A Study of Solar Flare Effects on Mid and High Latitude Radio Wave Propagation using SuperDARN

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Overview

A. *Over the Horizon (OTH) communication is strongly dependent on the state of the ionosphere, which is fragile to solar X-ray flares.*

B. *Signal properties of Super Dual Auroral Radar Network (SuperDARN) is altered (strongly attenuated and changes apparent phase) during solar flares, commonly known as Short-Wave Fadeout or SWF. Riometers also see sudden enhancement in cosmic noise absorption.*

C. *During an SWF the number of SuperDARN ground-scatter echoes drops suddenly followed by an apparent increase in Doppler velocity (also known as "Doppler Flash" reaches up to few hundreds of ms^{-1}), often to near zero, reflecting disruption.[Refer Figure-1]*

D. *Simple models (DRAP) are unable to completely describe the absorption (SWF) and velocity enhancement (SFD) processes.*

E. *Study tries to propose a relatively newer model to estimate the frequency anomaly (sudden Doppler velocity enhancement) that can be seen in the SuperDARN data prior to the signal loss.*

Open Questions

❑ ***How does an increase in ionization impacts HF propagation?***

❑ ***What is the spatial variation of the Doppler Flash across the different ionospheric regions (D, E, and F)?***

Significance

❑ Insights to the ionospheric properties and their variability during solar flares. Better predict the HF blackout and recovery phases following a solar flare.

❑ Understand physics behind relatively less studied Doppler flash feature. This also provides a different perspective to understand initial ionospheric response to a flare driven event.

Event Study

❑ Figure-1 shows one typical solar flare (GOES X-ray measurement) and its effects seen in SuperDARN and riometer observations.

