Observations and Modeling Studies of the Effects of the 2017 Solar Eclipse on SuperDARN HF Propagation

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2017 Total Solar Eclipse

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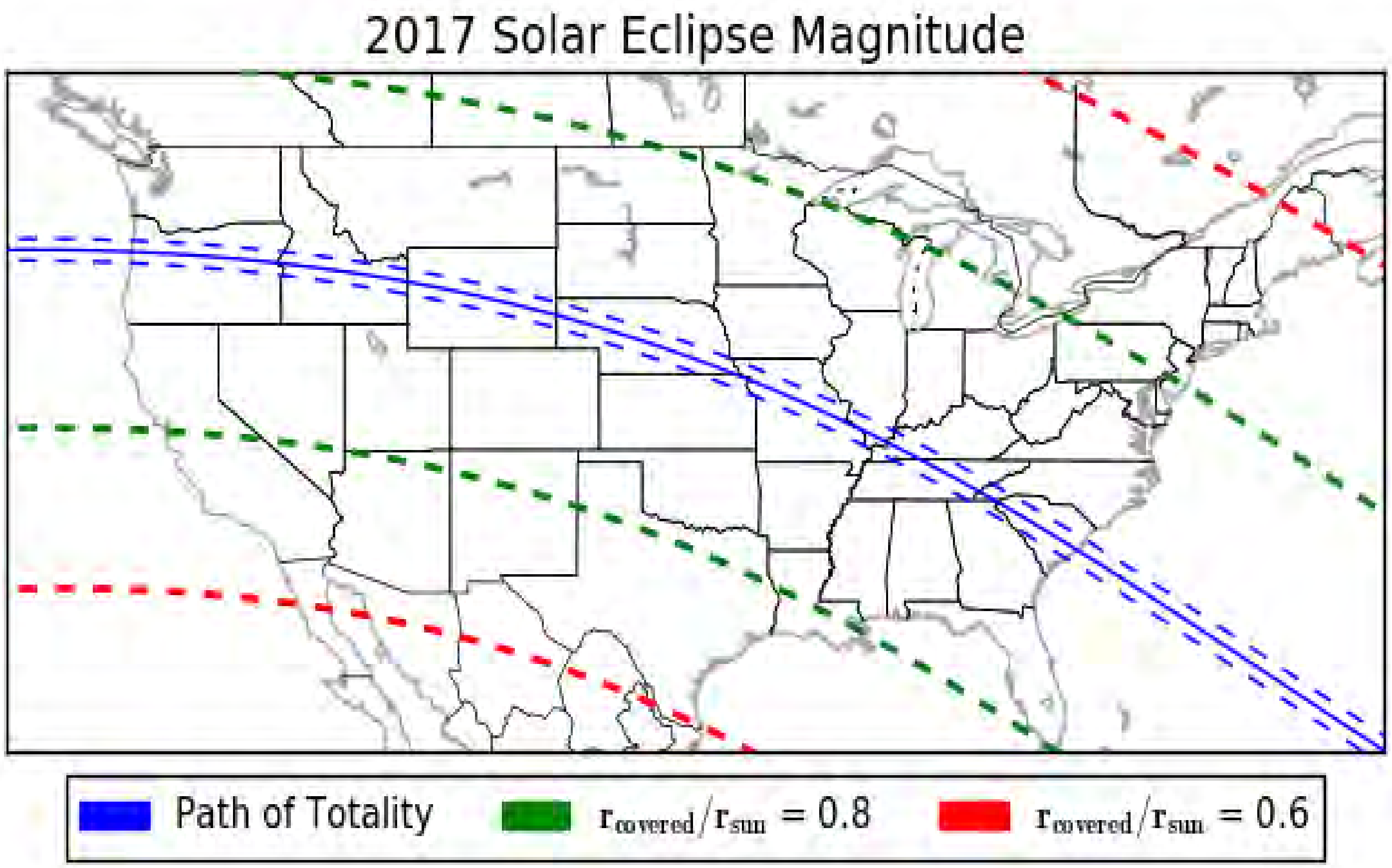

(Data from [Jubier, 2005]).

Differences between Eclipse and Sunrise/Sunset

→ West-to-East motion

→ Corona remains visible

→ Duration of totality short

→ Slow eclipse onset

Expected Eclipse Effects

- At low altitudes the recombination rate is high, so the plasma in the ionosphere will disappear quickly.
- At higher altitudes the plasma will never completely disappear.
- Plasma motion will play an important role in the evolution of the F layer during the eclipse.
- The artificial nighttime produced by the eclipse will change radio propagation through the eclipse region.
  - Specifically, this presentation focuses on the eclipse impact observed by Super Dual Auroral Radar Network (SuperDARN) radars.

Overview of SuperDARN

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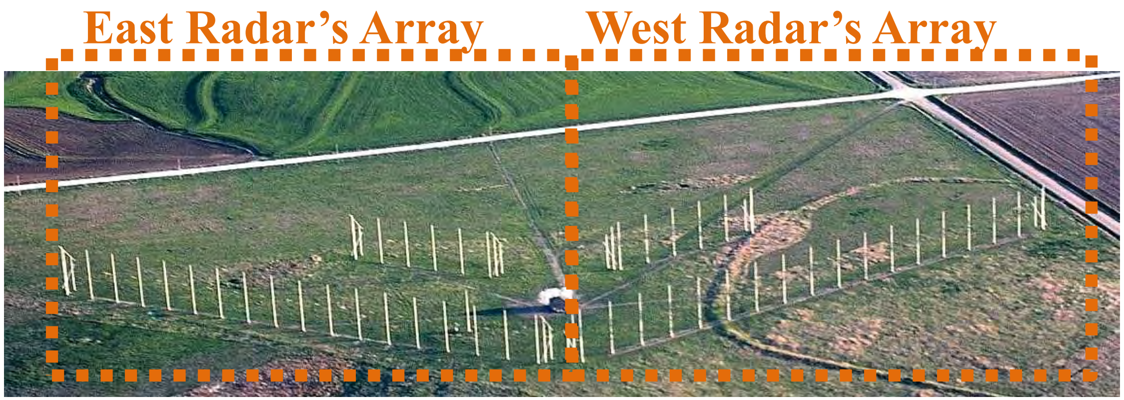
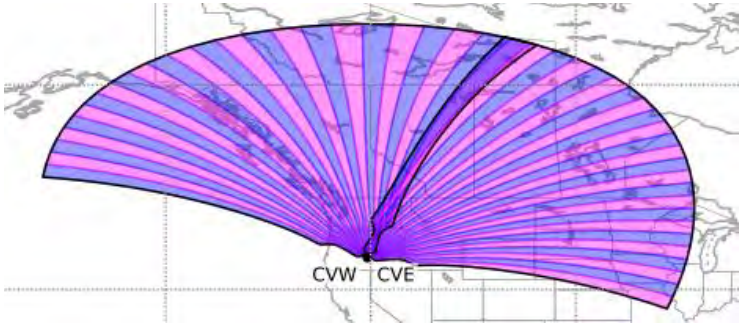
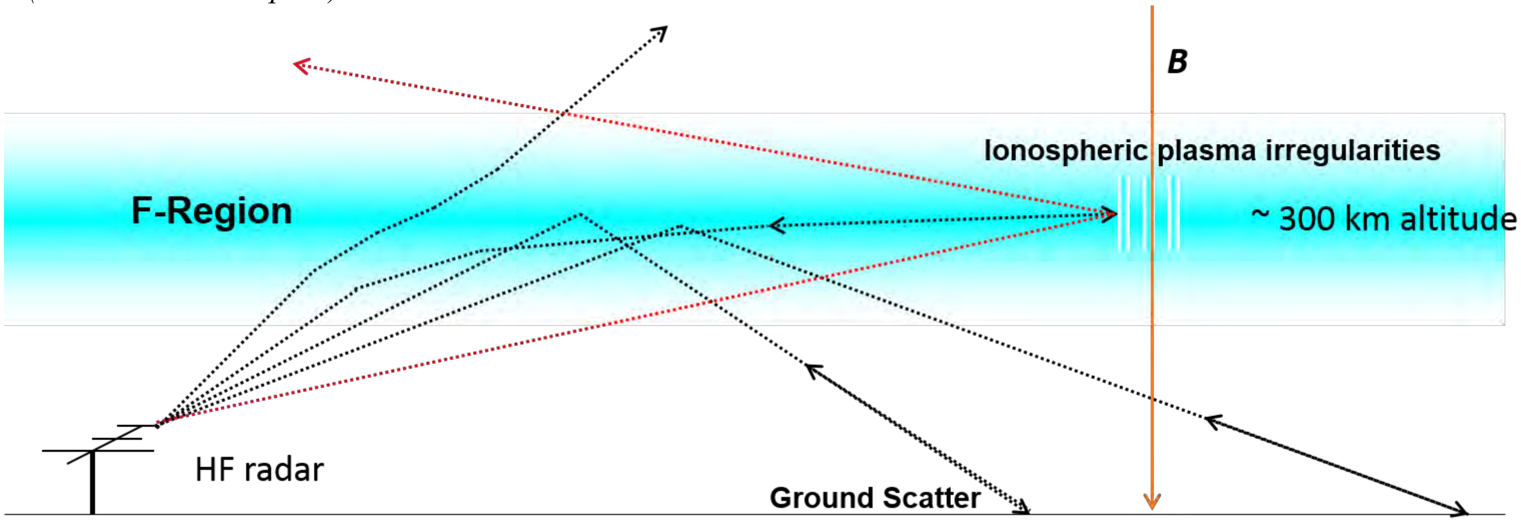


