CTU Presents

2020 Solar Cycle Update and the HF Response to Ionospheric Storms and Traveling Ionospheric Disturbances

Nathaniel Frissell, W2NAF
The University of Scranton

Space Weather Affect on HF Propagation

1. X-Ray Solar Flares
2. Geomagnetic/Ionospheric Storms
3. Traveling Ionospheric Disturbances

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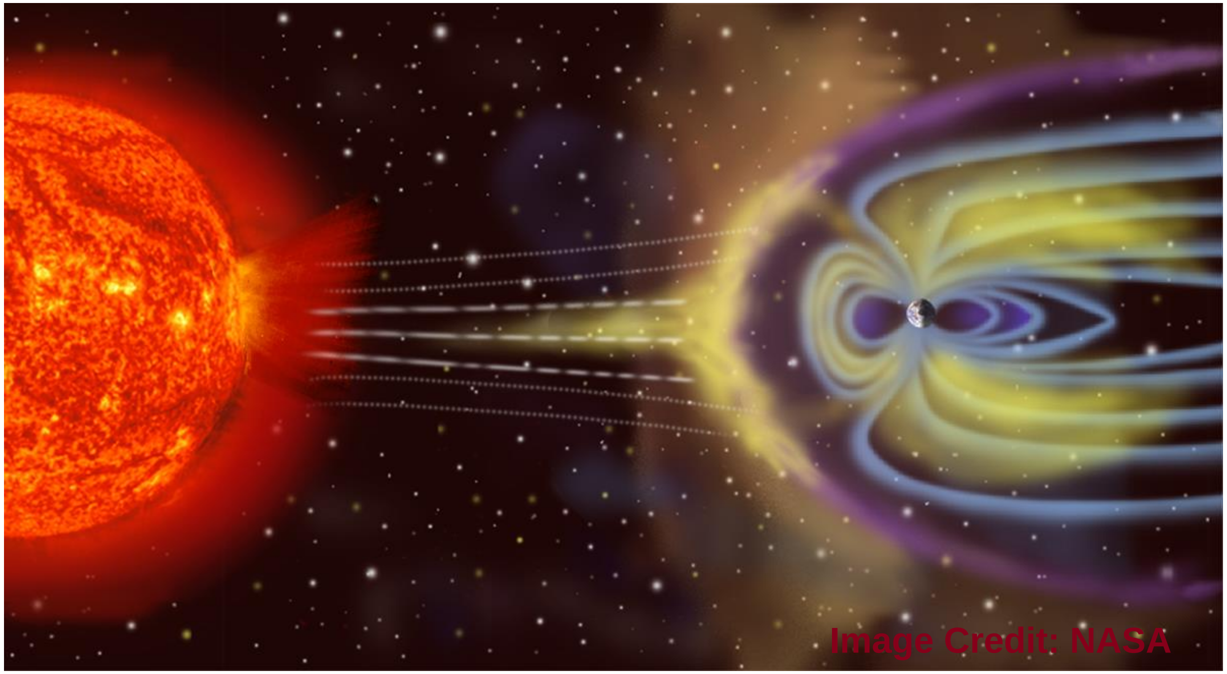
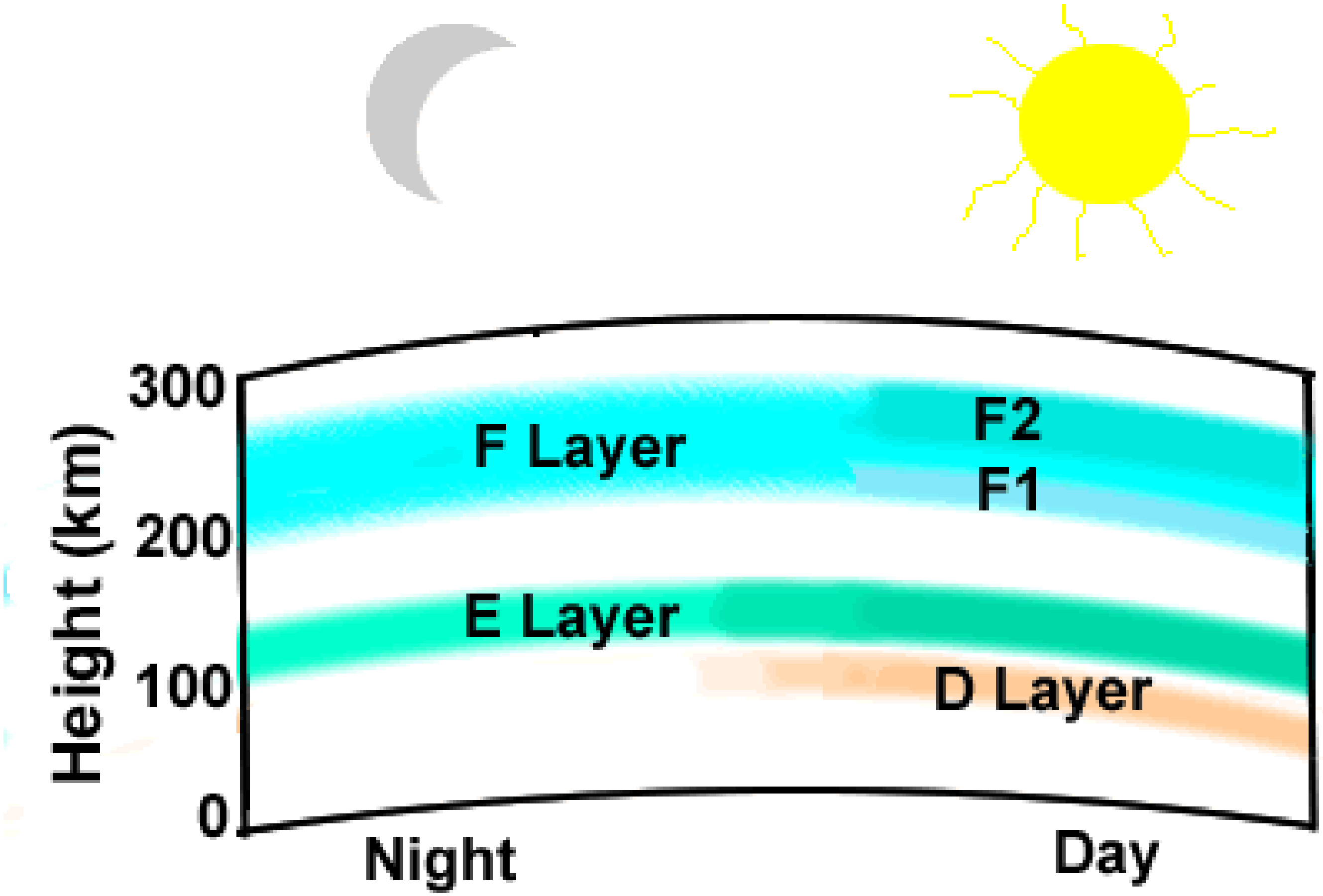
Where is Space Weather?

