Modeling of VLF network observations due to lower ionospheric perturbation during a solar eclipse

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Abstract

A large part of the path of the Annular Solar Eclipse of May $20, 2012$ ($magnitude$ 0.9439) (ASE-2012) was over southern Japan. The D-region ionospheric changes associated with the ASE-2012, led to several degree of observable perturbations of sub-ionospheric very low frequency (VLF) radio signal. The solar eclipse associated signal changes were identified in VLF several receiving stations (R_x) simultaneously for the VLF signals coming from both Japanese and US VLF transmitters (T_x). In this work, we have analyzed temporal dependences of VLF electric amplitude perturbation ($\Delta A_{ecl,obs}(t)$) from two Japanese VLF transmitters (JJI (22.2 kHz) and JJY (40.0 kHz)), and the spatio-temporal characteristics of respective subionospheric perturbations are studied in detail. We consider the 2-parameter D-region ionospheric model with the exponential electron density profile. To model the shadow effect on the D-region ionosphere due to obscuration of solar disk, we assume a generalized space-time dependent 2-Dimensional Elliptical Gaussian distribution Model (2DEGM) for ionospheric parameters, such as, effective reflection height (h') and sharpness factor (β). In the vicinity of the eclipse zone, we compute the subionospheric VLF signal propagation for several signal propagation paths. In the simulation, we obtain the perturbation of VLF signal amplitude ($\Delta A_{ecl,LWPC}(t)$) at each station and compare with its observtaional counterpart ($\Delta A_{ecl,obs}(t)$).

1 Introduction

Since the solar eclipse creates a shadow on the ionosphere and has been known to produce the local ionospheric disturbance. So it is an unique opportunity for studying a spatio-temporal response of the ionosphere with increasing and decreasing of solar radiation. That of the ASE-2012 was located within the dense VLF receiving network mostly over southern Japan. The solar eclipse provides an unique opportunity to study the local growth and decay of lower ionospheric charge density within measurable time-frame.

Here, a 2D-modeling of D-region perturbation during ASE-2012 has been done and most of the observed VLF amplitude perturbations were reproduced. We chose the LWPC code as a tool. We solved this problem of VLF-ionosphere interaction with LWPC and Wait's model of D-region. The effects of solar eclipse on the lower ionospheric physical characteristics and hence on the amplitude and phase of a subionospherically propagated VLF signal have been reported by a number of authors during last few decades. [3] presented the results of total solar eclipse (TSE) in Europe on 11th Aug 1999. They had five receiving stations which had observed several transmitters each, thus had altogether 17 different paths. Their path length varied from 90 km to $14,510$ km, but the majority was within ≤ 2000 km. The significant conclusion drown by them was for shorter signal propagation paths (≤ 2000 km), that the amplitude change was positive. But for path lengths $\geq 10,000$ km, the amplitude perturbation was negative. [3] explained them with LWPC analysis. The rise in ionospheric reflection heights (h') for short and medium paths are 8 km and 5 km respectively. In a recent paper, [2] used LWPC simulation [4] technique coupled with ion-chemistry model to reproduce both positive and negative VLF amplitude signals received at Kolkata and Malda stations (≥ 2000 km propagation paths).

In this paper, we interpret the observed VLF signal during ASE-2012 at 6 receiving stations by theoretical modeling of D-region ionosphere and we propose a modeling procedure using VLF network to determine the spatio-temporal characteristics of ASE-2012 induced D-region perturbation. We assumed a time dependent 2D-Elliptical Gaussian distribution Model (2DEGM) of D-region parameters. Using this model, we reproduced the VLF signal perturbation observed at a number of stations.

2 VLF observation of ASE-2012

The annular solar eclipse of May 20, 2012 started at 22:06 hrs from southern China and after crossing Japan, Northern Pacific, it terminated at 01:23 hrs near the coastlines of northern California. It was a 7000 km-long voyage lasting nearly 2 hrs. The point of greatest eclipse was at 23:52:47 hrs with a magnitude of 0.9439. The duration of annularity was 5 min 46 sec with shadow of 273 km, defined by antumbra. But, over Japan, zone of annular eclipse traversed over Japan between 22:00 and 23:00 hrs.

During ASE-2012, JJI-KCH, JJI-KSG, JJI-CHO, JJY-KCH, JJY-KSG and JJY-CHO propagation paths were well within annularity region. The JJI-TYM and JJY-TYM paths were just outside the annularity, that region but within the penumbra. Only MSR and NSB stations were a bit far away from penumbra, but the maximum obscuration for these stations was $75-80\%$ (according to *www.xjubier.free.fr*). Since the electron and ion-concentration in the eclipse affected part during ASE-2012 has been reduced, the anomalous effects of the ionosphere above Japan was significant then.