Fort Hayes Radars' (Credit: Simon Shepard)





(From [Ruohoniemi, 2012])

SuperDARN Eclipse Experiment

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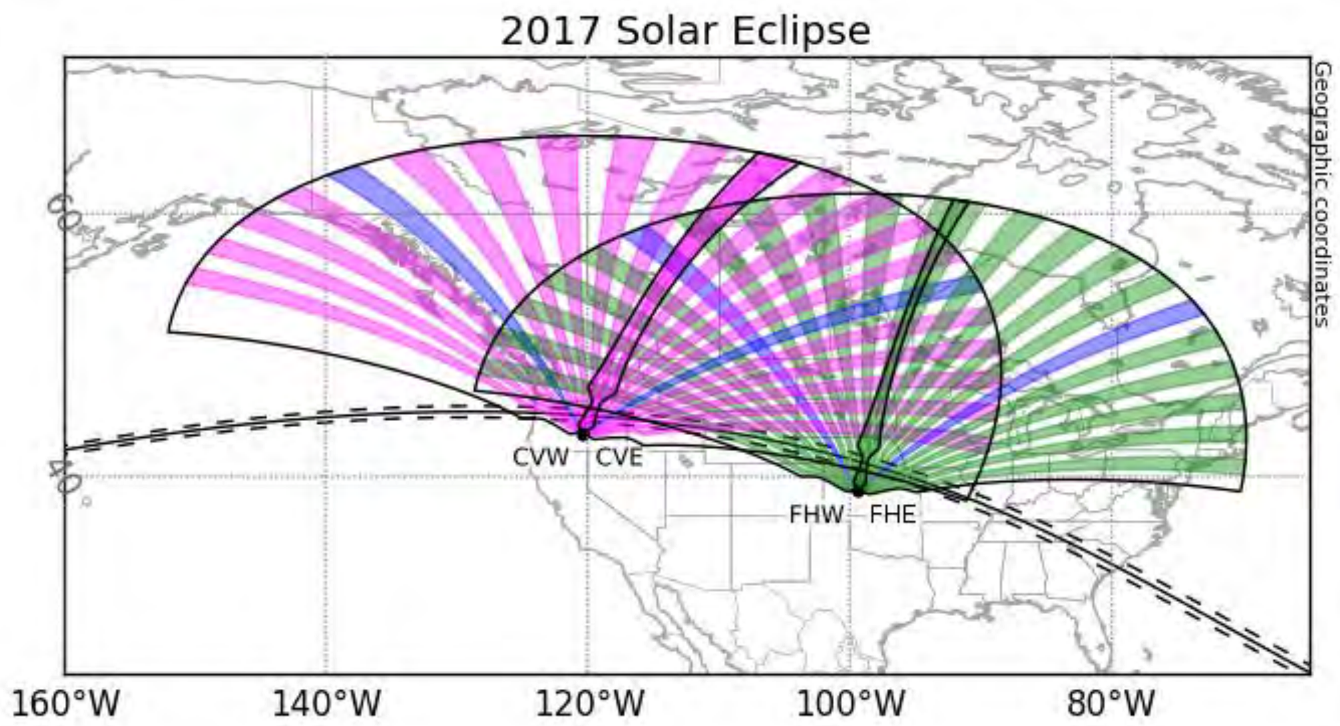

Operational beams intersecting the eclipse path (black) at the Christmas Valley (Magenta) and Fort Hayes (Green) SuperDARN radar sites.

- Space@VT employed SuperDARN radars in Christmas Valley, Oregon (CV) and Fort Hayes, Kansas (FH).

Camping Beam Data

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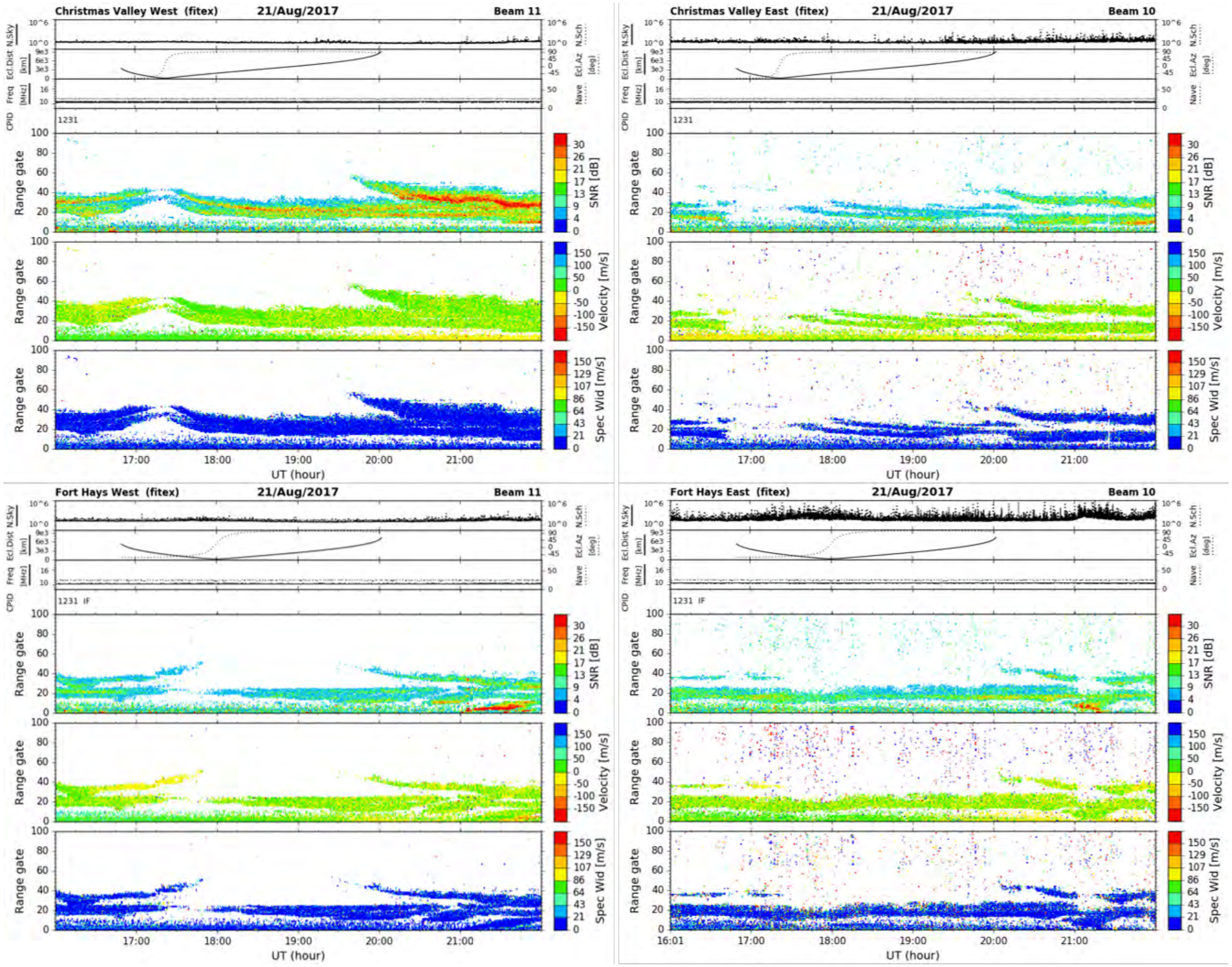

- During the eclipse period all radars observe a decrease in the amount of returned scatter → Signal escape from ionosphere or travel past SuperDARN's maximum observable range
- Westward-looking camping beams observed an increase in the slant range of scattered signals during the eclipse onset, though the timescales differed between the sites.