- Sun (Heliosphere)
- Solar Wind
- Magnetosphere
- Ionosphere



The Ionosphere

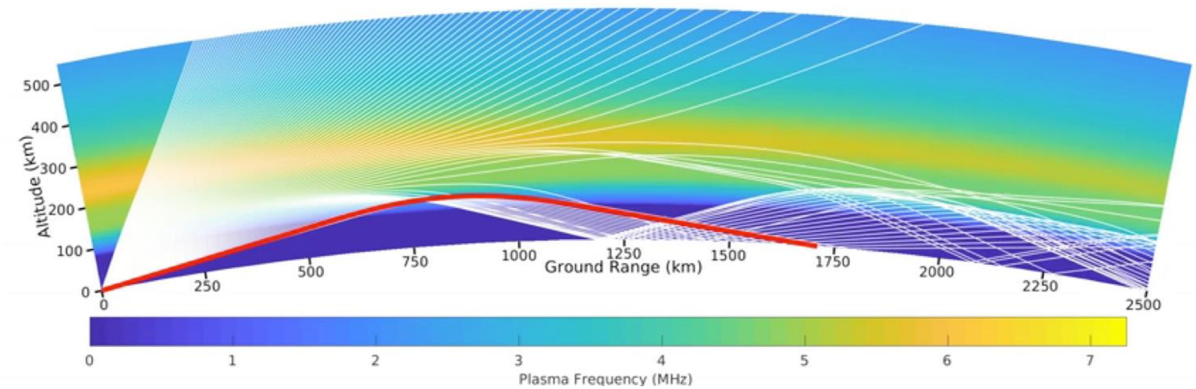


https://commons.wikimedia.org/wiki/File:IonosphereLayers-NPS.gif

Ham Radio Frequencies

	Frequency	Wavelength
LF	135 kHz	2,200 m
MF	473 kHz	630 m
MF	1.8 MHz	160 m
HF	3.5 MHz	80 m
HF	7 MHz	40 m
HF	10 MHz	30 m
HF	14 MHz	20 m
HF	18 MHz	17 m
HF	21 MHz	15 m
HF	24 MHz	12 m
HF	28 MHz	10 m
VHF+	50 MHz	6 m
VHF+	And more…	

PHaRLAP Raytrace
1600 UT 21 Aug 2017 14.03 MHz - Eclipsed SAMI3
TX: AA2MF (Florida) RX: WE9V (Wisconsin)



- Hams routinely use HF-VHF transionospheric links.
- Often ~100 W into dipole antennas.
  (Well, probably more in the Contest Community!)

- Common HF Modes
  - Digital: FT8, PSK31, WSPRNet, RTTY
  - Morse Code / Continuous Wave (CW)
  - Phone: Single Side Band (SSB)

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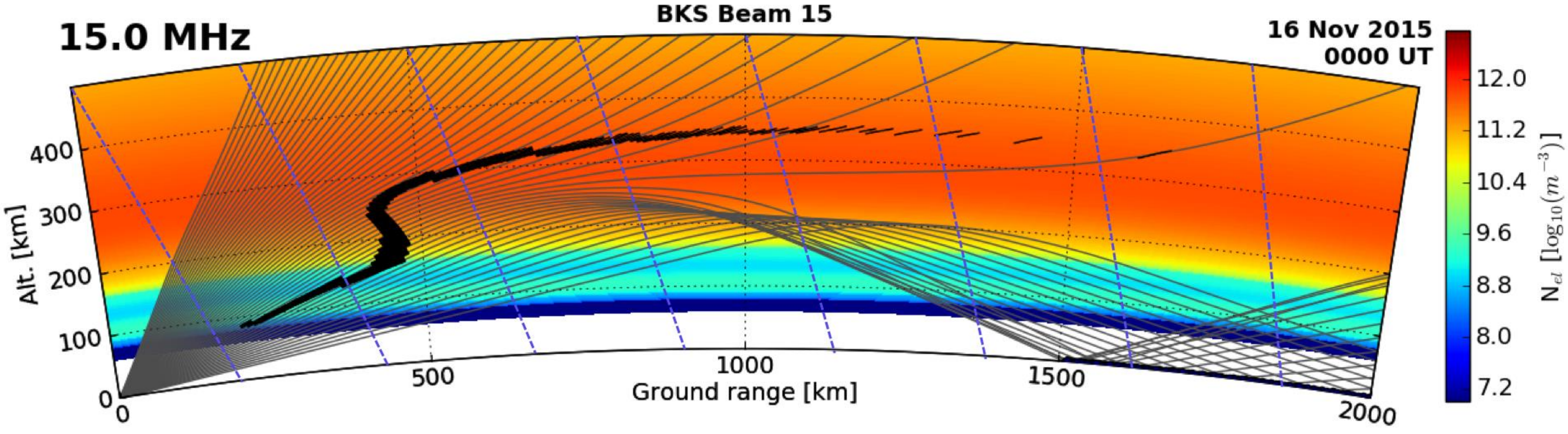
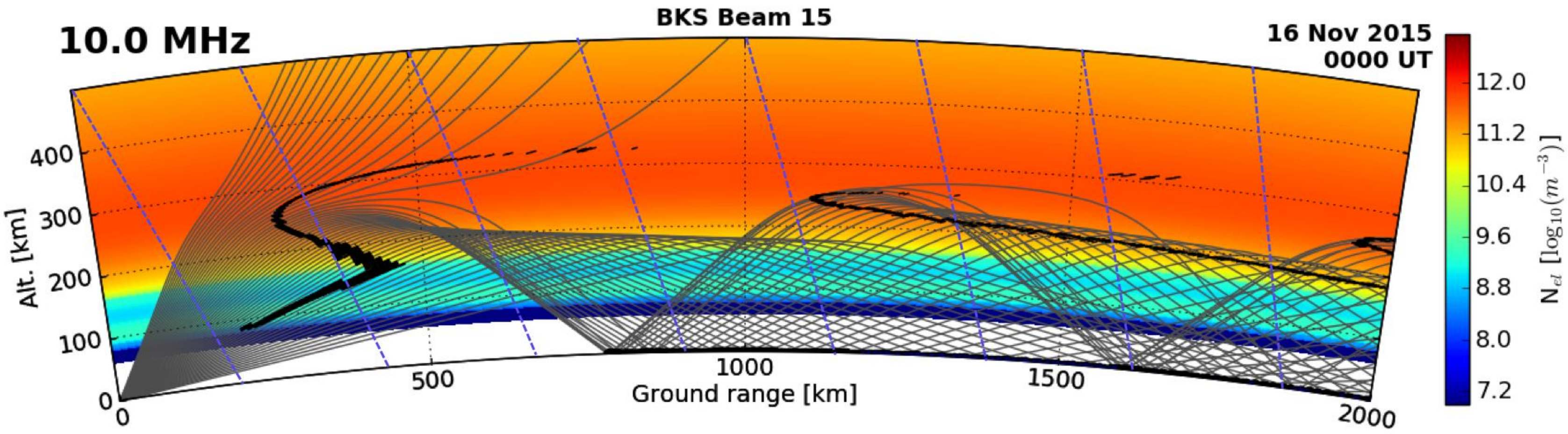
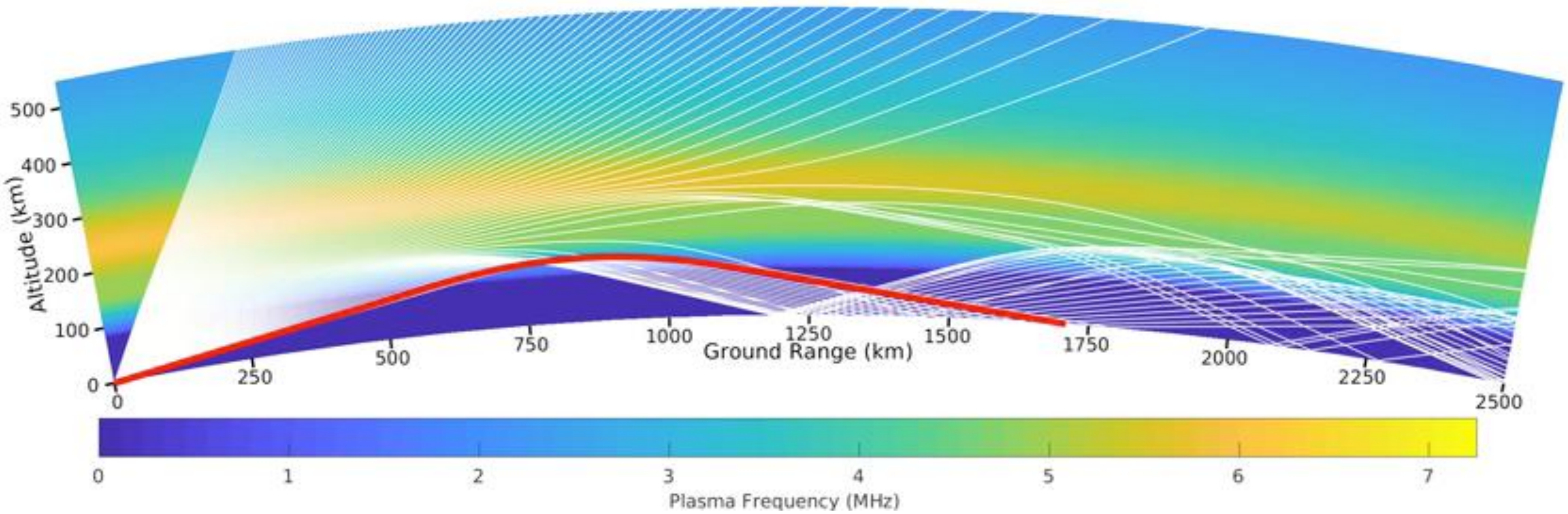
Refraction as a Function of Frequency