The objective of this paper is to simulate and reproduce the observed VLF anomalies and hence to determine the degree of D-region anomalies during ASE-2012 in partial absence of solar ionizing radiation. day for JJI and JJY signals respectively. We took the average values of the VLF amplitude for the same UT for two days before eclipse day, i.e. 18th and 19th May 2012. The geomagnetic activity parameter (K_p-index) of middle latitude region on 18th and 19th May 2012 were around 1 and 2. So, it is safe to assume that-those days can be used as those for the quiet days without effect from the eclipse. There are two different types of temporal dependences of the amplitude during the eclipse. For six transmitter-receiver paths, we found a positive change in the VLF signal amplitude, i.e. the signal amplitude increases during the solar eclipse time period over Japan (JJI-NSB, JJI-MSR, JJI-CHO, JJI-KSG, JJY-NSB and JJY-KSG), while in other four paths indicate negative changes (JJI-TYM, JJY-MSR, JJY-TYM, JJY-KCH) ([5], [1]). It is a notable point that half of the received signals from JJI transmitter show positive changes mostly, but those from JJY transmitters indicate negative changes. The differential amplitudes the data are plotted in Figs. 1. Generally, it is observed that for the paths ≥ 1500 km the perturbations are $\sim +2$ dB, but for the paths ≤ 800 km, it is large like several dBs. Especially, the $\Delta A_{ecl,obs}|_{max,JJY}$ goes from +24 dB to -11.0 dB, while the $\Delta A_{ecl,obs}|_{max,JJI}$ varies only within +6.2 dB and -2.5 dB.

3 Modeling methodology

We are dealing with VLF-ionosphere interaction process, the electron density (N_e) and electron-neutral collision frequency (ν_e) profiles of D-region will play the only crucial role. So, in this case, Wait's 2-component exponential ionospheric model [7] is capable to represent it, because it is related with 'N_e' and 'ν_e'. This model is represented by 2 parameters, namely, the effective reflection height (h') and conductivity or sharpness factor (β). They eventually relate the D-region electron density and electron-neutral collision frequency altitude profile by these following equations, namely,

$$N_e(h,h',\beta) \sim e^{0.15h'} e^{(\beta-0.15)(h-h')}, \quad (1)$$

in m^{-3} and

$$\nu_e(h) = 1.816 \times 10^{11} \times e^{-0.15h}, \quad (2)$$

in sec^{-1}. In this work, we connect the variation of h' and β to the VLF signal modulation. During an eclipse, due to the shadowing of the ionosphere for solar disk obscuration, gradual fall and rise of effective electron density take place. This results subsequent changes in h' and β, and hence it leads to VLF amplitude and phase modulation.

In this paper, we go through a multi-step modeling process. First, we construct a time-dependent 2D-Elliptical Gaussian Model (2DEGM) for h' and β parameters to represent the perturbation of the ionosphere within penumbra. The ellipticity has been taken into account by keeping the original shadow nature over the earth surface in mind. In the next step, we calculate the h' and β profile along each cross-section of 2DEGM along $T_x - R_x$-propagation path. Now, this h' and β-profile is being supplied to LWPC code for computation of respective VLF signal profile. This procedure is being repeated for all the timing within ASE-2012 duration to obtain the temporal signal profile of VLF the receiving point.

According to [6], the first level approximation of 'linear relationship' between h'_{ecl} and β_{ecl}, and the obscuration effect works well for VLF-ionosphere interaction modeling. Therefore, one can obtain the anomaly in h'_{ecl} and β_{ecl} during eclipse by simply summing up the respective perturbed values with logically defined unperturbed values. Here, we model the perturbation of $h'_{ecl}(lon,lat,t)$ and $\beta_{ecl}(lon,lat,t)$ using time-dependent 2-Dimensional Elliptical Gaussian distribution Model (2DEGM). Because, the shape of penumbral and antumbral shadow on the spherical earth surface in nearly elliptical in nature.

We choose the daytime ionosphere according to [4, 8, 1], i.e., $h'_d = 74$ km and $\beta_d = 0.3$ km^{-1}. For the night-time ionosphere, we choose, $h'_n = 87$ km, and the β_n is 0.3 km^{-1} and 0.8 km^{-1} for $10kHz$ and $60kHz$ frequencies of incoming VLF signals respectively. Moreover, we can model the ionospheric electron density ($N_{e,ecl}(lon,lat,h,t)$) and electron-neutral collision frequency ($\nu_e(h)$) perturbations using eqns, (1) and (2). Our objective is to calculate the $[h',\beta]_{ecl}(gcp,t)$ profile along a given signal propagation path (GCP) from transmitter to receiver. For doing this, we divide the entire path into justified number of segments (of equal width).