Elevation Angle Data

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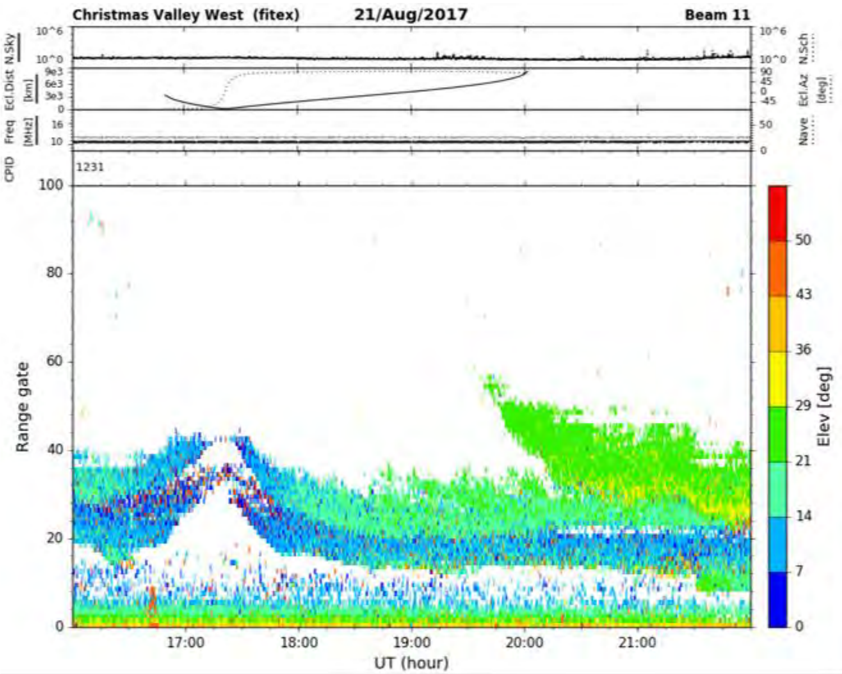
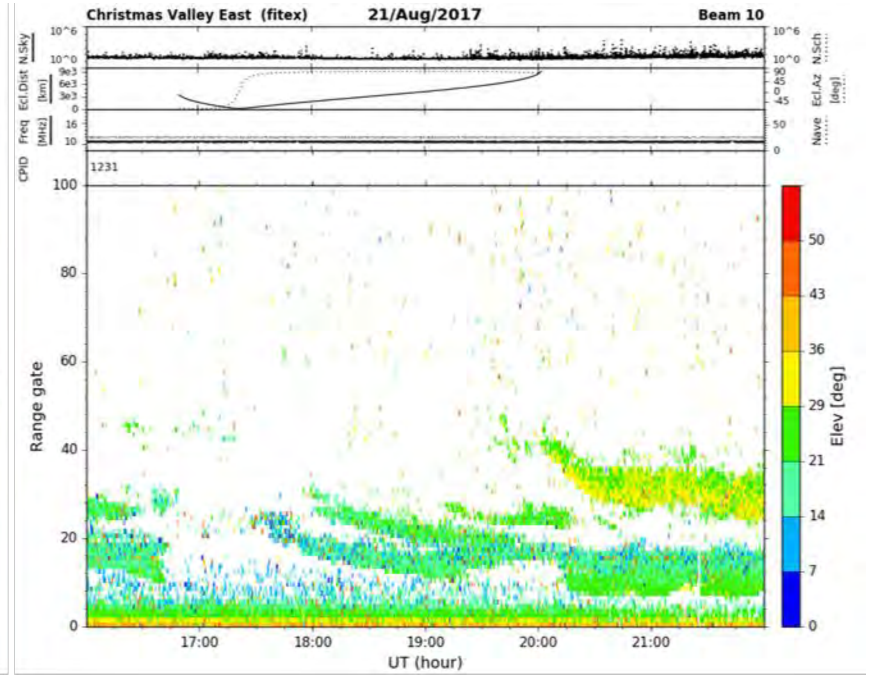




- The elevation angles of returned scatter are relatively low during the eclipse.
- Higher elevation scatter appears to travel further during the eclipse onset and then mostly disappear at maximum eclipse.

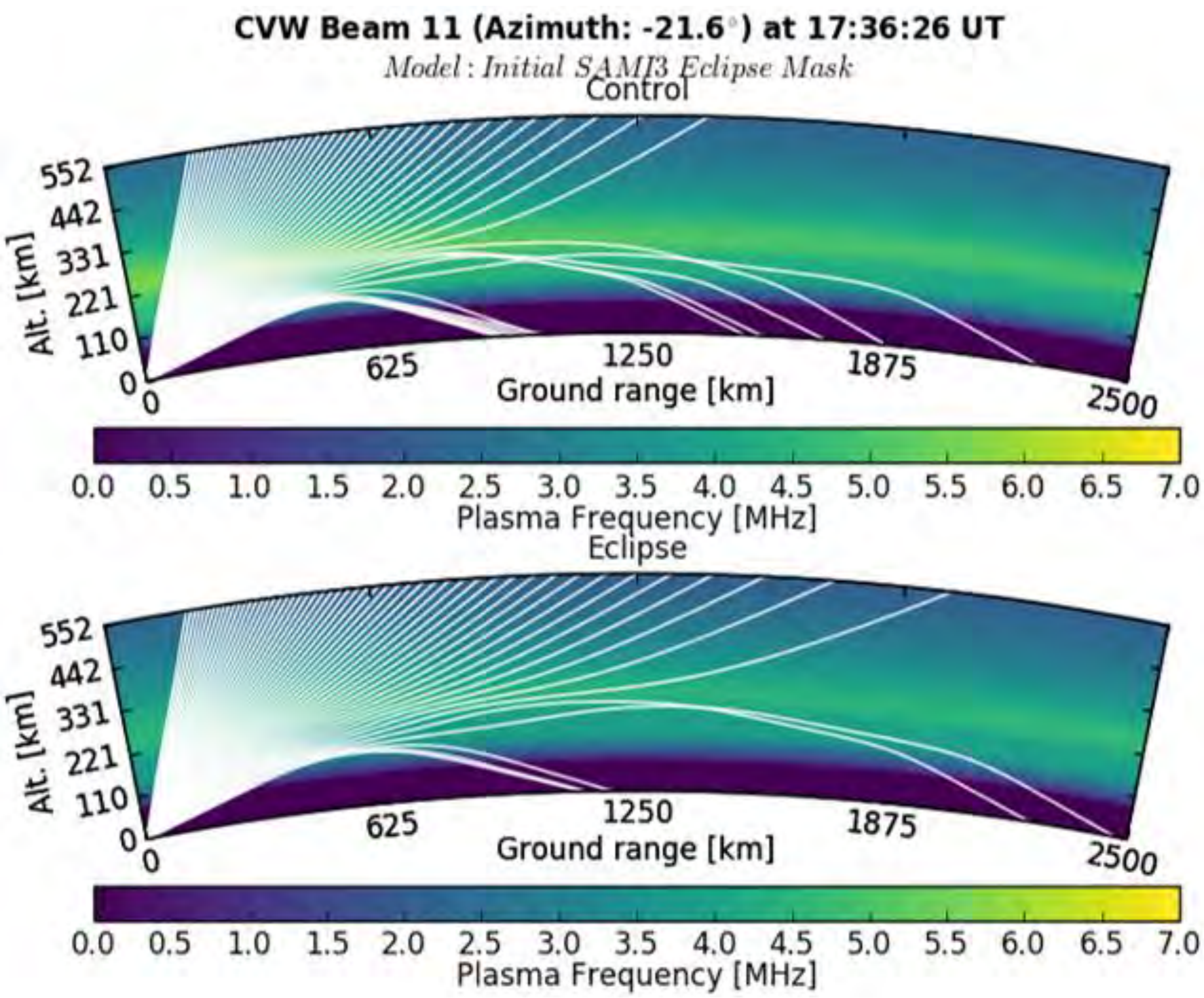
Questions

1. Are the increases in path lengths observed during the eclipse due to changes in the altitude of peak plasma density, or due to ducting of the signals through the region where plasma is depleted?
2. Why do data from different sites appear to be so different?