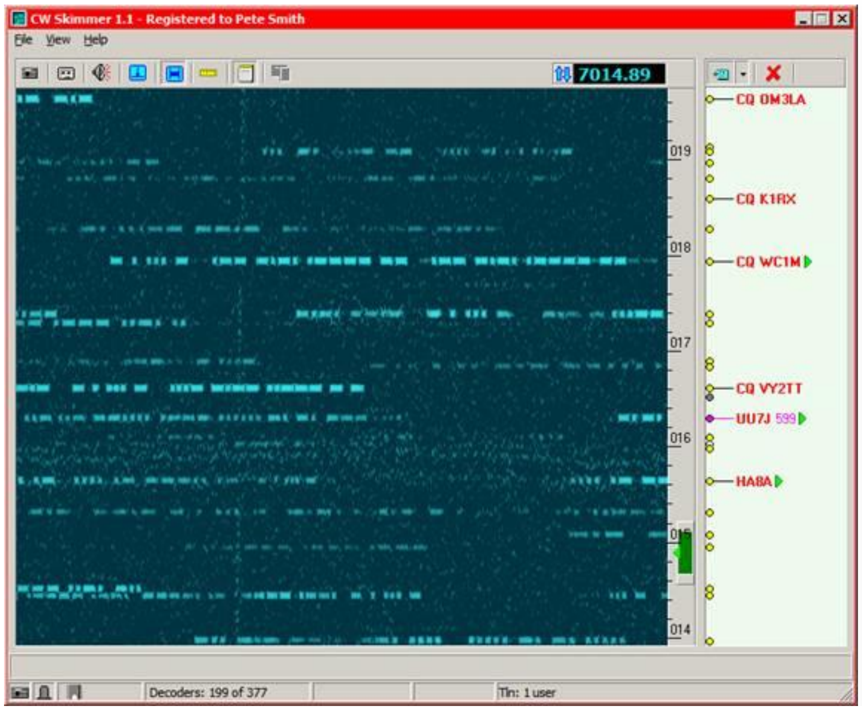
Refraction as a Function of Electron Density

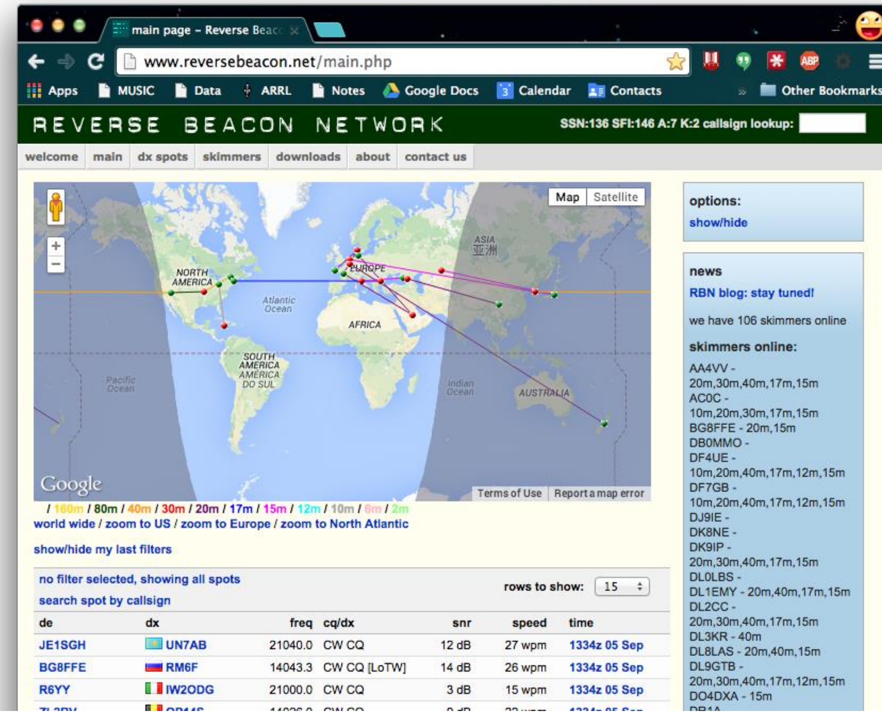
Propagation Model of August 21, 2019 Total Solar Eclipse
SAMI3-PHaRLAP Raytrace
1600 – 2200 UT 14.03 MHz
TX: AA2MF (Florida) RX: WE9V (Wisconsin)



[*Frissell et al.*, 2018, doi:10.1029/2018GL077324]

CW Skimmer and RBN





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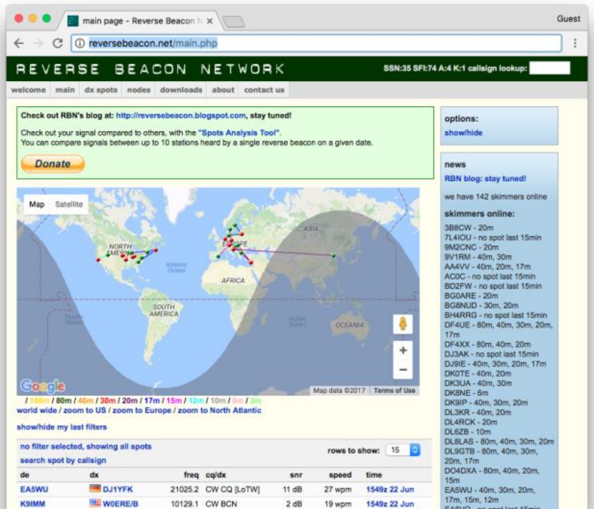
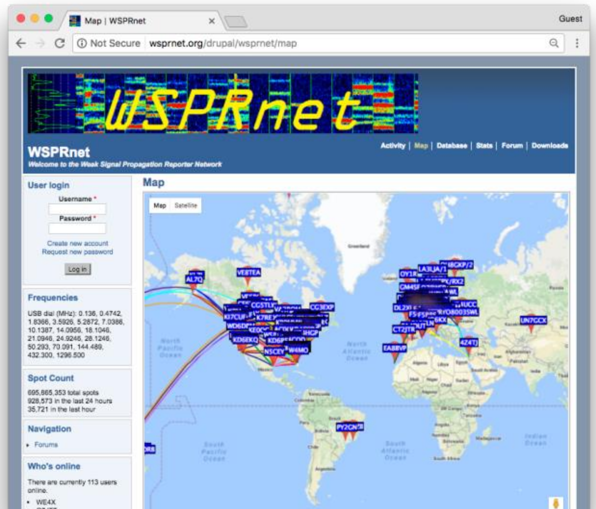
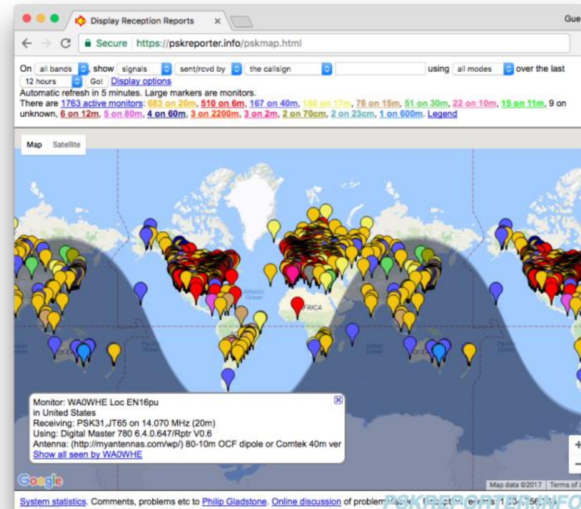
Ham Radio Observation Networks



Reverse Beacon Network (RBN)
reversebeacon.net



WSPRNet
wsprnet.org



PSKReporter
pskreporter.info

- Quasi-Global
- Organic/Community Run
- Unique & Quasi-random geospatial sampling
- Data back to 2008 (A whole Solar Cycle!)
- Available in real-time!

