# Study of mid-latitude lower ionospheric D-region electron density and response time delay during solar flares using numerical method

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The impinging solar irradiation causes changes in electron and ion densities in the ionosphere. The rate of ionization in D-region ionosphere during a solar flare is governed by the 'electron continuity equation'. In Chakraborty et al. (2022) and Chakraborty and Basak (2020), we numerically solve the 'electron continuity equation' for computation of D-region electron density ($N_e(t)$) at a particular time '$t$'. We analyze the solar irradiance in the form of soft x-ray profile observed by GOES-15 satellite. Solar zenith angle profile $(\chi(t))$ plays a very important role in this variation. In our direct method of study, the D-region ionospheric perturbations, we use $(\chi(t))$ to study the latitudinal, longitudinal and seasonal variation of $N_e(t)$. Keeping in mind the limitations of 'electron continuity equation', we restrict our computations in mid-latitude region only. Further, the response of ionosphere to the incoming solar irradiation is not instantaneous, rather, there is always a significant amount of time delay. We define the D-region response time delay ($\Delta t$) as the time gap between times of maximum solar flare flux ($\phi_{max}$) and maximum electron density ($N_{e,max}$). We report a significant latitude, longitude and seasonal dependency in $N_e(t)$ and $\Delta t$ in Chakraborty and Basak (2020). We check the seasonal dependency of $\Delta t$ for three different classes of solar flares assuming the flares to be occurred repeatedly every day at the same time.

Sub-ionospheric radio signal propagation is another well-established method and widely used to study the ionospheric perturbations during a solar flare. Basak and Chakrabarti (2013) reported, from their VLF observation of $\Delta t$, that $\Delta t$ has a nature of decreasing with $\phi_{max}$. They did this analysis for a very limited number of solar flares. In order to investigate this phenomenon in depth, we chose a large set of solar flares from all three different classes, occurred almost during same time of years (Jan-Feb) and computed their respective $\Delta t$ values by the method mentioned in Chakraborty and Basak (2020) and Chakraborty et al. (2022). We chose six different latitudes over the mid-latitudinal region to perform the analysis. We report that although the observation of $\Delta t$ decreasing with $\phi_{max}$ is true, the $\Delta t$ -$\phi_{max}$ profile is dispersed rather than a fixed trajectory over each of the six chosen latitudes. In order to quantify the dispersed nature of $\Delta t$ -$\phi_{max}$ profile and its latitude dependence, we did a statistical analysis by introducing different other parameters such as RMS value of $\Delta t$, gradient of the slope ($m$) of the linear fitting on $\Delta t$ –$log_{10}\phi_{max}$ profile, latitudinal difference in $\Delta t$ for a set of latitudes, and RMS value of latitudinal difference in $\Delta t$. Finally, we make comparative remarks on $N_e(t)$ and $\Delta t$analysis by these two methods.

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