Analysis Method

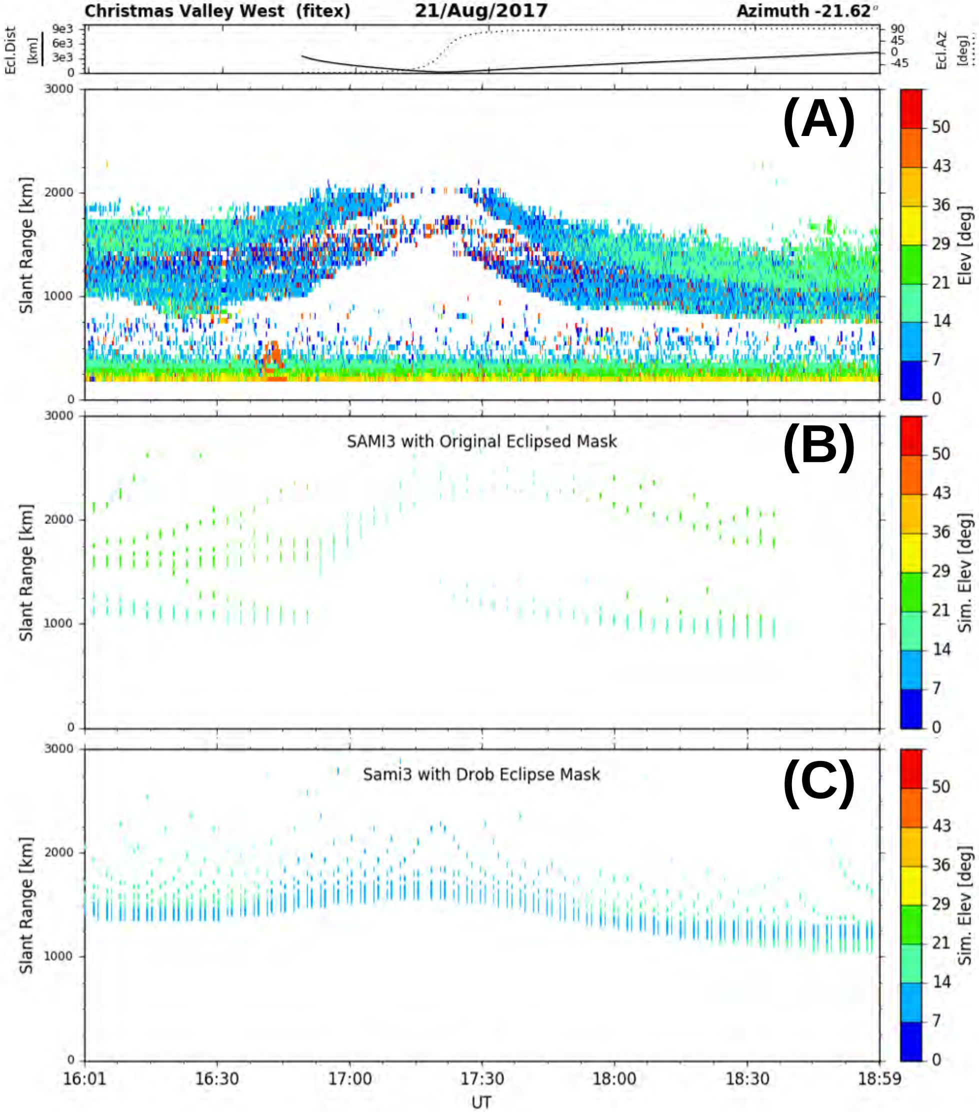
1. Generate models of the eclipsed ionosphere with various assumptions.
2. Simulate radar data for each model ionosphere by modeling the propagation of radio waves (i.e. raytracing using the PHaRLAP toolbox).
3. Compare simulated radar data with measured radar data in order to determine the validity of different hypotheses.

Nature of Eclipse Path Lengthening



Eclipse Mask Improvement

- Plot A gives SuperDARN CV West radar camping beam data
- Eclipsed ionosphere models were initially each generated by imposing an eclipse mask on the EUV input to SAMI3.
- Initial Eclipse Mask (Plot B)
  - Calculated mask over time at ground level as described in [*Huba and Drob*, 2017]
  - Simulated data represent the onset period's ionospheric response timescale fairly well, but there are some important model inaccuracies.
- Drob Eclipse Mask (Plot C)
  - Calculated mask as a function of latitude, longitude, altitude, and time as described in [*Hairston et al.*, 2018]
  - Addressed some of these issues and produces better agreement.



Magnetic Field Influence on Plasma Motion

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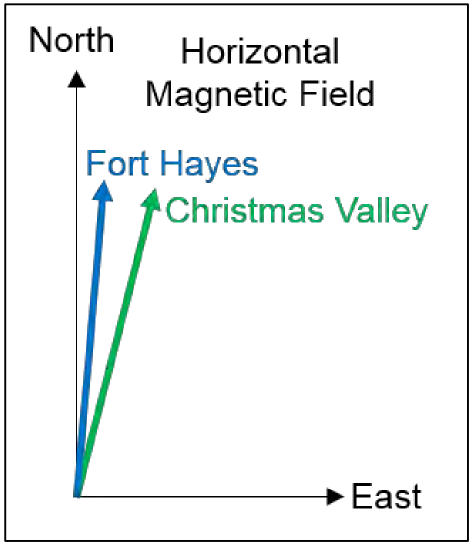
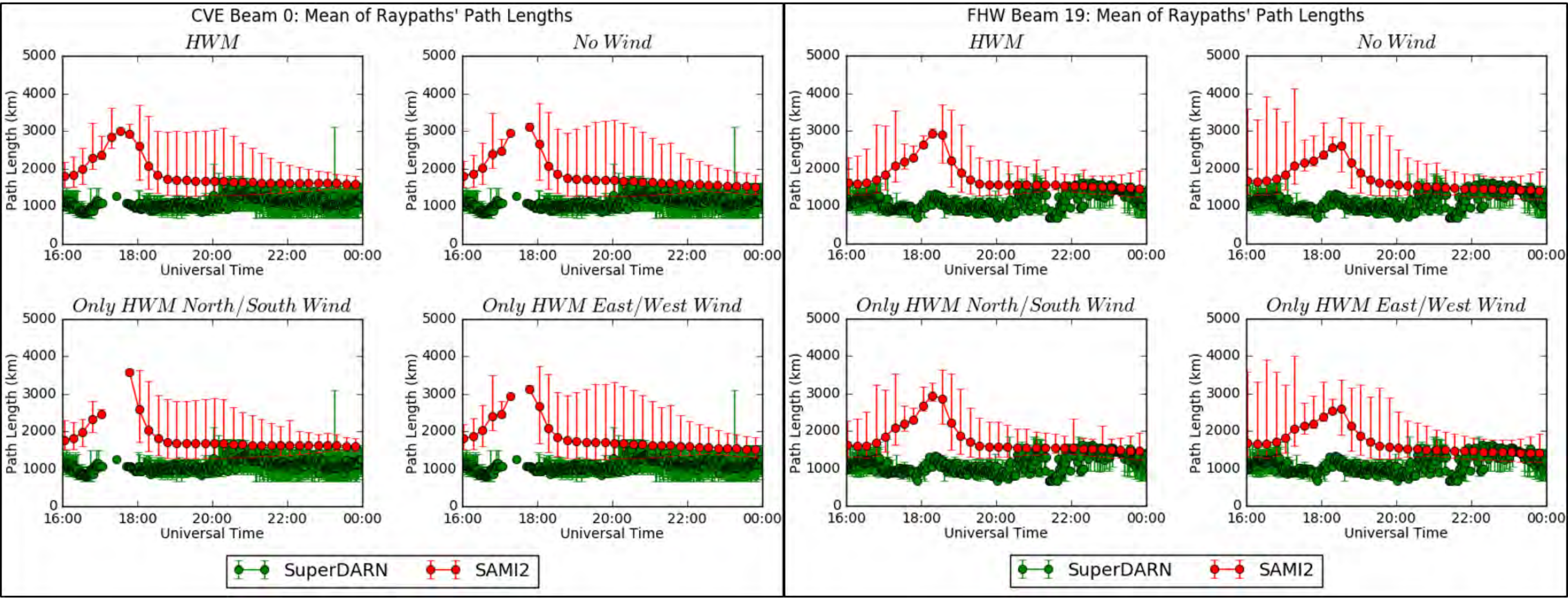
- Charged particles move more freely along magnetic field lines than across them.
- Like gases and liquids, plasma moves to fill a "vacuum". Unlike gases and liquids, plasma is charged and hence "restricted" to move along magnetic field lines.
- Thus, the speed at which plasma can move from unelipsed to eclipsed regions will depend on the magnetic field orientation relative to the eclipse shadow.
- The magnetic field orientation in Fort Hayes, KS is different than that in Christmas Valley, OR. → Plasma will move at different speeds to refill the depleted region. → Recovery times will be different.
- **However,** this is not the whole story!
  - Model ionospheres already take into account differences in the magnetic field, yet modeled data still has some significant discrepancies from measured data.
  - Some phenomena associated with ionospheric eclipse dynamics are still not correctly accounted for in the SAMI model.