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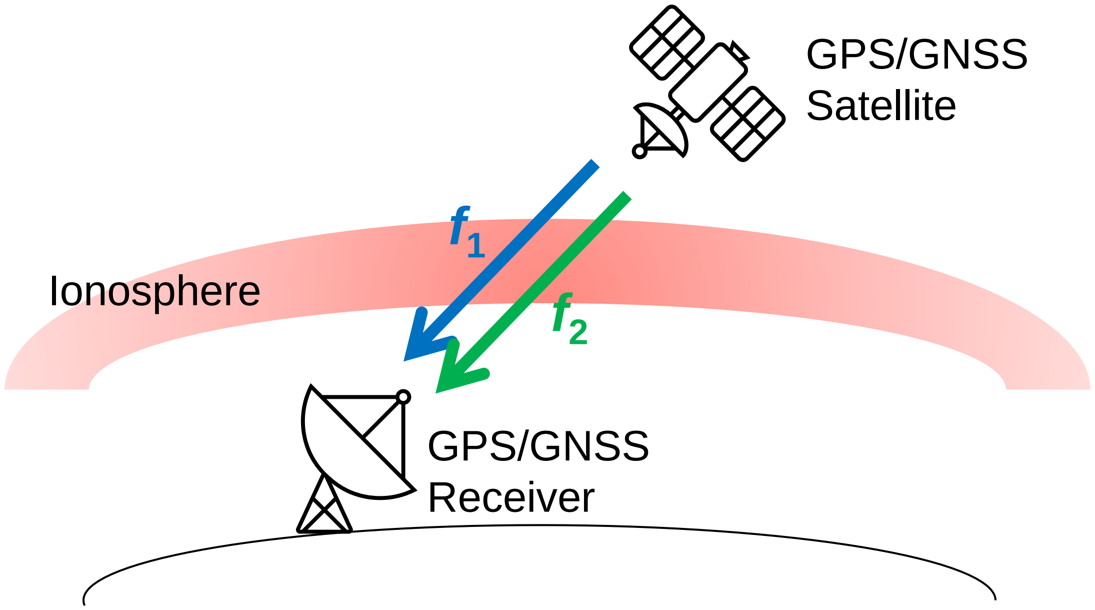
What is Total Electron Content (TEC)?

- TEC is a measure of the total number of electrons between a GPS/GNSS satellite transmitter and GPS/GNSS receiver.
- It is derived from the difference in phase delay of two different frequencies passing through the ionospheric plasma.



f_1 = 1575.42 MHz (GPS L1)
f_2 = 1227.60 MHz (GPS L2)
1 TECU = 10^{16} Electrons m^{-2}

What is Total Electron Content (TEC)?

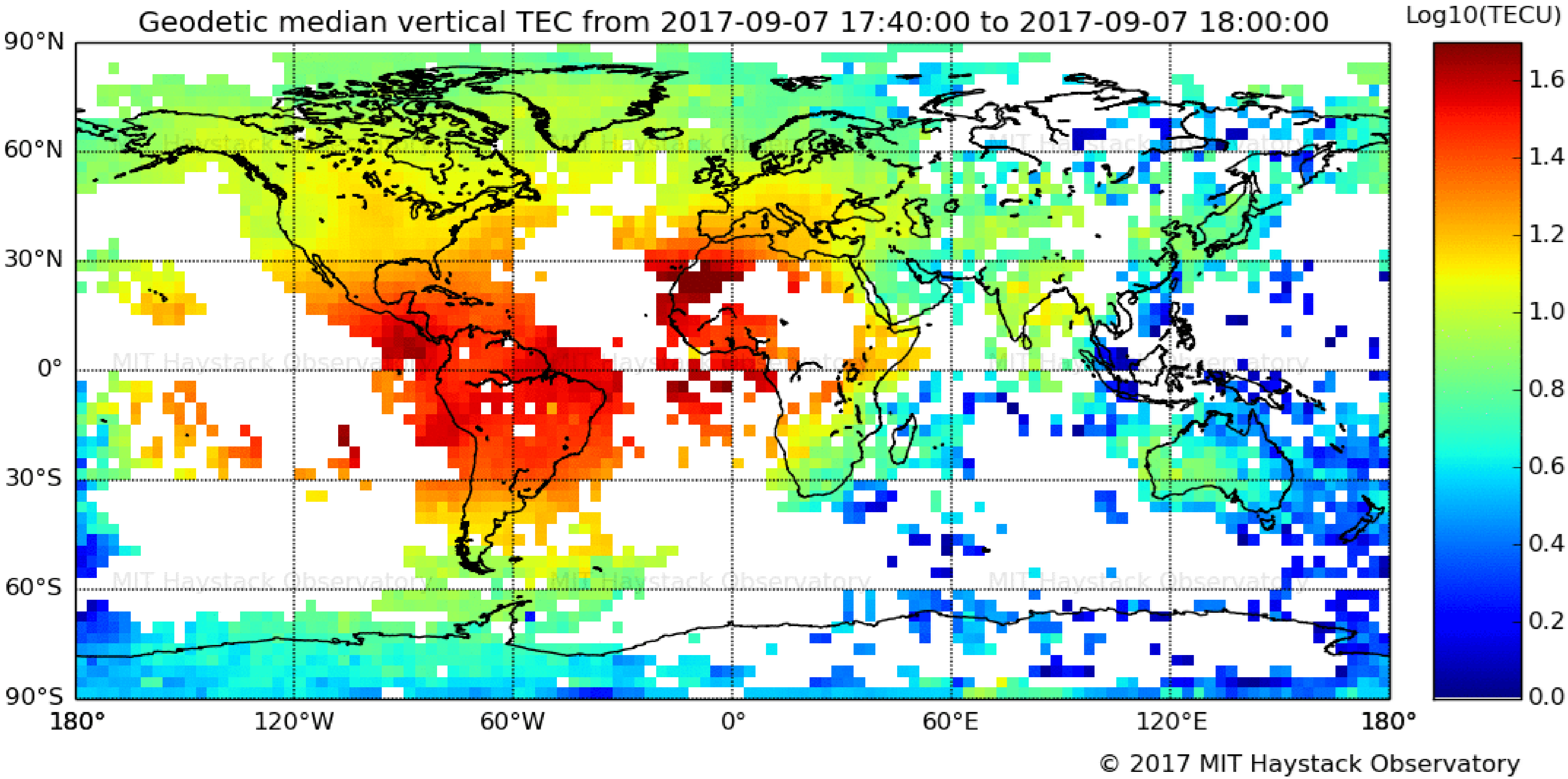
$$I_s = \frac{1}{40.3}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\left[(L_1 - L_2) - (\lambda_1 n_1 - \lambda_2 n_2) + b_r + b_s\right]$$

- **Slant TEC** (I_s)
- **Frequency Terms** ($\frac{1}{40.3}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}$)
- **Recorded carrier phases of the signal (converted to distance units)** ($L_1 - L_2$)
- **Integer cycle ambiguities** ($\lambda_1 n_1 - \lambda_2 n_2$)
- **Instrument (satellite and receiver) bias terms** ($b_r + b_s$)

f_1 = 1575.42 MHz (GPS L1)
f_2 = 1227.60 MHz (GPS L2)
1 TECU = 10^{16} Electrons m^{-2}

[Tsugawa et al., 2007, doi:10.1029/2007GL031663]

What is Total Electron Content (TEC)?