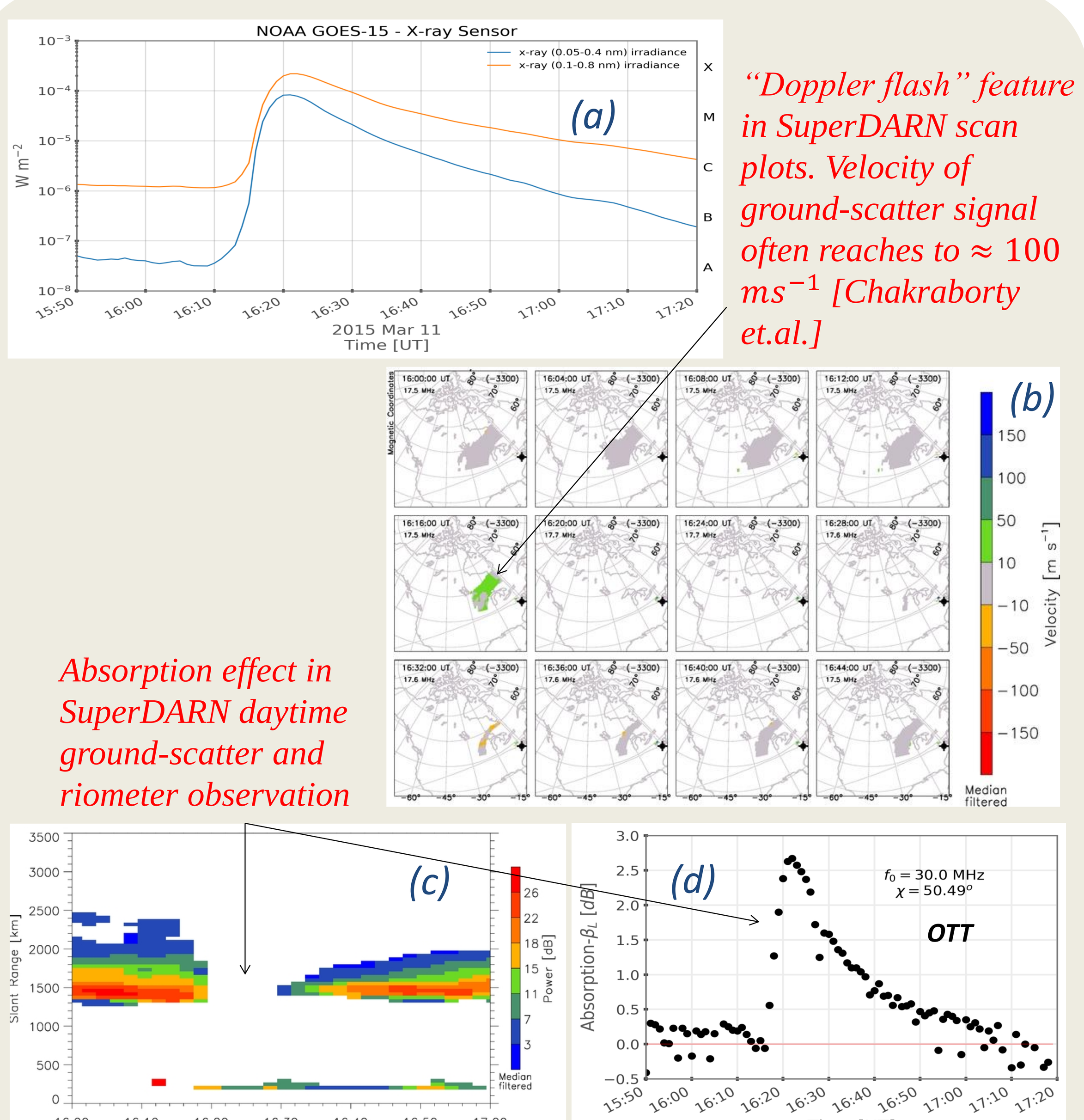


Figure 1: Typical solar flare event and its impacts on various HF systems: (a) GOES-15 X-ray sensor data, (b) FoV Doppler velocity scan plots for m SuperDARN Blackstone radar, (c) SuperDARN (Blackstone, beam 7) received power response during solar flare, (d) riomer (Ottowa station) response (HF absorption) to the solar flare.

HF Absorption & Doppler Theory

❑ HF absorption occurs due to the collision of electrons and atoms with the neural atoms. Flare enhanced ionization in the lower (D & E regions) ionosphere leads to enhancement in HF absorption [Davies 1990, Zawdie et. al. 2017].

❑ Doppler phase shift is mainly caused due to change in phase path length. Phase path length changes due to two reasons as described in Kikuchi et. al.[1986] First, enhancement in D-region ionization (thickening) and the second is lowering the F-region lower boundary.

❑ Watanabe et. al.[2013] empirically showed that enhancement in D-region ionization is the major driving criteria among these two. Figure-2 illustrates how these two factor alters phase path length.

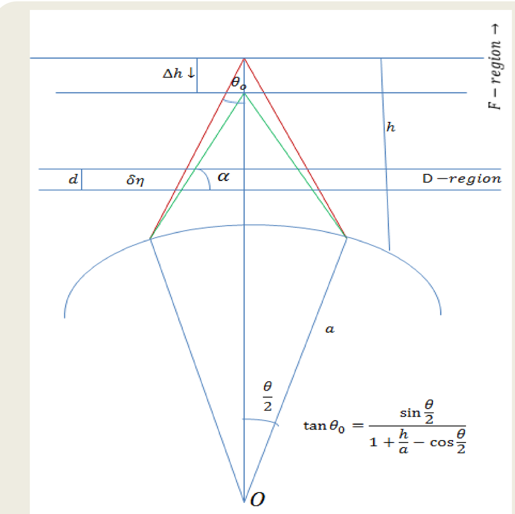


Figure 2: Schematic diagram showing spatial distribution of Doppler flash phenomenon (D versus F-region).

❑ Appleton-Hartree equations for absorption (1) and Doppler shift(2) due to flare impact: [Kikuchi et. al. 1986] is described as.

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y^2\sin^2\theta}{2(1-X-iZ)} \pm \frac{1}{1-X-iZ}\left[\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1-X-iZ)^2\right]^{\frac{1}{2}}} \ldots (1)$$

$$X = \frac{\omega_0^2}{\omega^2}, Y = \frac{\omega_H}{\omega}, Z = \frac{\nu}{\omega}, \omega_0 = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}}, \omega_H = \frac{B_0 e}{m_e}, \theta \rightarrow \text{angle between } \vec{b_0} \text{ and } \vec{k}$$

$$\Delta f = -\frac{2f}{c}.\frac{E}{B_o}\cos I\cos\Phi_0 + \frac{k}{cf}.\frac{dN_e}{dt}d\sec\alpha \ldots (2); d \rightarrow D \text{ region thickness}, I \rightarrow \text{dip angle}, \Phi_0 \rightarrow \text{incident angle between wave and normal to F region.}$$