Neutral Wind Study

- Goal: Evaluate the impact of various changes to the neutral wind direction in SAMI-2D on simulated SuperDARN data (red).



- The zonal (eastward wind) does not have as much of an impact on the model's eclipse response as the meridional (northward wind) does.
- The zonal wind has a small influence on the ionospheric eclipse response at CV, but almost no influence at FH.
- Comparison with measured data (green): Modeled data for some wind cases do show some of the features observed around totality. However, there are still significant differences between measured and modeled data.

Summary and Conclusions

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- SuperDARN radars in CV and FH observed the ionospheric response to the 2017 eclipse
  - Ground scatter
  - Increase in slant range
  - Decrease in amount of returned scatter
  - Low angles-of-arrival
- Created a SuperDARN ray-trace simulation to evaluate SAMI models and investigate radio propagation during the eclipse
- Three studies conducted with this tool:
  1. Path Lengthening Cause: Signal ducting through the depleted eclipse layer
  2. Eclipse Mask Improvement: Validated the new Drob eclipse mask and determined that the effects of additional phenomena must be investigated.
  3. Neutral Wind Study: The ionospheric response to the eclipse is sensitive to changes in the meridional neutral wind more than to changes in the zonal neutral wind, especially at FH.
- These studies also all showed that SAMI and PHaRLAP can be used together to understand eclipse dynamics.

Future Work - 2024 Eclipse

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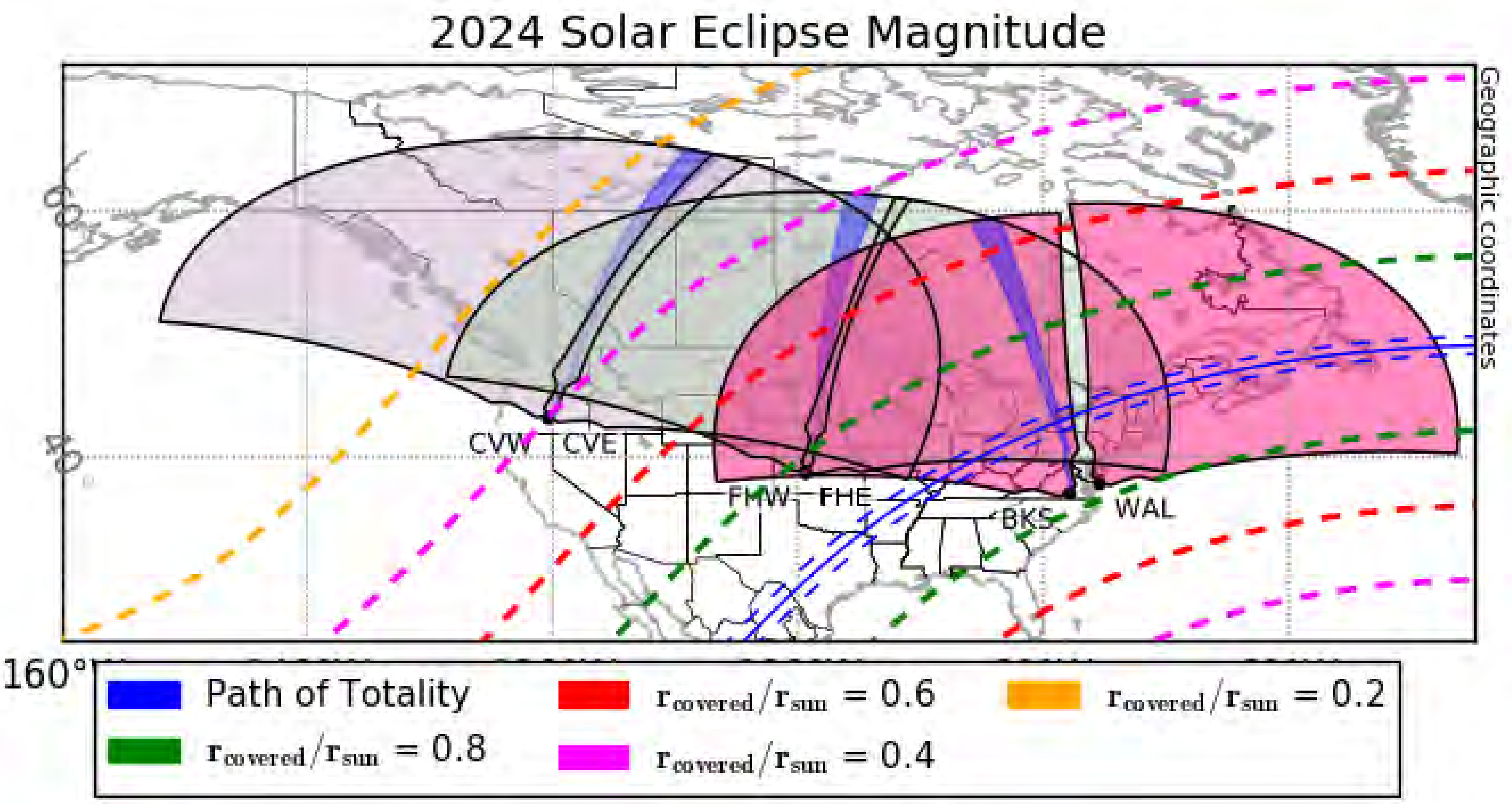

(Data from [Jubier, 2005]).

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- Eclipse Photo: https://commons.wikimedia.org/wiki/File:Total_Solar_Eclipse_8-21-17.jpg
- Fort Hays Photo: http://vt.superdarn.org/tiki-list_file_gallery.php?galleryId=23#

Acknowledgement

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- This work was supported by NSF Grant # AGS-1552188 and NASA Grant #NNX17AH70G.
- The results presented in this thesis were obtained using the HF propagation toolbox, PHaRLAP, created by Dr. Manuel Cervera, Defence Science and Technology Organisation, Australia (manuel.cervera@dsto.defence.gov.au). This toolbox is available by request from its author.
- Joe Huba and Doug Drob, for SAMI3 output files used in ray-trace simulation.
- We acknowledge the use of the Free Open Source Software projects used in this analysis: Ubuntu Linux, Python, iPython, matplotlib, NumPy, SciPy, scikit-learn, DavitPy, DIVA-GIS and others.

