The effect of the August 21, 2017 total solar eclipse on the phase of VLF/LF signals

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Key Points:

• Variations in phase of VLF/LF signals observed during a total solar eclipse of 21.08.2017 is analysed
• Theoretically estimated variation of D region electron density coincide with observational results

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Abstract
An experimental study of the phase and amplitude observations of sub-ionospheric very
low and low frequency signals is performed to analyse the response of the lower ionosphere
during the August 21, 2017 total solar eclipse in the United States of America. Three
different sub-ionospheric wave paths are investigated. The length of the paths varies from
2200 to 6400 km and the signal frequencies are 21.4 kHz, 25.2 kHz and 40.75 kHz. The
two paths cross the region of the total eclipse and the third path is in the region of 40-
60% of obscuration. None of the signals reveal any noticeable amplitude changes dur-
ing the eclipse while negative phase anomalies (from $-33^\circ$ to $-95^\circ$) are detected for all
three paths. It is shown that the effective reflection height of the ionosphere in low and
middle latitudes is increased by about 3-5 km during the eclipse. Estimation of the elec-
tron density change in the lower ionosphere caused by the eclipse, using linear recom-
bination law, shows that the average decrease is by 2.1 to 4.5 times.

1 Introduction
The total solar eclipse on August 21, 2017, named the “Great American Eclipse”
was observed within a narrow band (117 km) across the middle part of the United States
from the Pacific to the Atlantic coasts (Fig. 1). The first external contact of the penum-
bral shadow with Earth (point P1 in Fig. 1) occurred at 15:46:51 UT to the north-east
from the Hawaiian Islands and the last external contact (point P4 in Fig. 1) took place
at 21:04:23 UT near the northern coast of Brasilia. The total eclipse began at 16:48:36
UT and lasted until 20:02:34 UT.

The maximum eclipse had a duration of 160 sec and occurred at the location with
coordinates: 37°N 87.7°W starting at 18:26:40 UT. The partial solar eclipse was visi-
ble over a region thousands of kilometres wide from Canada to South America and par-
tially in northwestern Europe and in the Chukchi Peninsula in Asia.

Solar eclipses give us unique possibility to study physical and chemical ionospheric
processes when the solar radiation changes abruptly. They are also known to produce
a decrease in the electron density in the ionosphere, a decrease in electron and ion tem-
perature and a change in ionic composition in outer ionosphere (Rishbeth, 1968).

One of the few experimental techniques, which can be used to monitor ionization
perturbations within lower ionosphere, is very low and low frequency (VLF/LF) radio
wave probing. Such electromagnetic waves propagate in the lower ionosphere - Earth waveg-
uide due to reflection from the upper boundary (lower ionosphere at altitudes of $\approx 70$
km in the daytime and $\approx 90$ km at night) and lower boundary (Earth surface) (Wait
& Spices, 1964). Because of this, these waves inherently contain information about the
reflection region of the ionosphere and its variability. The propagation of sub-ionospheric
VLF signals over distances of thousands of kilometres enables remote sensing over large
regions of the upper atmosphere in which ionospheric modifications lead to changes in
the received amplitude and phase.

After the pioneering studies of Bracewell, 1952 (Bracewell, 1952), numerous obser-
vations of the phase and amplitude variations of sub-ionospheric signals in different fre-
cquency bands (10-60 kHz) during the solar eclipses were performed in the 1960’s. These
researchers examined a number of VLF transmitter signals along paths of different dis-
tances and orientations (Crary & Schneible, 1965; Kamra & Varshneya, 1967; Kaufmann

In particular, these studies detailed the phase and amplitude perturbations asso-
ciated with total or partial solar eclipses. It was found that the most effective method
to monitor the variations of propagation characteristics is analysis of phase changes. Over
paths of 1000 to 10000 km the amplitude was typically found to increase by about 1 dB

and the phase decreased by about 40°. Increases in the effective reflection height of the ionosphere were estimated to be between 6 and 11 km. Many authors (Reeve & Rycroft, 1972; Gupta et al., 1980; Lynn, 1981; Mendes Da Costa et al., 1995) suggesting that ionospheric effects related to the solar eclipse depend on both the length of the path and the signal frequency.