Model Description

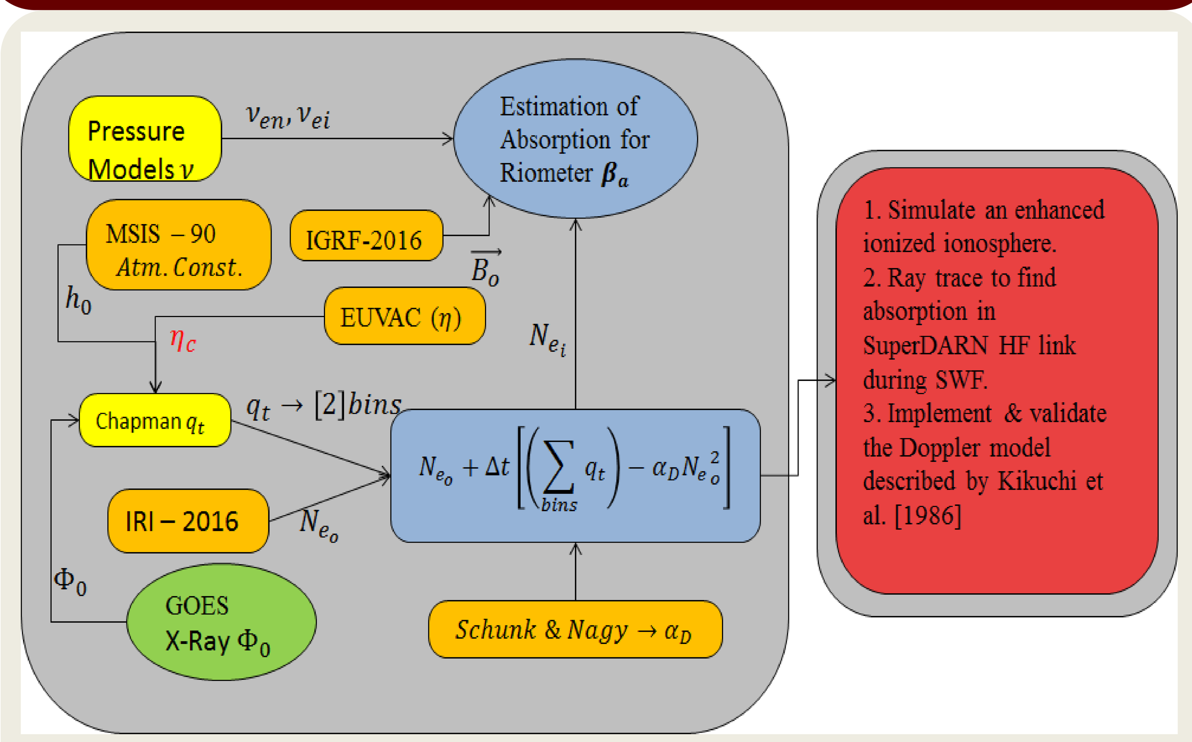


Figure 3: Flow diagram of the physical model. This model estimates electron density N_e, with the help of some well known physics and semi empirical models . Then it estimates absorption from Appleton-Hartree dispersion relation, and lastly uses same electron density to estimate Doppler frequency shift and compares the impacts of D-region thickening versus F-region lowering on Doppler effect, using raytracing.

The model prediction is validated by comparing with riometer absorption data and the methods described by Zawdie et al., [2017]