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EXTRA SLIDES

Summary of Data Across the FOV

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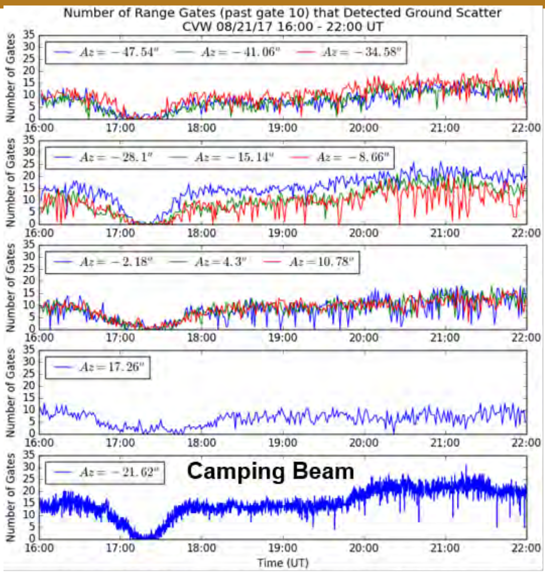
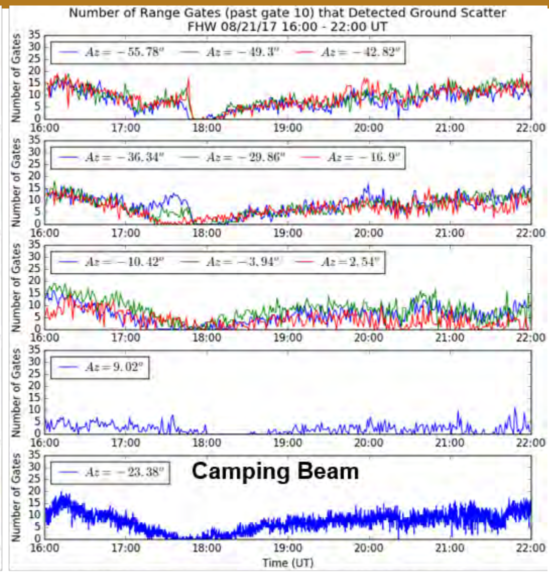
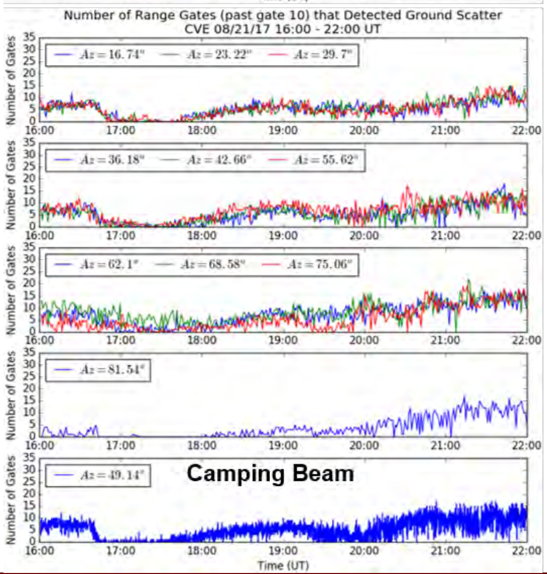
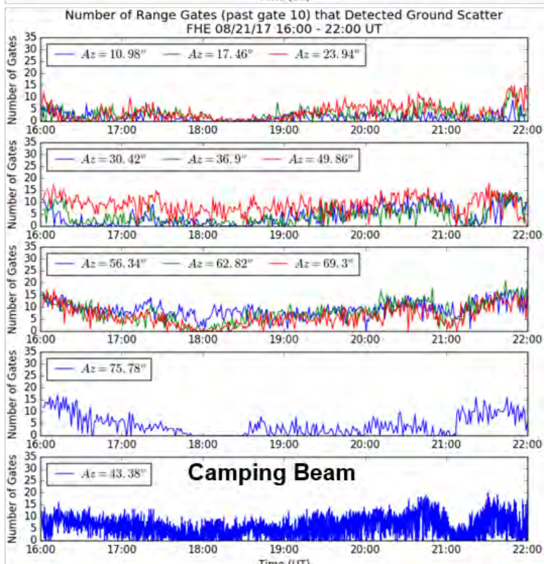








Format

- Each line is a plot of the number of range gates (past gate 10) with measured ground scatter over time for a given beam.
  - Columns ⇔ Location
  - Top-to-bottom ⇔ West-to-East beam azimuths (Except for camping beams)
- Eclipse response is indicated qualtitatively by decreases in the amount of received ground scatter.

Trends

- Eclipse response observed becomes less pronounced as the radar looks away from the west and to the east.
- Only CVW (except at 17.26°) has symmetric pre-totality and post-totality data. All other data is asymmetric in time with respect to the pre and post-totality periods.

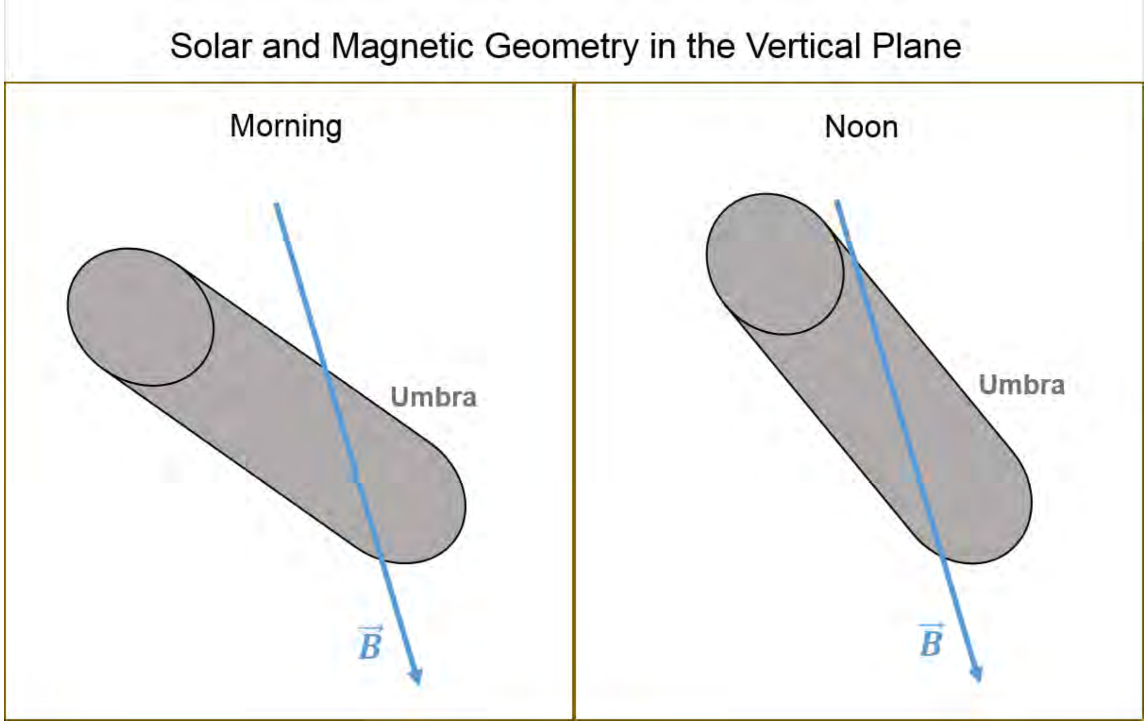
Plasma Motion

- The steady-state motion of a given species of charged particles, denoted by j, in a plasma can be described by the following equation

$$\vec{v}_j = \pm\frac{q_j(\vec{E}+\vec{v}_j \times \vec{B})}{m_j \nu_j} - \frac{\nabla p_j}{m_j n_j \nu_j} + \vec{U}$$

m_j : Particle Mass	ν_j : Collison Frequency	$\vec{U}$: Neutral Wind Velocity
n_j : Number Density	$\vec{v}_j$: Particle Velocity	$\vec{E}$: Electric Field
q_j : Charge	∇p_j : Pressure Gradient	$\vec{B}$: Magnetic Flux Density

- In the eclipse case, the types of motion most likely to be relevant over short timescales are:
  1. ExB drift
  2. Diffusion due to density gradients
  3. Neutral wind-induced drift
- Magnetic field orientation has a significant influence on all eclipse-induced plasma motions.



Motivation

- Some phenomena associated with ionospheric eclipse dynamics are still not correctly accounted for in the SAMI model. One such quantity is the eclipsed neutral wind velocity.
- The neutral wind is included in SAMI's model calculation; however, the value of the neutral wind velocity is obtained from the Horizontal-Wind-Model (HWM).

Goal: Evaluate the impact of various changes to the neutral winds in SAMI on simulated SuperDARN data.

Wind Study Methodology

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- Four neutral wind cases:
  a) default wind values from HWM,
  b) no wind,
  c) north/south wind values from HWM with no east/west wind, and
  d) east/west wind values from HWM with no north/south wind.
- Ran cases with and without the Drob eclipse mask in SAMI-2D (SAMI2).
- Simulated beams are chosen to closely align with local magnetic declination.

Wind Study Methodology (cont.)