Clilverd et al., 2001 studied in detail ionospheric effects during the total solar eclipse observed in Europe on August 11, 1999. The analysis of the amplitude and phase of four VLF transmitters in the frequency range 16-24 kHz was performed for 19 paths of different distances (from 90 to 14,510 km). Positive amplitude changes were observed on short paths, i.e. less than 2000 km, while negative amplitude changes were observed on longer paths, i.e. more than 10000 km. Negative phase changes were observed on most paths and were therefore independent of path length. The typical changes observed were 3 dB and 50°. These experimental results have been successfully modelled by taking into account chemical processes in the lower ionosphere.

In more recent works (see e.g. (S. S. De et al., 2011; K. B. De et al., 2011; Guha et al., 2010)) the eclipse’s effects on the equatorial lower ionosphere were reported for the total solar eclipse on July 22, 2009. The signals from different transmitters were registered in India. Analysis of the data confirmed that phase is a more sensitive characteristic than amplitude. It was found that during the eclipse, the effective reflection height of the ionosphere increased by 3 km.

In our previous work (Solovieva et al., 2016) we considered the amplitude and phase variations of VLF/LF signals (20-45 kHz) received in Moscow, Graz (Austria), and Sheffield (UK) during the total solar eclipse on March 20, 2015 in North West Europe. Four long paths crossed the 90-100% obscuration region, and the 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. They did not exceed 5 dB. It was also found that the effective height of the ionosphere varied from 6.5 to 11 km during the eclipse.
Unlike previous works we found that the solar eclipse effected neither the signal frequency or path length. Further experimental measurements of the ionospheric parameters at the time of solar eclipses are needed to understand this behavior and the characteristics of the ionosphere.

In the current work we use phase and amplitude observations of sub-ionospheric VLF/LF signals to analyze the response of the lower ionosphere to the Great American Eclipse on August 21, 2017. This eclipse has been analyzed in detail by (Cohen et al., 2018) using observations from 11 VLF/LF receivers across the continental United States. Results of the analysis have shown increase in amplitude up to 5 dB during eclipse together with decrease in phase $\approx 10^{-50}$ degrees. No quantitative analysis of the ionospheric conditions during eclipse was made. Another work also presents the analysis of VLF signal during this eclipse (Moore & Burch, 2018). These authors observed both amplitude and phase perturbations on many middle length VLF paths from NLM transmitter. They reported a change in amplitude of $\approx 1-6$ dB and a change in phase from $-10^\circ$ to $-50^\circ$.

2 Data description and analysis

For analysis of sub-ionospheric VLF/LF perturbations caused by the Great Solar Eclipse we used measurements of ground-based UltraMSK receiving stations installed at the Chapman University, Orange, CA, the USA (CHA) and Birr, Ireland (BIR). These receivers have been developed by Dr James Brundell, University of Otago, New Zealand. They can simultaneously record both the phase and amplitude of MSK (Minimum Shift Key) modulated signals in the frequency range 10-50 kHz from several VLF/LF transmitters. MSK signals have fixed frequencies in a narrow band of 200 Hz around the main frequency with adequate phase stability. The receiver station consists of a VLF antenna with a pre-amplifier, GPS receiver with a GPS antenna for accurate signal timing, an analog-to-digital converter and a computer with specialised software. The receiver can record signals with time resolutions ranging from 50 msec to 60 sec. More details are available here: http://ultramsk.com/. For our purpose we use a sampling frequency of 20 sec. The locations of the receivers and transmitters are shown in Fig. 2. Three of them were used in the present study: NML (La Moure, North Dakota, USA), NPM (Pearl Harbor, Hawaii, USA), and NAU (Aguadu, Puerto Rico).

Unfortunately, during this solar eclipse, the most powerful transmitter (NAA, Cutler, Maine, frequency 24 kHz) was inactive. Additionally, we did not use the phase measurements of the NLK (24.8 kHz) and NAU (40.75 kHz) signals in CHA station because of unstable phase reception in this station. The NML and NLK signals were not received in Birr and NPM signals were too weak for reliable analysis.