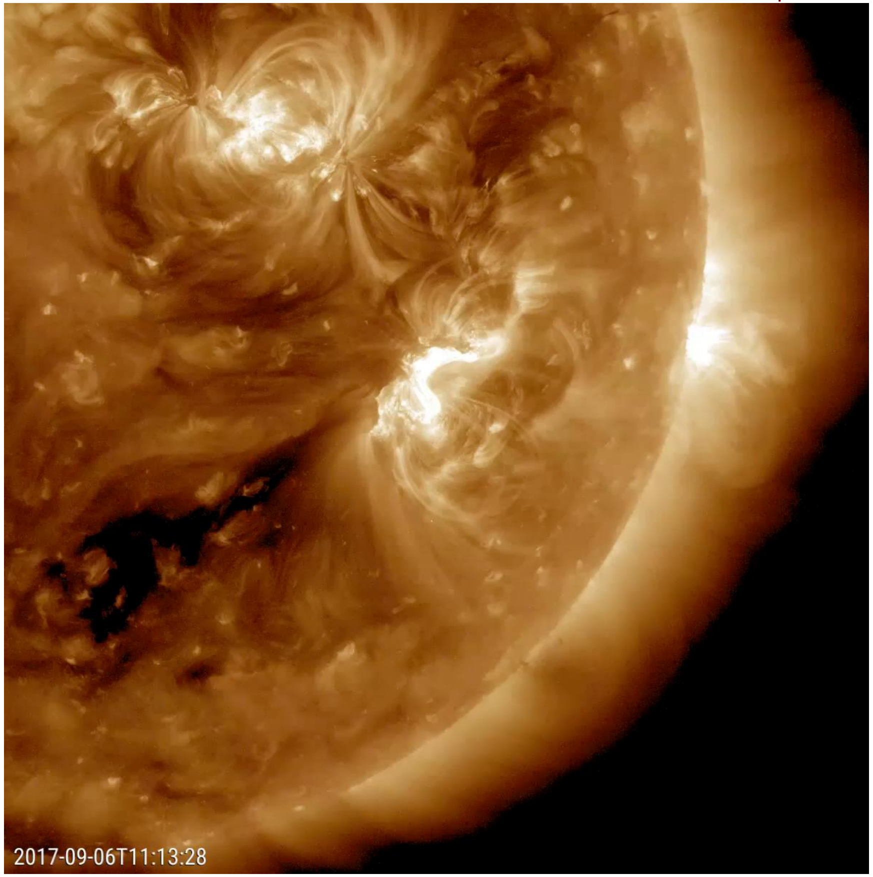
© MIT Haystack Observatory / Anthea Coster

[Rideout and Coster, 2006, doi:10.1007/s10291-006-0029-5]

SOLAR FLARES

Solar Flares

- Sudden increase in electromagnetic energy from localized regions on the sun.
- Energy travels at the speed of light (8 min to Earth)
- Soft X-Ray (0.1-0.8 nm) Earthward-directed energy can cause HF radio blackouts.
- Often, but not always, accompanied by a CME.



NASA SDO Observation of X9.3 Solar Flare on Sept 6, 2017

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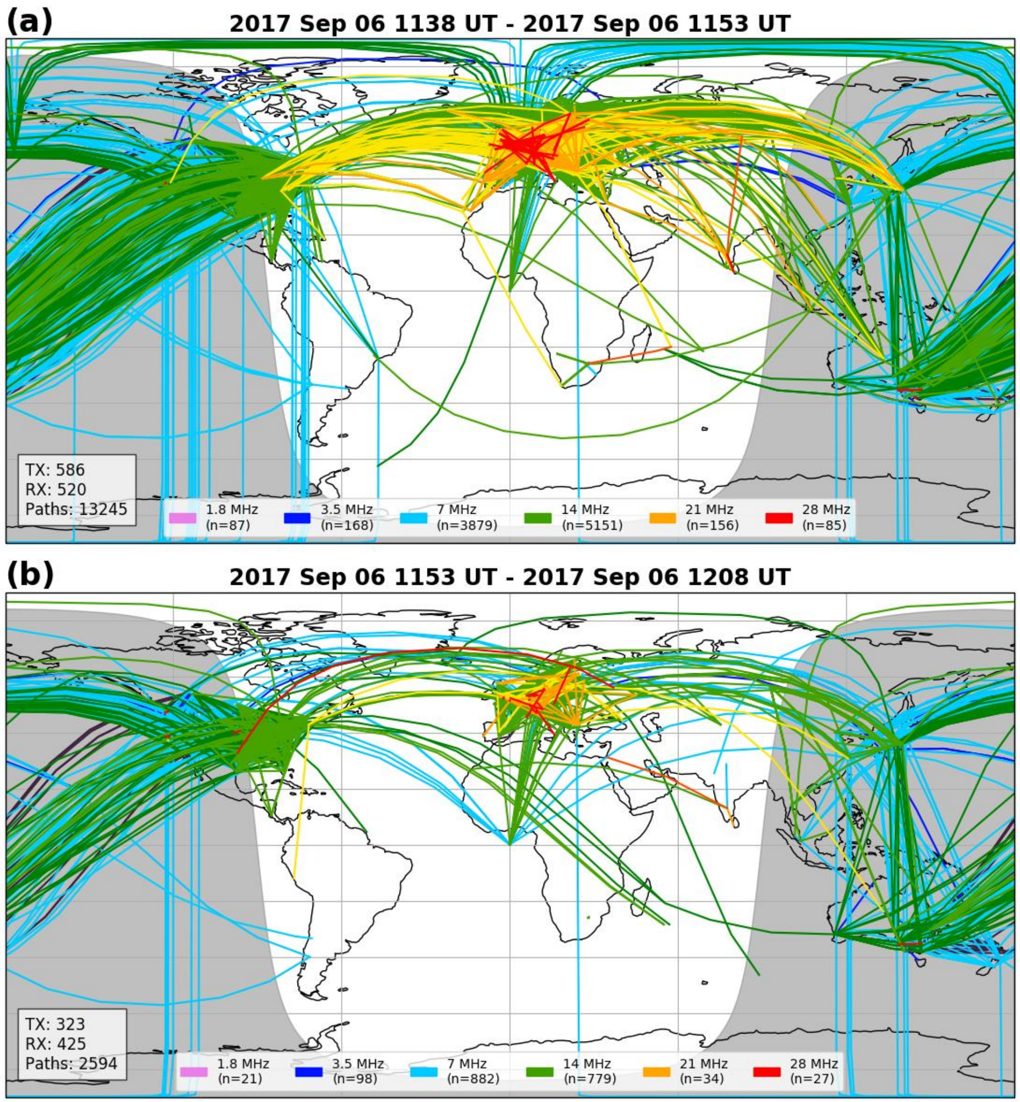
HF Response to Solar Flare

13,245 Paths

6 Sept 2017
1153 UT
X9.3 Flare

2,594 Paths



28 MHz
21 MHz
14 MHz
7 MHz
3.5 MHz
1.8 MHz

[*Frissell et al.*, 2019]