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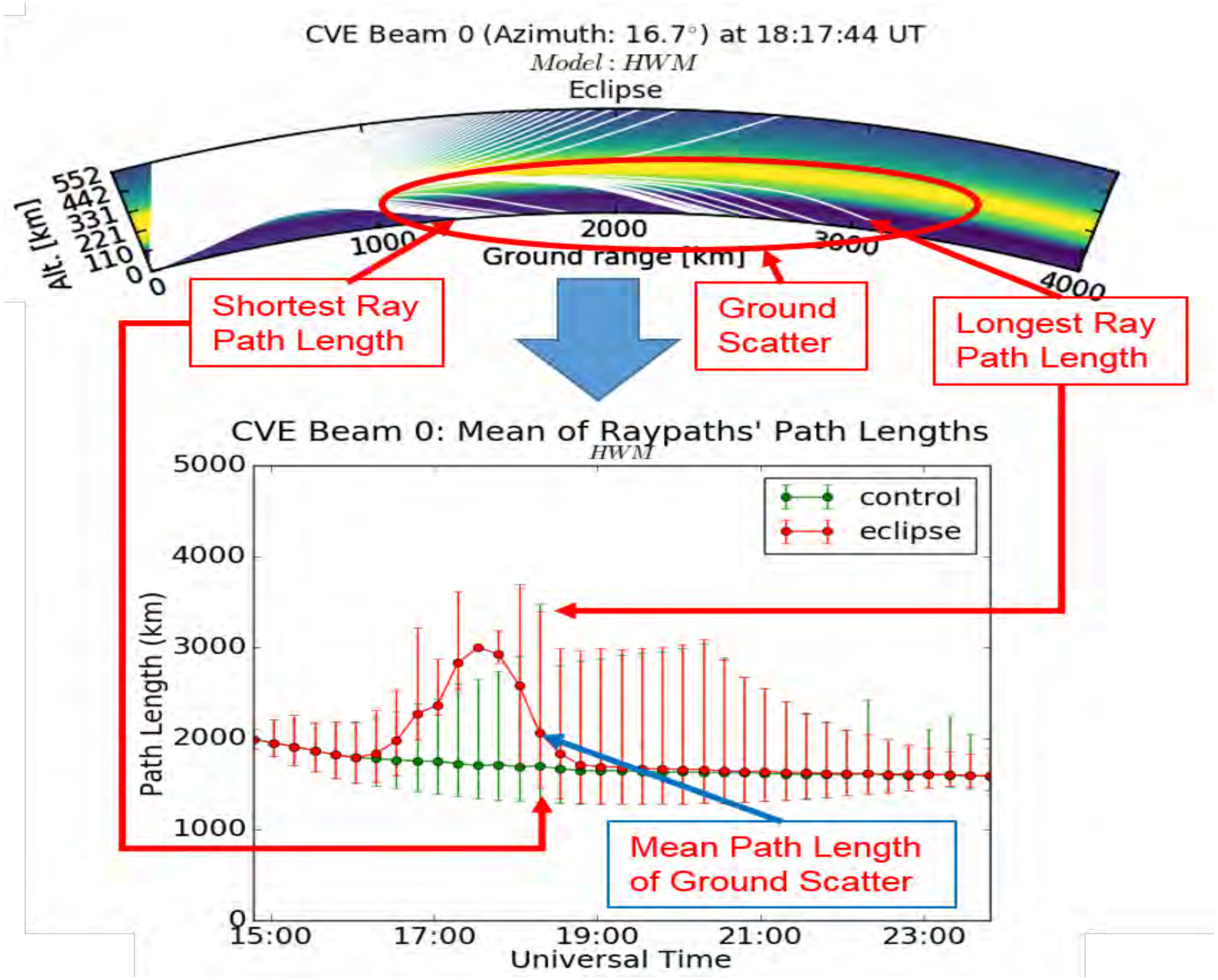
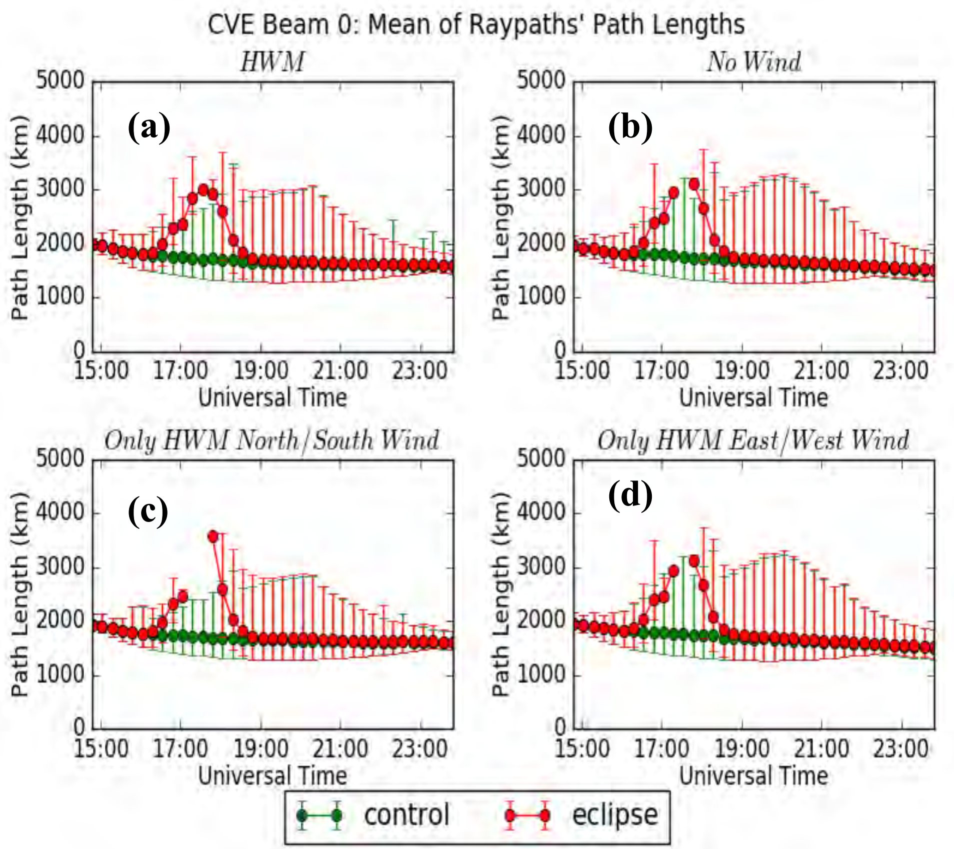
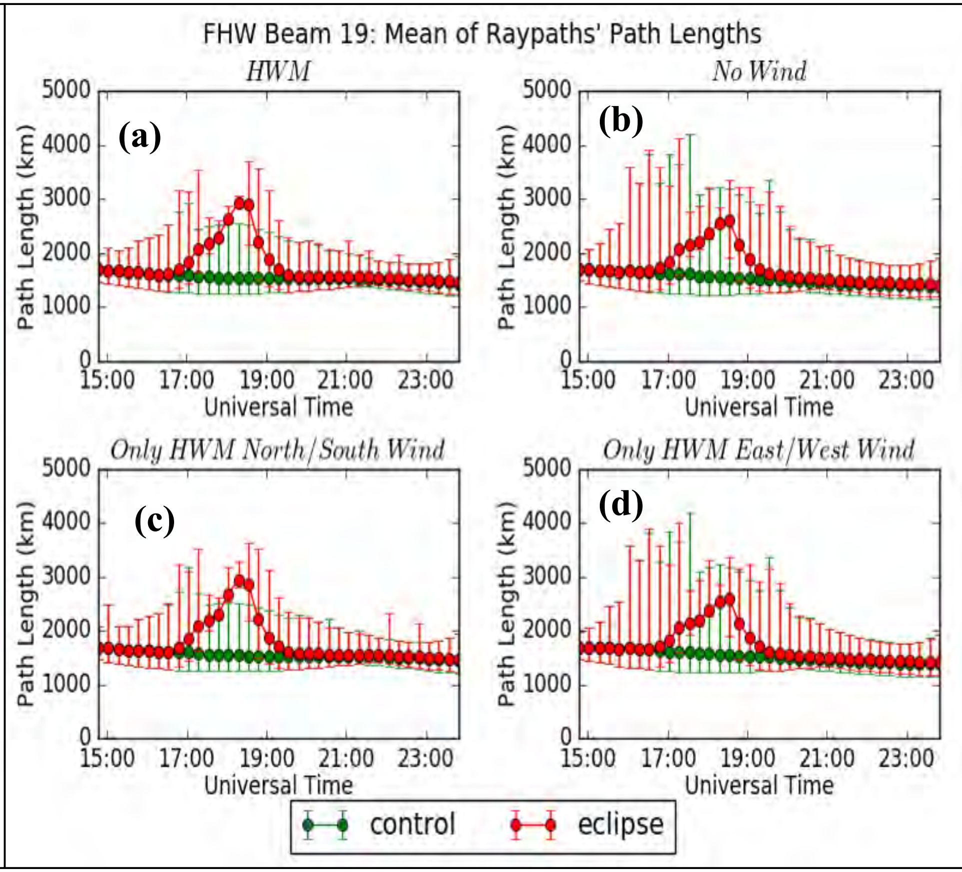


Neutral Wind Study





- The zonal (eastward wind) does not have as much of an impact on the model's eclipse response as the meridional (northward wind) does.
- The zonal wind has a small influence on the ionospheric eclipse response at CVE, but almost no influence at FHW.