We use the Long Wave Propagation Capability (LWPC) code to calculate the VLF amplitude at receiving site corresponding to normal and partially eclipsed ionospheric conditions. In this work, we use 'RANGE' model. Here, we can use different ionospheric parameters at different points on the path. Two different substrings are used to fed input in this model. Obviously, we use the 'EXPONENTIAL' substring, where the ionospheric boundary conditions are given in the form of $h'(gcp)$ and $\beta(gcp)$, i.e., as a function of GCP from transmitter to receiver. Here, we supply $[h',\beta]_{ecl}(gcp,t)$, for a given time 't', to LWPC, and it calculates the respective VLF amplitude and phase profile along

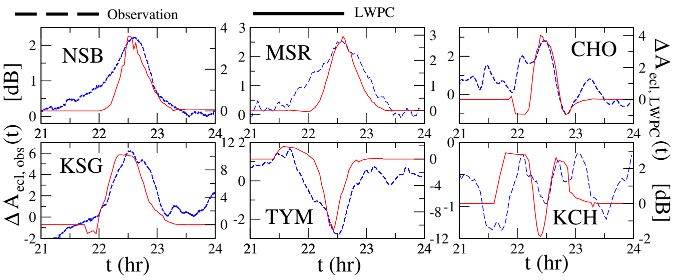

Figure 1. The differential VLF amplitude, observed ($\Delta A_{ecl,obs}(t)$) (dashed blue line) and LWPC computed ($\Delta A_{ecl,LWPC}(t)$) (solid red line) at the UEC-VLF receiving stations for JJI during ASE-2012.

GCP from transmitter to receiver. Now, we pick up the value of amplitude corresponding to receiver location. By repeating this process for all available time instants within the duration of ASE-2012, we construct the temporal VLF amplitude profile ($A_{ecl,LWPC}(t)$) at a receiver location.

The $[h', \beta]_{ecl}(gcp, t)$ is controlled by a number of parameters introduced in the earlier sections, namely, scale factor (s_f), $\theta(t)$, $\sigma_{lon,lat}$, and $[lon, lat]_0(t)$. At this step of simulation, we take values of $[lon, lat]_0(t)$ from 'central line latitude and longitude' data of ASE-2012. Next, we compute the $\theta(t)$ from 'northern (and southern) limit latitude and longitude' data provided by '*eclipse.gfsc.nasa.gov*'. Now, to obtain an optimum agreement with the observed differential VLF amplitude ($\Delta A_{ecl,obs}(t)$), we repeatedly run the entire procedure of reproducing VLF amplitude ($A_{ecl,LWPC}(t)$) described above, for six receiving stations (and two transmitters), by choosing several sets of the remaining free parameters, namely, s_f and $\sigma_{lon,lat}$. The normal unperturbed VLF amplitude ($A_{normal,LWPC}(t)$) has been calculated by same mechanism but setting, '$s_f = 0$'. Now, we obtain the differential VLF amplitude as,

$$\Delta A_{ecl,LWPC}(t) = A_{ecl,LWPC}(t) - A_{normal,LWPC}(t). \qquad (3)$$

Finally, the optimum agreement between $\Delta A_{ecl,obs}(t)$ and $\Delta A_{ecl,LWPC}(t)$ has been found for $\sigma_{lat} = 9°$ and $\sigma_{lon} = 16°$, for both the transmitter data. But the 's_f' values we found, were 0.4 and 0.25 for JJI/22.2kHz and JJY/40.0kHz respectively. The results for JJI/22.2kHz are given in Fig. 1.

4 Results

The multi-parametric nature of VLF-propagation makes it difficult to reproduce the exact signal variation during a regular extra-terrestrial event like ASE-2012. But, it was proved at several occasions of short and long propagation path analysis, that 2-component exponential ionospheric model, which is simplified and at the same time approximated, works well [3]. In Fig.1, the differential amplitude of VLF signal, both observation and simulations are shown.

Hence for $\sigma_{lon,lat} = 16°, 9°$ and $s_f = 0.4^{JJI}, 0.25^{JJY}$, we obtained the results of the Fig.1 for JJI/22.2kHz. The 'maximum perturbation' for $[h', \beta]_{ecl}(lon, lat, t)$ for JJI is found to be, $h'_{ecl,JJI,max} = h'_d + s_{f,JJI} \times \Delta h'_{max} = 79.2$ km and $\beta_{ecl,JJI,max} = \beta_d + s_{f,JJI} \times \Delta\beta_{max} = 0.349$ km^{-1}, because, for $f_{VLF} = 22.2kHz$, the $\Delta\beta_{max} = 0.122$ km^{-1} [4]. Now, the maximum of $[h', \beta]_{ecl}(lon, lat, t)$ for JJY are, $h'_{ecl,JJY,max} = h'_d + s_{f,JJY} \times \Delta h'_{max} = 77.25$ km and $\beta_{ecl,JJY,max} = \beta_d + s_{f,JJY} \times \Delta\beta_{max} = 0.375$ km^{-1}, because for $f_{VLF} = 40.0kHz$, the $\Delta\beta_{max} = 0.30$ km^{-1}.