Model Assumptions

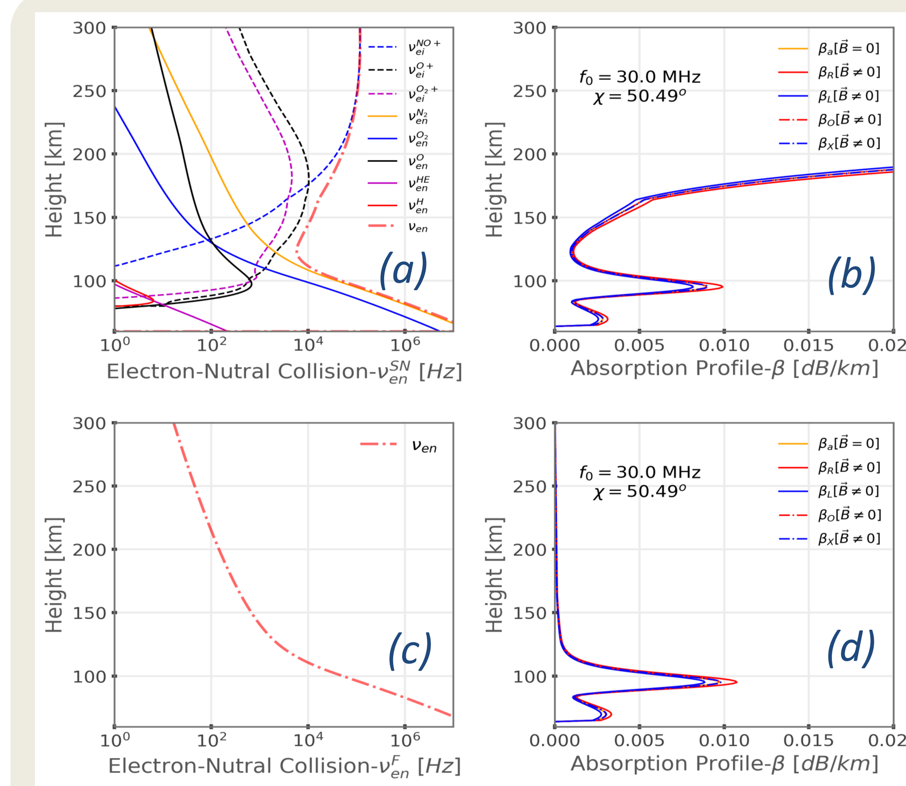
❑ IRI-2016 as a background ionization and IGRF-2016 as background magnetic field, and Model takes input from Friedrich-Torkar collision frequency.

❑ Intrinsic temperature and electron ion recombination rate is approximately constant.

❑ Model considers first two frequency bins (X-ray) of the EUVAC model as solar flux.

❑ Chapman ionospheric profile and no grazing angle effect.

Simulation Results



Output of the model, shows how absorption height profile changes with different collisions: (a)-(b) Schunk & Nagy collision over estimates the absorption while (c)-(d) Friedrich-Tonkar collision estimates provides more realistic values.

Figure 4: Collision-height and absorption height profile. Sample output from the simulation during an unperturbed ionosphere, considering Schunk and Nagy collision frequency and Friedrich-Torkar collision frequency.

Figure-5 shows model validation against Zawdie et. al.[2017] (unperturbed ionosphere) – Comparison of absorption <u>[magenta line in panel (c) versus blue dash dot line in panel (a)]</u> height profile for a vertically incident X mode, 5 MHz signal. The simulation time is 23 March 2010 at 8 UT and the transmitter is located at $28^0, 0^0$. The absorption height profile of X-mode wave matches till 150 km. Only difference is the reflection height, and as per the IRI-2016 model plasma frequency at160km is the 5MHz, which is the reflection point of a O-mode wave.