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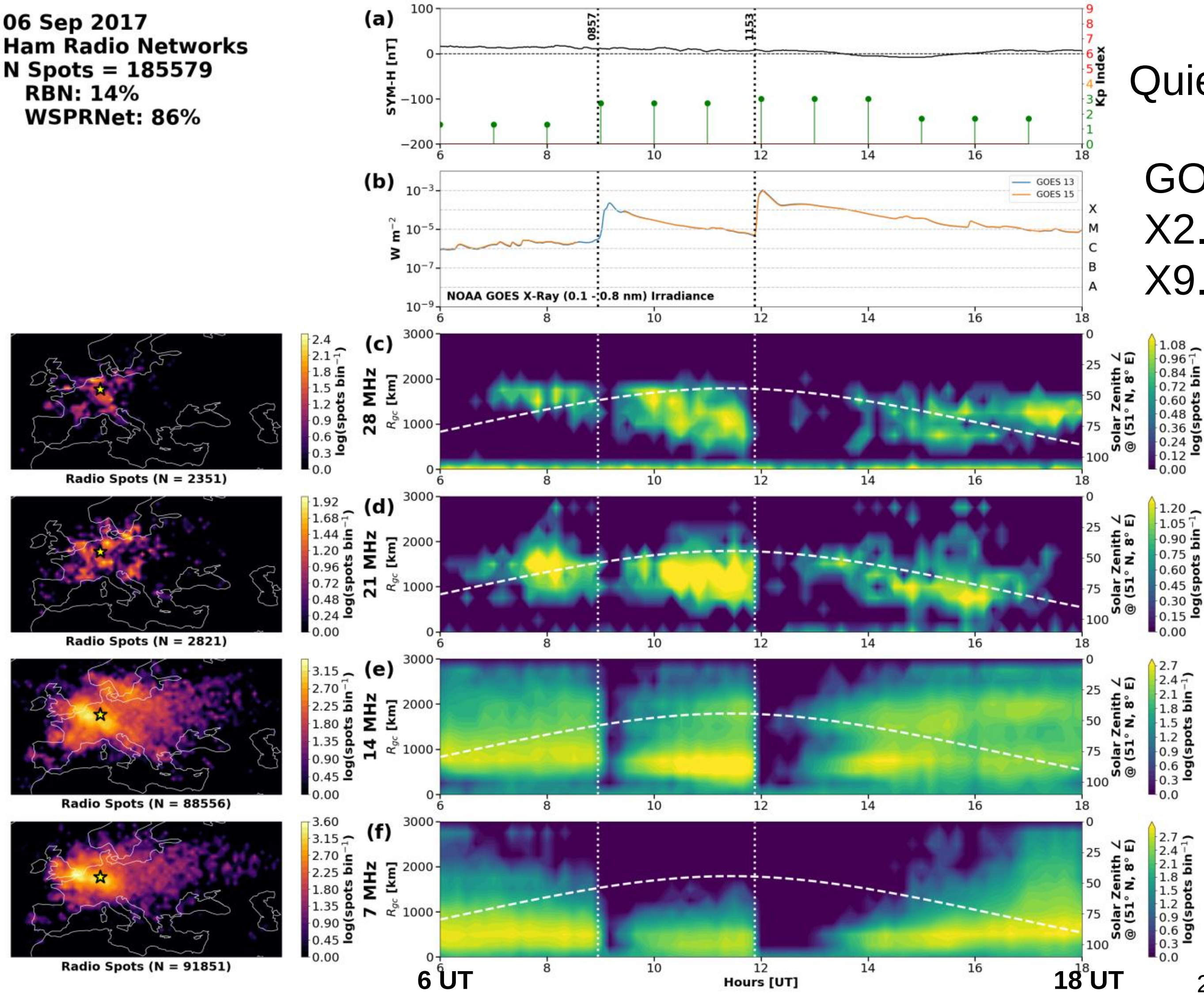
EU Response to Solar Flares



Quiet Kp/Sym-H

GOES Flares
X2.2: 0857 UT
X9.3: 1153 UT

28 MHz

21 MHz

14 MHz

7 MHz

- Europe in daylight.
- Both flares cause deep blackouts.

250 km × 10 min bins

[*Frissell et al.*, 2019, doi:10.1029/2018SW002008]

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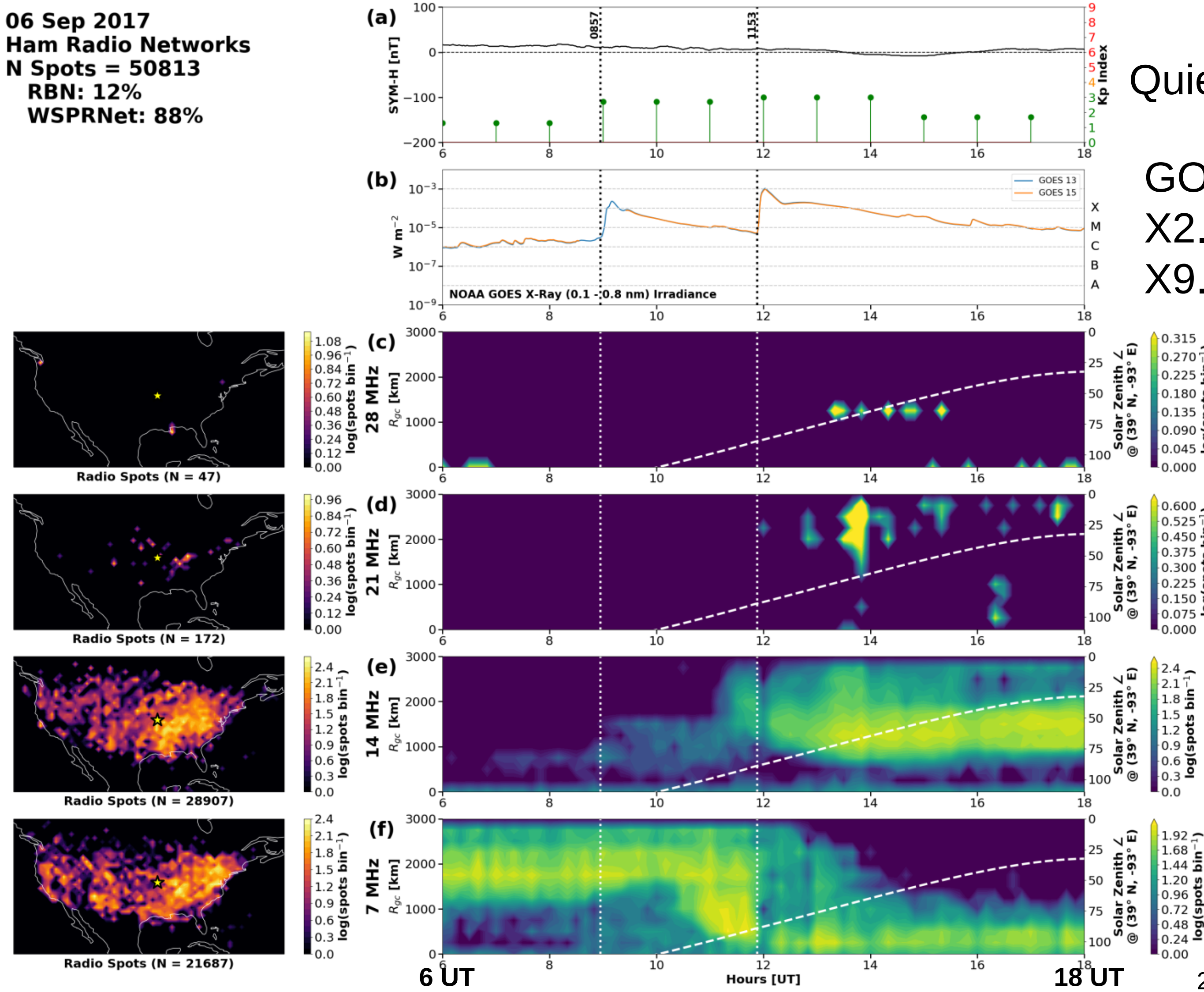
US Response to Solar Flares



Quiet Kp/Sym-H

GOES Flares
X2.2: 0857 UT
X9.3: 1153 UT

- US is at dawn.
- Diurnal variations evident
- 1st Flare has little effect
- 2nd flare has small effect

28 MHz

21 MHz

14 MHz

7 MHz

250 km × 10 min bins

[*Frissell et al.*, 2019, doi:10.1029/2018SW002008]