The results are quite convincing, as both the '+ve' and '-ve' anomalies are the natural outcomes of our simulation, which also go with observations (see, Fig.1). In Fig.1, total six propagation paths from JJI are included. For NSB, the $\Delta A_{ecl,LWPC}|_{max} = +3.5$ dB and $\Delta A_{ecl,obs}|_{max} = +2.3$ dB. For MSR, there is even better agreement, i.e., $\Delta A_{ecl,LWPC}|_{max} = +3$ dB and $\Delta A_{ecl,obs}|_{max} = +2.8$ dB. The TYM-JJI is a comparatively shorter path, but the negativity of the anomaly has nicely been reproduced, though the $\Delta A_{ecl,LWPC}|_{max} = -10.0$ dB and $\Delta A_{ecl,obs}|_{max} = -2.7$ dB. The presence of dominant ground wave effect and limitation of 2DEGM over shorter path may be the possible reasons for this mismatch. The JJI-KSG path is nearly parallel to the ASE-2012 trajectory. So, the relative anomaly time of KSG is a bit longer. Hence, the 'blunt peak' was observed there and justifiably reproduced by our simulation. In this case, the $\Delta A_{ecl,LWPC}|_{max} = +9.1$ dB and $\Delta A_{ecl,obs}|_{max} = +6.2$ dB respectively. The CHO data is a bit noisy with low SNR. So, its comparison with simulation is tough. But, during simulation, we found a nice sharp '+ve' anomaly with $\Delta A_{ecl,LWPC}|_{max} = +4.1$ dB. Its interesting to note that, this modeling mechanism, we are discussing here, can be used to investigate the VLF anomalies, where, the observational data is absent due to unavoidable reasons. Now, on the other hand, for KCH, the $\Delta A_{ecl,LWPC}|_{max} = -2$ dB. There, the data is noisy, but overall, we see a negative tendency in $\Delta A_{ecl,obs}$. Interestingly, we see '-ve' VLF amplitude changes for the KCH and TYM paths, where, both the JJI-KCH and JJI-TYM paths are the shortest possible paths, and well within annularity domain. Though for a different eclipse, [3] has shown the same '-ve' anomaly for shorter paths like, GBZ-Cambridge, FTA2-Cambridge etc. The '+ve' VLF anomalies in DHO-Saint Wolfgang, FTA2-Saint Wolfgang, FTA2-Saint Ives etc. are shown here in this medium paths, which support our results too ([1]).

5 Conclusions

In this paper, we have modeled the effects of the annular solar eclipse of May 20th 2012 (ASE-2012), using VLF-ionosphere interaction. We choose total twelve propagation paths of UEC-VLF network. It consists of six receiving stations and two VLF transmitters, namely, JJI/22.2kHz and JJY/40.0kHz. The receiving stations are distributed along the length and breadth of Japan. We noticed the observed VLF-anomalies from a dozen of receiving stations that, there is no linear correspondence of it with the degree of solar obscuration over the respective path. Both '+ve' and '-ve' types of VLF amplitude anomalies are observed, depending on the distance and 'geographical bearing angle' at the receiving site from the transmitter. Roughly, we can conclude that, we observed '+ve' VLF anomaly for the paths $\geq$ 1000 km paths and mixed reactions for rest of the paths (Fig.1).

We modeled the $[h', \beta]_{ecl}(lon, lat, t)$ parameters of 2-component exponential Wait's lower ionospheric model [7] according to the elliptical nature of the penumbral shadow of ASE-2012. For the first part of analysis, we took $\theta(t)$ and $[lon, lat]_0(t)$ from '*eclipse.gfsc.nasa.gov*' and we compute the $[h', \beta]_{ecl}(gcp, t)$ for each propagation path. Now, with the help of LWPC, we compute temporal profile of $\Delta A_{ecl,LWPC}(t)$, and compare them with their observational counterpart ($\Delta A_{ecl,obs}(t)$). We noticed significant agreements for JJI-NSB, JJI-MSR, JJI-KSG, JJI-TYM, JJY-NSB, JJY-MSR, JJY-KSG and JJY-TYM (Figs. 1) ([1]).

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