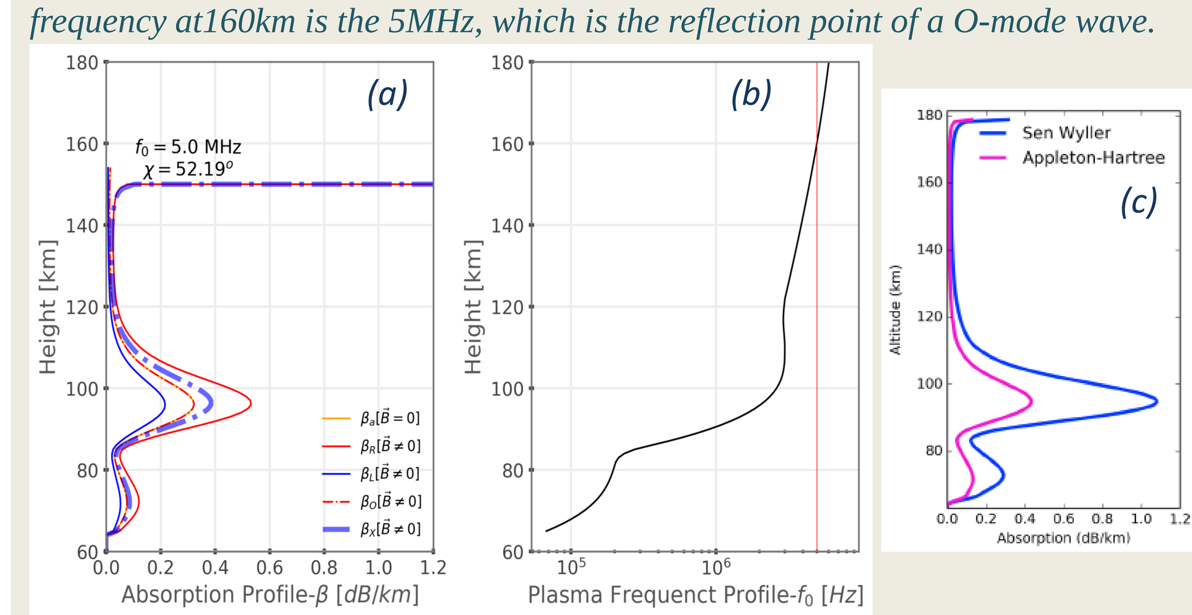


Figure 5: Comparison of proposed model output with the output described at Zawdie et. al.[2017] : (a) absorption height profile from the proposed model, (b) plasma frequency height profile from IRI-2016, (c) absorption height profile from the Zawdie et. al.[2017]

Figure shows time evolution of electron density profile at different height and height integrated modeled absorption versus riometer absorption data. <u>There is a time delay (Δt ≈ 90s) between modeled and riometer observation, which is sluggishness of the ionosphere (ionospheric response time to solar flare)</u>.

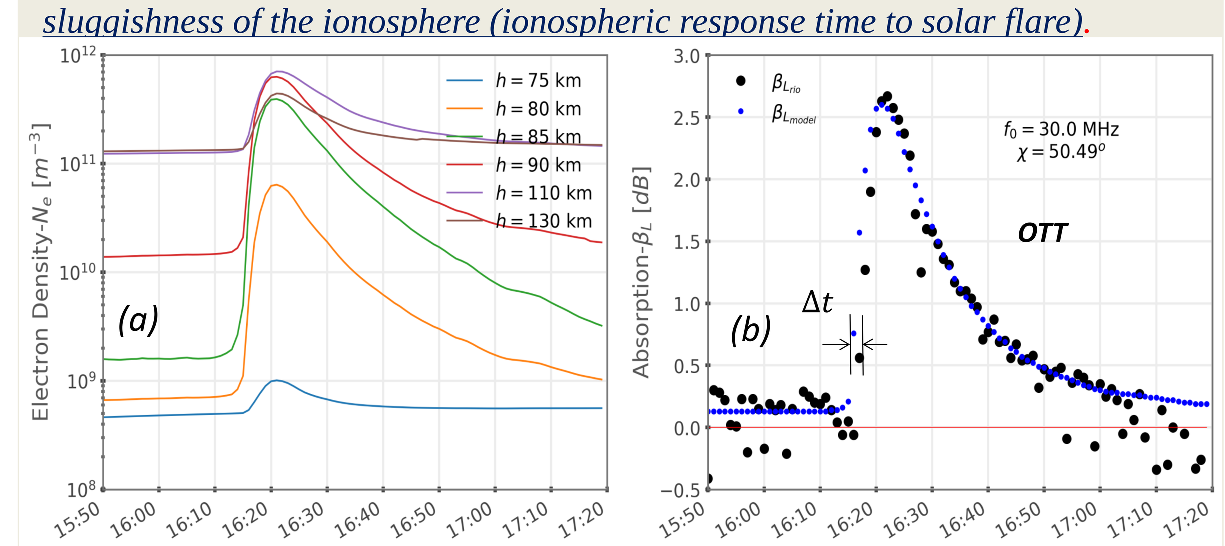


Figure 6: Comparison of modeled output versus riometer data: (a) time evolution of electron density at different altitude; (b) riometer (Ottowa station) absorption data versus model absorption data.

Simulation Results(cont.)