Therefore we selected only three sub-ionospheric paths, namely NPM-CHA, NML-CHA and NAU-BIR (see Fig. 2). The location of transmitter-receiver pairs enabled us to monitor the region from Hawaii, through North America, and on to Puerto-Rico.

The results of the analysis are shown in Fig. 3-5. In comparison to our previous study (Solovieva et al., 2016) none of the signals received during the eclipse revealed any noticeable changes in the amplitude. Fig. 3 shows the amplitude and phase variations on August 21, 2017 (in red colour), and the monthly averaged values (in black colour). Small decrease (about 1 dB) of the NPM signal amplitude can be seen in Fig. 3. Note, the decrease in the amplitude is within the standard deviation of the signal for quiet days. For the two other paths the amplitudes of signals are rather noisy and it is impossible to identify any effects. Next we describe the results of the analysis on the three different paths, NPM-CHA, NML-CHA and NAU-BIR separately.

First we consider the NPM-CHA path which has an approximate length of about 4000 km and is in the region of 40-60% of obscuration (see Fig. 1). On this path the ob-
Figure 2. Relative positions of the receivers and transmitters together with the obscuration’s degree (the last information has been taken from: https://www.timeanddate.com/eclipse/solar/2017-august-21). The positions of the receivers in Birr, Ireland (BIR) and Orange, CA, the USA (CHA) are shown by green circles. The positions of transmitters NPM (21.4 kHz), NML (25.2 kHz) and NAU (40.75 kHz) are shown by red triangles.

Served partial phase of the total eclipse started at 15:46 UT. From Fig. 3 (bottom panel), it can be seen that just after 17:00 UT the eclipse reached the receiver (this period is shown by the grey rectangle along the time axis). At 18:00 UT (at the time of the solar X-ray flare of C3 class was registered by geostationary satellite the GOES 14) the whole path was sunlit. Both in the phase and amplitude of signal the effect of the solar flare is clearly visible. Thereafter, signal returns to its normal level. The maximum phase decrease in the NPM-CHA path was observed between 17:00 and 17:15 UT when practically the whole path was obscured and the phase deviated from its normal level by 33°.

The next wave path, MML-CHA, which is actually on the total eclipse path, has a length of about 2200 km. Results of the analysis for this particular path are shown in Fig. 4. The top panel corresponds to the measured X-ray flux detected by GOES 14 satellite in the wavelength range of 0.1-0.8 nm. The bottom panel shows phase variations on August 21, 2017 (red) and its monthly averaged values (black). It is important to note that the NML transmitter for this is located in the region of 80% obscuration and the CHA receiver is in the area of 60% of obscuration. For this path the eclipse reached the receiver and transmitter at 17:30 UT and 18:00 UT, respectively. The grey rectangle along the time axis marks this interval (see Fig. 4). The signal crossed the region of 90-100% obscuration at approximately 17:45-17:50 UT. This is at the same time as we can see the maximum drop in the phase of VLF signal. The recorded phase change is about −35° and it took only 20 minutes for a full phase recovery. The effect from the solar flare at 18 UT is not noticeable in this signal. The amplitude is oscillates chaotically. The oscillations are inside dispersion boundaries.

Finally we analyse the phase and amplitude changes along the NAU-BIR path (Fig. 5). This path has a length of about 6400 km and crosses the region with 90-100% obscuration. This rather long path has a sub-meridional orientation and it is obscured for a relatively short period of time, i.e. between 19:10 UT till 19:40 UT. The maximum decrease in the phase is observed during the maximum obscuration around 19:30 UT. The phase decrease of 95° is more than for the other two paths, NPM-CHA and MML-CHA. This could be related to the greater length of NAU-BIR path, the different orientation of the geomagnetic field or, most probably, the higher LF signal frequency. In this case the phase recovered about 1 hour after the signal dropping. The amplitude oscillates chaotically.
Figure 3. Results of the analysis for wave path NPM-CHA. Top panel shows X-ray flux measured with the GOES 14 satellite in the wavelength range of 0.1-0.8 nm. Middle panel shows the amplitude variations on August 21, 2017 (red) and its monthly averaged values (black). Bottom panel shows phase variations on August 21, 2017 (red) and its monthly averaged values (black). Grey rectangles along the time axes show period when a large part of the path has been obscured.

