

4. DISCUSSION

The effect of the total solar eclipse of March 20, 2015, on the variations in the VLF/LF signal amplitudes and phases was analyzed on 22 European paths that are differently directed and cross the 40–100%

Solar eclipse effects in the amplitude and phase of VLF/LF signals

Path	Frequency, kHz	Length, km	Maximal occultation, %	Phase, deg	Amplitude, dB
NRK-GRZ	37.5	2700	100	–75	–3/+4.5
NRK-SHF	37.5	1600	100	–80	+3.5
NAA-MOS	24.0	6100	90	–85	–3/2.5
NAA_SHF	24.0	4200	90	–90	+2.5
ICV-GRZ	20.27	740	70	–50	d.a.
GQD-MOS	22.1	2300	90	+15	d.a.

occultation regions. The effects were found for six paths presented in the table.

The table indicates that the effects are rather different. A decrease in the signal phase value was maximal for the four paths crossing the 90–100% occultation region. The amplitude anomalies on these paths were less significant and different. The anomaly shape was 1 close to sinusoid on two paths and demonstrated a single peak on two other paths. An analysis of signals was complicated by geomagnetic activity, as a result of which reliable data could not be obtained for the shortest path (GQD–SHF). The data confirm the conclusion made previously by many researchers that a signal phase is more sensitive to a change in ionospheric parameters.

Since solar radiation (the main ionization source) is absent above the solar eclipse zone, ionization processes in the ionospheric D region proceed at lower altitudes, which results in an increase in the ionospheric height and, consequently, in the propagation path of VLF/LF signals that reflect from the boundary of the lower ionosphere. As a result, a phase delay of received subionospheric signals is observed. This delay is determined as (Pant and Mahra, 1994):

$$\Delta\varphi = 2\pi(d/\lambda)(1/2a + \lambda^2/16H^3)\Delta h,$$

where d is the distance between the transmitter and receiver, λ is the signal wavelength, a is the Earth's radius, H is the normal height of reflection, and Δh is a change in the reflecting height. Therefore, an increase in the ionospheric height is defined as:

$$\Delta h = \Delta\varphi/(2\pi(d/\lambda)(1/2a + \lambda^2/16H^3)).$$

Based on the data (table), we estimated the variation in the ionospheric height during the eclipse. The estimates indicated that the ionospheric height increased by 6.5–11 km (or by 8.7 on average), which is in rather good agreement with the data obtained in other works. However, in contrast to many works considered above, no dependence of the solar eclipse effects on the signal frequency and path length was found.

5. CONCLUSIONS

1. Evident effects caused by the solar eclipse were found in the amplitude and phase of VLF/LF signals (24.0 and 37.5 kHz) on differently oriented (sublatitudinal and submeridional) paths with different lengths (from 1600 to 6100 km) that crossed the 90–100% occultation region.

2. The maximal anomalies were observed during the eclipse maximum phase.

3. The average duration of anomalies varied from 1 h 20 min to 1 h 30 min.

4. The phase of VLF/LF signals was more sensitive to a change in the parameters of the lower ionosphere than the amplitude.

5. The ionospheric height increased by 6.5–11 km during the eclipse.

6. No dependence of the solar eclipse effects on the signal frequency and path length was found.

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