Figure-7 shows how enhancement in lower ionospheric (D-region & lower E-region) electron densities and F-region thickening introduce sudden change in Doppler velocity in the SuperDARN ground-scatter band. Panels (a)-(c) present Blackstone radar (SuperDARN) beam-7 ray-trace through N_e distribution for quite time and flare time conditions and panels (b)-(d) present Doppler frequency distribution along the ray path. <u>Observations:</u> Model shows D and lower E region electron density is the major driver for Doppler velocity enhancement. But note that we only consider X-ray bins of solar flux to estimate electron density. <u>Estimated line-of-sight Doppler velocity during the normal ionospheric conditions is $-2.21ms^{-1}$ but enhanced up to $178.96\ ms^{-1}$.</u>

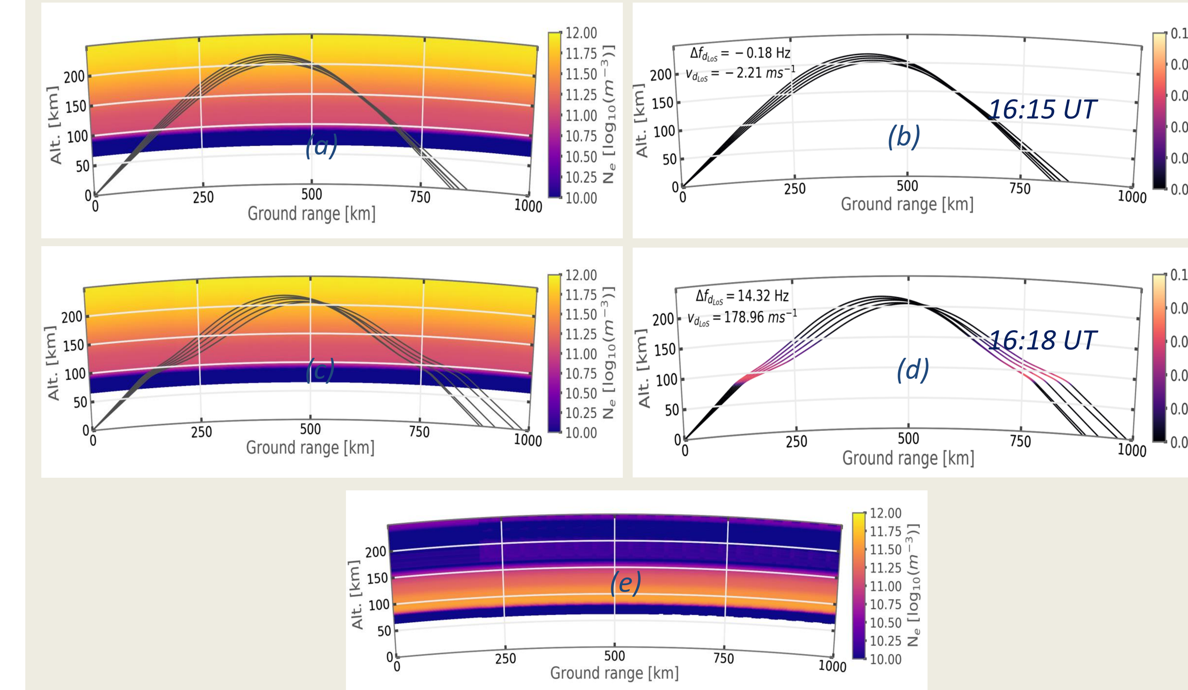


Figure 7: Electron density [panels: (a),(c)], line-of-sight Doppler frequency (velocity) [panels: (b),(d)] and different in electron density [panel (e)] plots. Outputs from the Doppler model [described by Kikuchi et. al. 1986] shows two different conditions: (a)-(b) pre-flare 16:15UT, (c)-(d) flare 16:18 UT conditions and (e) difference in electron densities.

Conclusions

❑ D and lower E region is losses dominates even in normal conditions.

❑ There is a significant time delay between solar flux heating the ionosphere and ionospheric response to it $\Delta t \approx 90\ sec$ (sluggishness time of relaxation of the ionosphere). <u>It is the physical delay due to recombination or attachment.</u>

❑ <u>Solar X-ray flux is the main source of absorption [drives lower ionospheric N_e enhancement], and also source for Doppler frequency shift in lower ionosphere</u>. Solar EUV flux is the source of F-region dynamics. [Yet to be implemented]

Future Work

❑ Detailed analysis of the Doppler velocity distribution along the ray-path is yet to be done (F-region analysis). Introduce lower frequency (EUV) solar flux bins to incorporate F-region dynamics into the model.

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