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Solar Flare Summary

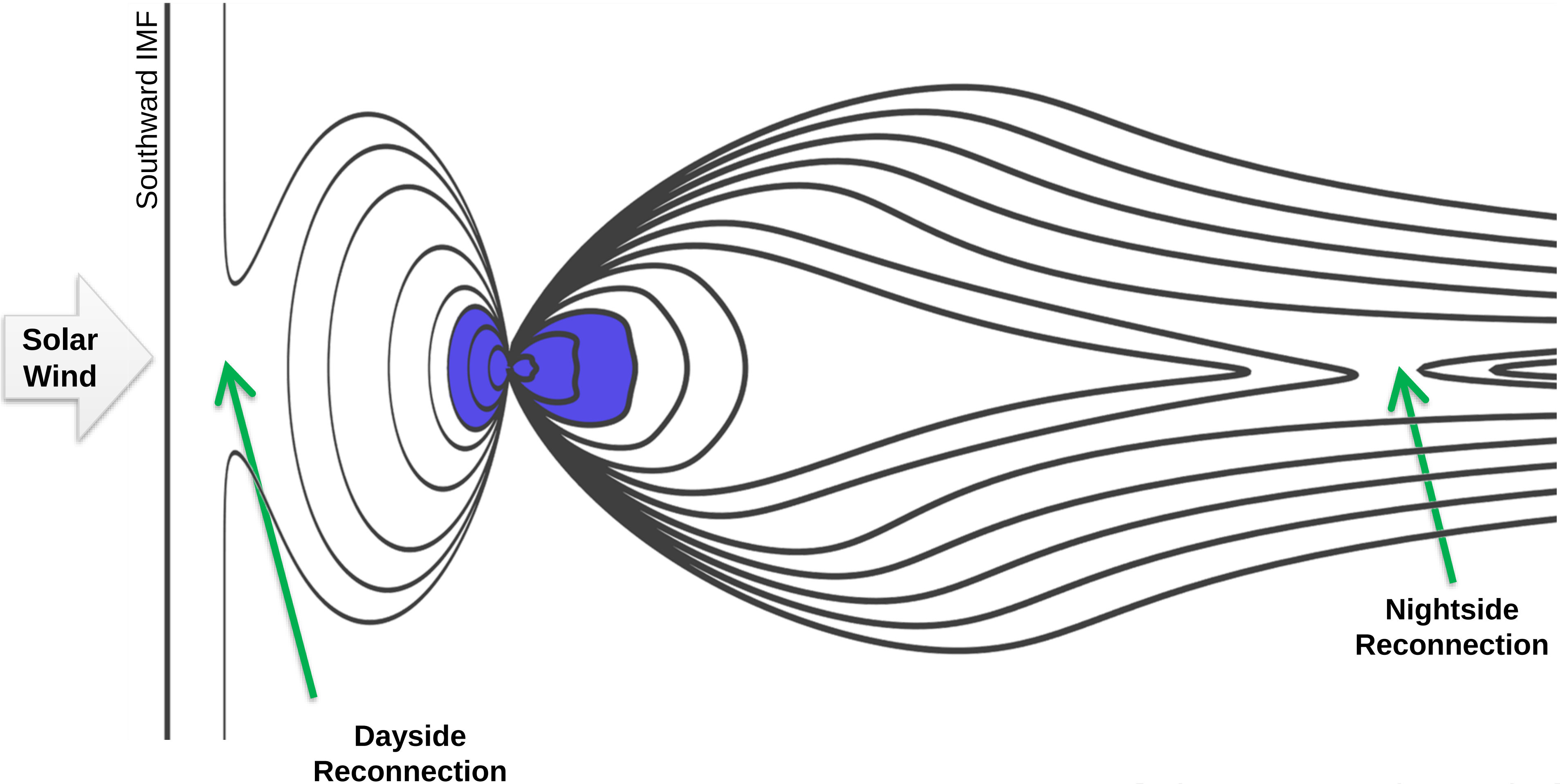
- **X-class flares on 6, 7, and 10 September 2017**
  - acute radio blackouts during the day in the Caribbean
  - with recovery times of tens of minutes to hours, based on the decay time of the flare.

IONOSPHERIC STORMS

Geomagnetic Storms

- Caused by a fast Coronal Mass Ejection (CME) or High Speed Stream (HSS) from the Sun
- The CME or HSS must be Earth-Directed
- There must be an extended period of efficient energy exchange between solar wind and magnetosphere (extended periods of southward Bz and high-speed solar wind).

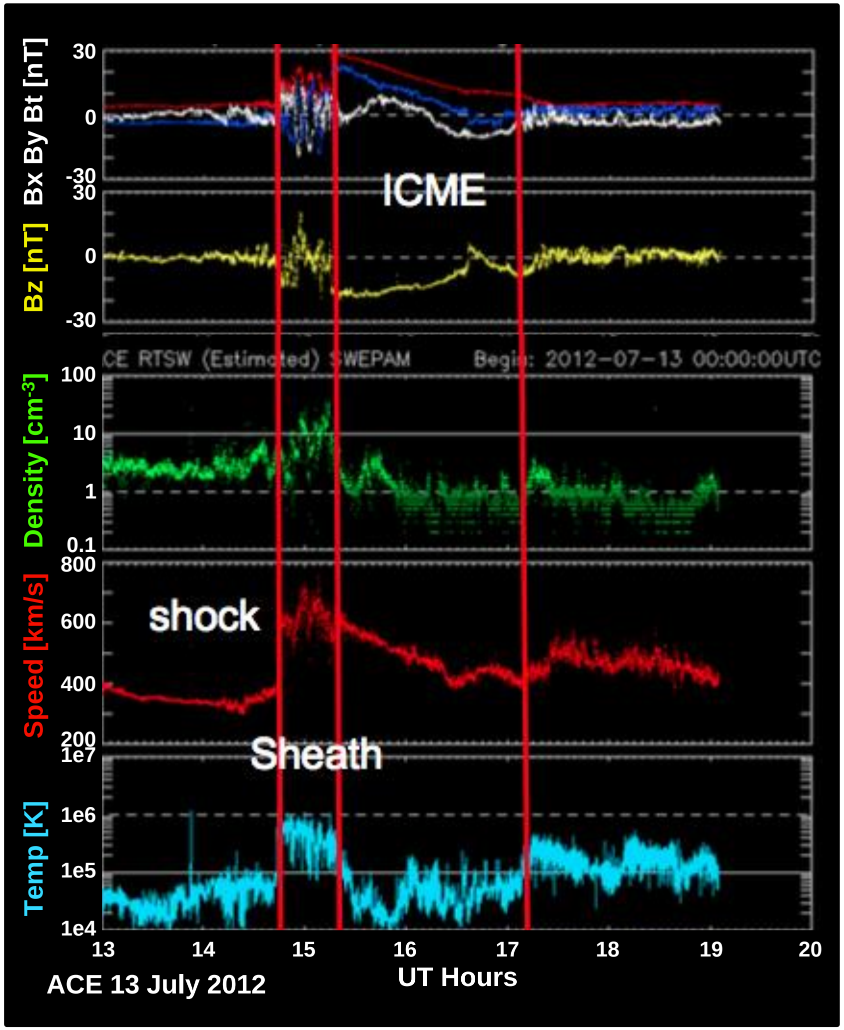
Getting Energy into the Magnetosphere



[Frissell, 2016, Dissertation]

Coronal Mass Ejections (CME)

- Large eruption of plasma and magnetic field from the solar corona.
- More common during solar maximum.
- Most distinguishing feature: A strong magnetic field with large out-of-the-ecliptic components.
- Speeds from 250 to 3000 km/s (0.75-5 days to Earth).
- Slow CMEs merge into solar wind.
- Fast CMEs plow into solar wind and form shock waves.



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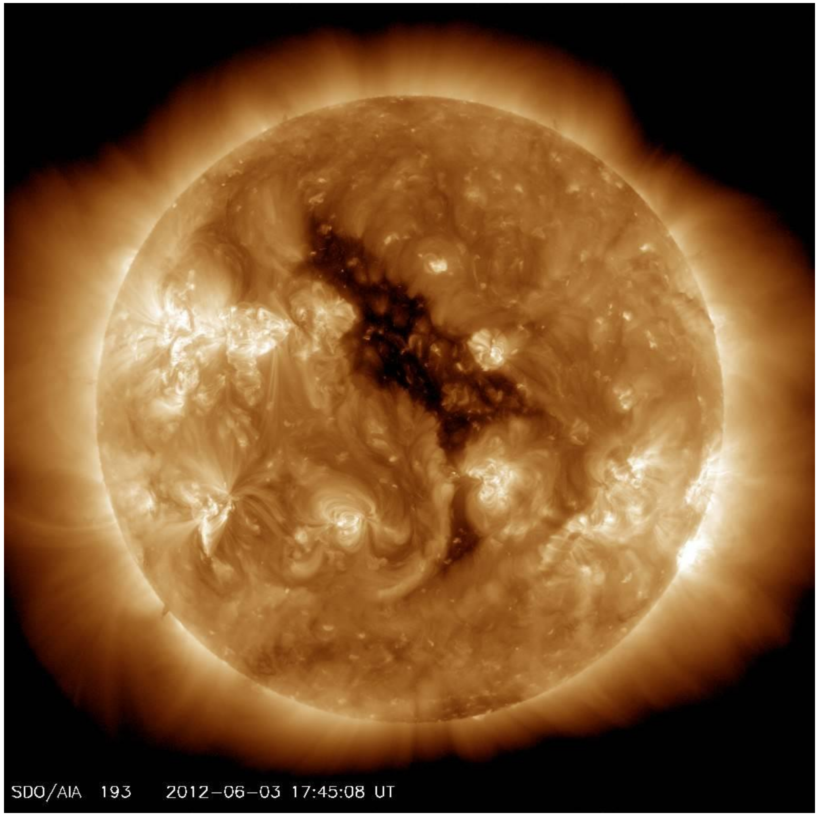
High Speed Streams (HSSs)