Analytical Analysis

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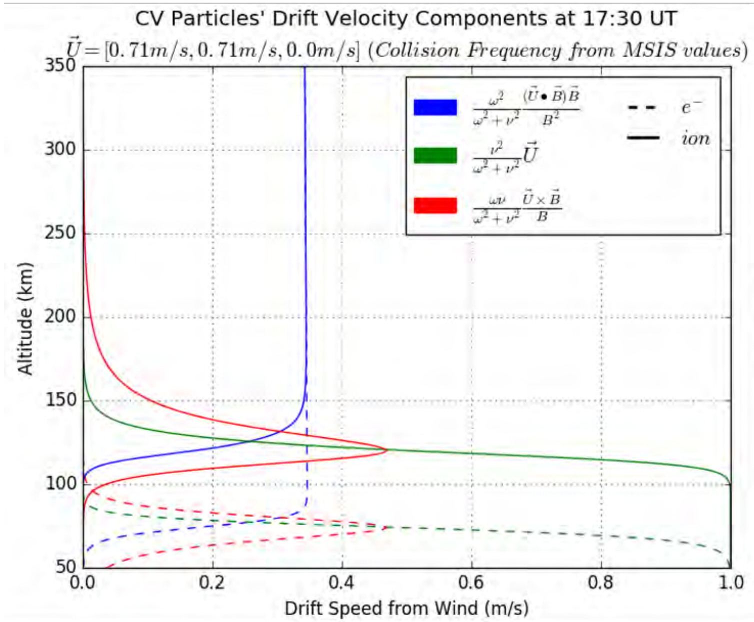
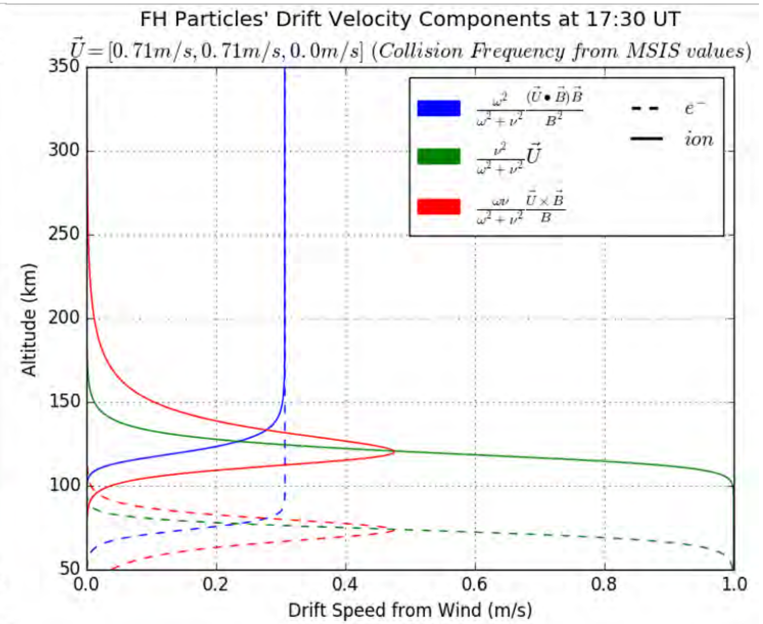
- Under steady-state conditions, the drift velocity of species j due the neutral wind is given by this equation:

$$\vec{v}_{j,w} = \underset{(Pederson)}{\frac{\nu_j^2}{\omega_j^2+\nu_j^2}\vec{U}} + \underset{(Direct)}{\frac{\omega_j^2}{\omega_j^2+\nu_j^2}\frac{(\vec{U}\cdot\vec{B})\vec{B}}{|\vec{B}|^2}} + \underset{(Hall)}{\frac{\nu_j\omega_j}{\omega_j^2+\nu_j^2}\frac{\vec{U}\times\vec{B}}{|\vec{B}|}}$$

$\vec{v}_{j,w}$: Drift Velocity due to Neutral Wind
ν_j: Collison Frequency
ω_j: Gyrofrequency
$\vec{U}$: Neutral Wind Velocity
$\vec{B}$: Magnetic Flux Density

- The three components of the neutral wind-induce drift velocity are differentiated by their directions relative to $\vec{U}$ and $\vec{B}$.
- As shown below, the relative magnitude of these components vary with gyrofrequency and ion-neutral collision frequency, which in turn vary with altitude.
- These plots show that at F-region altitudes the dominant component of the wind-driven drift velocity comes from the field-aligned (Direct) component of the neutral wind.





Analytical Results

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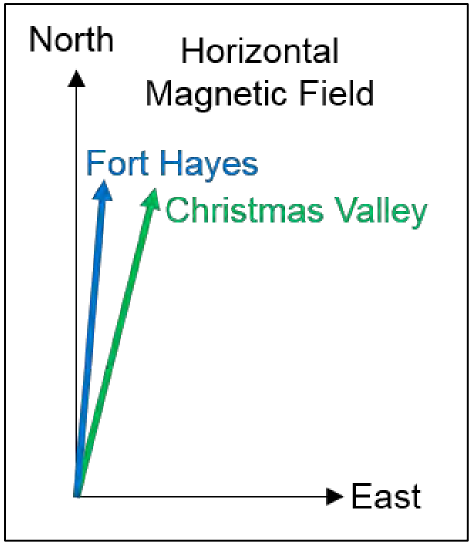
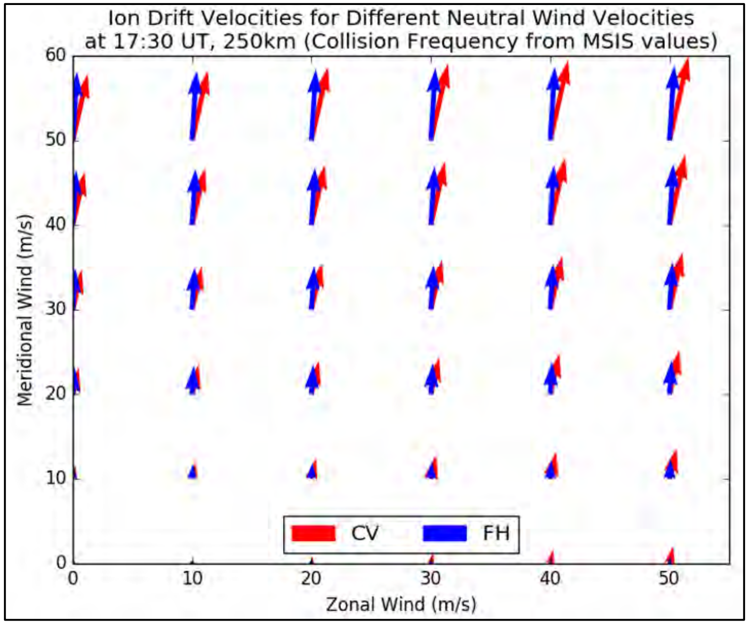
Magnetic Field	CV	FH
Declination	~14.3°	~4.8°
Inclination	~66.1°	~66.3°

- The differences in the magnetic field orientation between the two sites result in each site having a different response to the same neutral wind as illustrated in the figures.





- The meridional wind has a greater effect on the simulation than does the zonal wind.
- Thus, the dominant drift velocity direction will be northward and downward for a northward wind.