Figure 4. Results of the amplitude and phase analysis for wave path NML-CHA. Explanations are the same as in Fig. 3.
and, therefore, it is difficult to identify effects caused by the eclipse. The oscillations are inside dispersion boundaries.

It should be also mentioned that the magnetic activity was rather low during 21 August ($Dst < -20$ nT). Therefore, the observed anomalies in the VLF signals cannot be attributed or explained by influence of the geomagnetic environment.

Our explanation of the effect of the solar eclipse on phase of VLF/LF signals is as follows. It is known that ionisation of the ionosphere strongly depends on the solar activity. Ultraviolet (UV) and X-ray radiation dominate the ionisation processes during the day, but disappear above solar eclipse region. As a result, the ionisation of the D-region significantly decreases. This process leads to an increase of the effective reflection height of the ionosphere. As the transmitted signals propagate within the the Earth-ionosphere waveguide, the propagation paths of the VLF/LF signals increase in length and this is responsible for the observed phase delay of the sub-ionospheric signals. The phase delay due to an increase in reflection height can be determined as (Pant & Mahra, 1994):

$$\Delta \varphi = \frac{2\pi d}{\lambda} \left( \frac{1}{2a} + \frac{\lambda^2}{16h^3} \right) \Delta h$$

where $d$ is distance between transmitter and receiver in km, $\lambda$ is wavelength of signal in km, $a$ is radius of the Earth, $h$ is the reflection height and $\Delta h$ is increase in reflection height. From this it follows that the increase in reflection height is:

$$\Delta h = \frac{\Delta \varphi}{2\pi \frac{d}{\lambda} \left( \frac{1}{2a} + \frac{\lambda^2}{16h^3} \right)}$$

Using the obtained experimental values of $\Delta \varphi$ and by taking as $h = 70$ km, we found that, $\Delta h$ for path NPM-CHA was 2.67 km, for path NML-CHA it was $\approx 5.1$ km, and for path NAU-BIR the increase in reflection height was $\approx 3.4$ km. These results are in a good agreement with the data obtained previously by (S. S. De et al., 2011; K. B. De et al., 2011; Guha et al., 2010) for low latitudes.

3 Estimates of electron density change

Due to the relatively short lifetime of the ions in the lower ionosphere, a steady-state computation of the electron density provides an adequate description over a wide
range of conditions, so that electron density $N_e$ can be considered to be the result of an equilibrium between ion production rate, $q$, and effective electron loss. There exist two approaches regarding the electron loss in the D region, which we consider now, namely, the quadratic recombination law (Chernogor et al., 2019) and the linear recombination law (Belikovich et al., 2006). Introducing the ratio (eclipse obscuration) $S_1/S_0$, where $S_1$, $S_0$ are the shaded part of the Sun’s disk and the area of the Sun’s disk, respectively, one may estimate the ion production rate as $q_1 = q_0 (1 - S_1/S_0)$, where $q_1$, $q_0$ are the disturbed ionisation rate and the ionisation rate in the absence of an eclipse, respectively.

Therefore, in case of the quadratic recombination law $q = \alpha n^2$, where $n$ is the electron density, we obtain

$$\frac{n_1}{n_0} = \sqrt{\frac{\alpha_0}{\alpha_1} \left( 1 - \frac{S_1}{S_0} \right)}, \tag{3}$$

where $\alpha_0$, $\alpha_1$ are the recombination coefficient in the absence of an eclipse and disturbed recombination coefficient, and $n_0$, $n_1$ are the undisturbed and disturbed electron density, respectively. On the other hand, in case of the linear recombination law $q = \gamma n$, one obtains

$$\frac{n_1}{n_0} = \frac{\gamma_0}{\gamma_1} \left( 1 - \frac{S_1}{S_0} \right), \tag{4}$$

Now we use the calculated obscurations (https://eclipse.gsfc.nasa.gov/SEgoogle2001/SE2017Aug21Tgoogle.html) for the three different paths. For the path NML-CHA the ratio $S_1/S_0$ varies from 0.56 to 1, with an average value equal to 0.78. Putting in our estimates $\alpha_0 = \alpha_1$, $\gamma_0 \approx \gamma_1$ we obtain from equation 3 $n_1/n_0 \approx 0.47$ and from equation 4 $n_1/n_0 \approx 0.22$. This corresponds to $\Delta n/n_0 = 0.53$ in the former case and to $\Delta n/n_0 = 0.78$ in the latter case. Accordingly, the average decrease of the electron density along the path is 2.1 and 4.5 times.

Let’s estimate the electron density change during the eclipse in another way. For that we assume a linear profile of the electron density in the vicinity of the radio wave reflection height. This yields the following expression

$$\frac{\Delta n}{n_0} = \frac{n_1 - n_0}{n_0} = \frac{\Delta h}{H}, \tag{5}$$

where $\Delta h$ is the change of the reflection height due to the eclipse and $H$ is the characteristic scale of the electron density profile. The change in the reflection height can be determined from equation 2. For this path, using equation 2, $\Delta h \approx 5.1$ km with $H = 6.5$ km (Whitten & Poppoff, 1971) and equation 5 gives $\Delta n/n_0 = 0.78$. This corresponds well to our previous estimate with the linear recombination rate.

Likewise, assuming linear recombination rates for paths NPM-CHA and NAU-BIR the average $S_1/S_0$ ratio for these paths is 0.4 and 0.53, respectively. So, again using equation 4 we obtain $n_1/n_0 \approx 0.60$ for the first path which corresponds to $\Delta n/n_0 = 0.40$ and $n_1/n_0 \approx 0.47$ for the second path which corresponds to $\Delta n/n_0 = 0.53$.

On the other hand, we may estimate the quantity $\Delta n/n_0$ using equation 5. Taking calculated value $\Delta h$ for the path NPM-CHA as $\Delta h \approx 2.67$ km and for the path NAU-BIR as $\Delta h \approx 3.4$ km with $H = 6.5$ km we obtain from equation 5 that $\Delta n/n_0 = 0.41$, $\Delta n/n_0 = 0.53$ for these paths, respectively. These values are in good agreement with our previous estimates assuming a linear recombination rate.

4 Conclusions

In this work we present VLF/LF observations of the phase and amplitude of three sub-ionospheric wave paths during the total solar eclipse of August 21, 2017. The length of these paths varied from 2200 to 6400 km, signal frequencies were 21.4 kHz, 25.2 kHz
40.75 kHz and obscuration along the paths was different. Two sub-ionospheric paths crossed the total eclipse path and the third path was in the region of 40-60% of obscuration. We found that for all three paths there was no noticeable influence on amplitude, however the phase revealed a significant decrease during the eclipse. For the two signals transmitted from NPM and NML transmitters which both had frequencies close to 20 kHz the negative phase anomalies were $-33^\circ$ and $-35^\circ$ correspondingly, which is in good agreement with the experimental results, obtained by (Cohen et al., 2018) and (Moore & Burch, 2018) for the American paths. Note, the anomalies were lasted longer for the longer path. The strongest decrease in phase was found for the wave path NAU-BIR ($-95^\circ$). For the same path the time duration of anomalies also lasted the longest.

These results, again, confirm that the effect of solar eclipses are more distinct in the phase of VLF/LF signals (Kaufmann & Schaal, 1968; Hoy, 1969; Guha et al., 2010). Although previous works have reported very small ($\approx 1$ dB) amplitude variations during solar eclipses such variations in our measurements are invisible against background oscillations, i.e., they are comparable with measurement error.

It was also found that the effective reflection height of the ionosphere in low and middle latitudes increased by about 3-5 km during the eclipse. An estimation of the electron density change in the lower ionosphere during the eclipse was made using two different assumptions regarding the electron loss in the D region, i.e. the quadratic recombination law and the linear recombination law. The values obtained were in good agreement and showed that the average decrease was between 2.1 to 4.5 times.

Acknowledgments

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References


De, K. B., De, S. S., Bandypadhyay, B., Pal, P., Ali, R., Paul, S., & Goswami,