- High Speed Streams are fast moving solar wind released from coronal holes.
- HSSs overtaking slow plasma creates compressed Corotating Interaction Regions
- Coronal holes
  - Appear dark in EUV and soft X-ray because of cooler and less dense than surrounding plasma
  - Regions of open, unipolar magnetic fields (this allows HSS to escape)
  - More common during solar minimum
  - Can last through several solar rotations



[NASA SDO]

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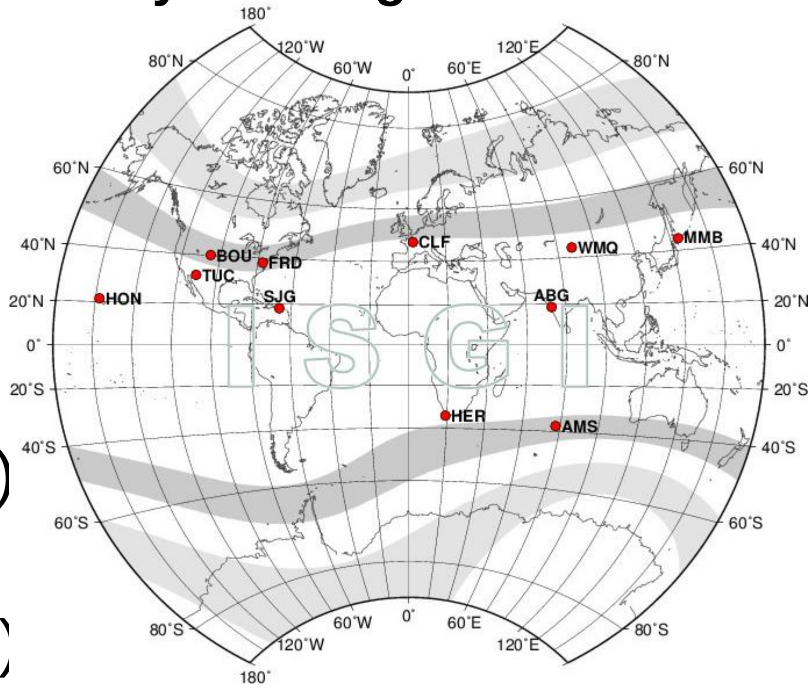
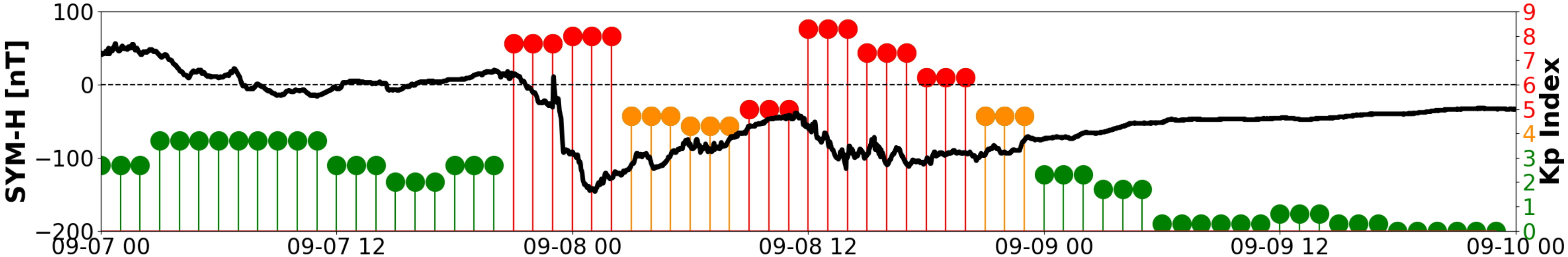
Geomagnetic Storms

- Fast CMEs and CIR/HSSs can lead to geomagnetic storms.
- Defined by negative excursion in
  - Dst (Disturbance Storm Time Index)
  - Sym-H Indices (High resolution version of DST)

Sym-H Magnetometers



http://isgi.unistra.fr/indices_asy.php



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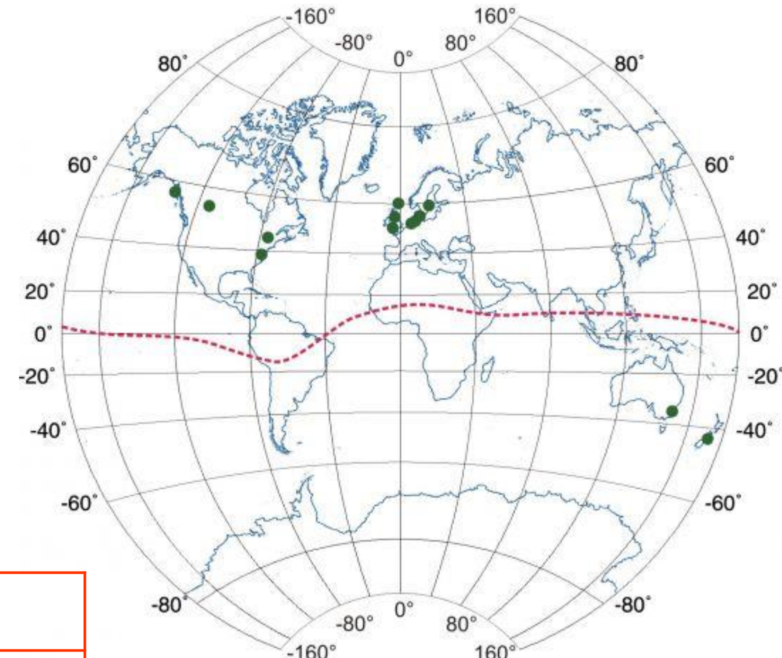
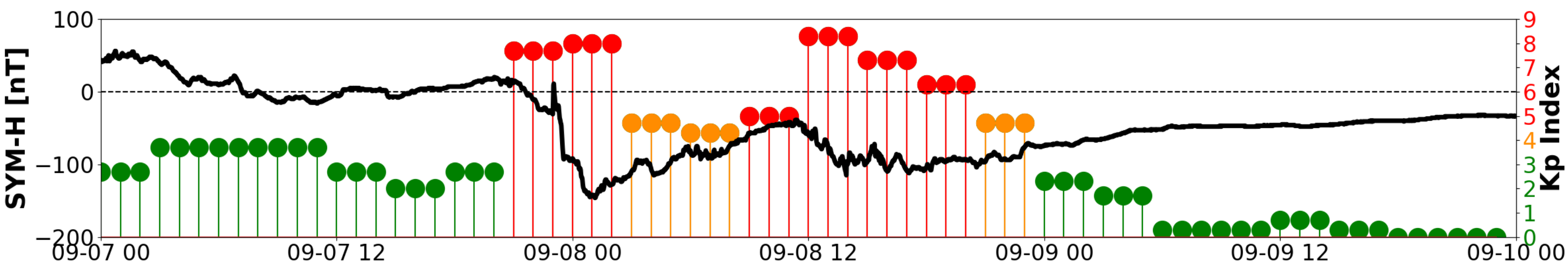
Kp/ap

- Index of geomagnetic perturbation
- Kp is logarithmic, ap is linear
- 3-hour resolution
- “p” stands for planetary
- Perturbations are normalized for each station before being combined into a planetary value.

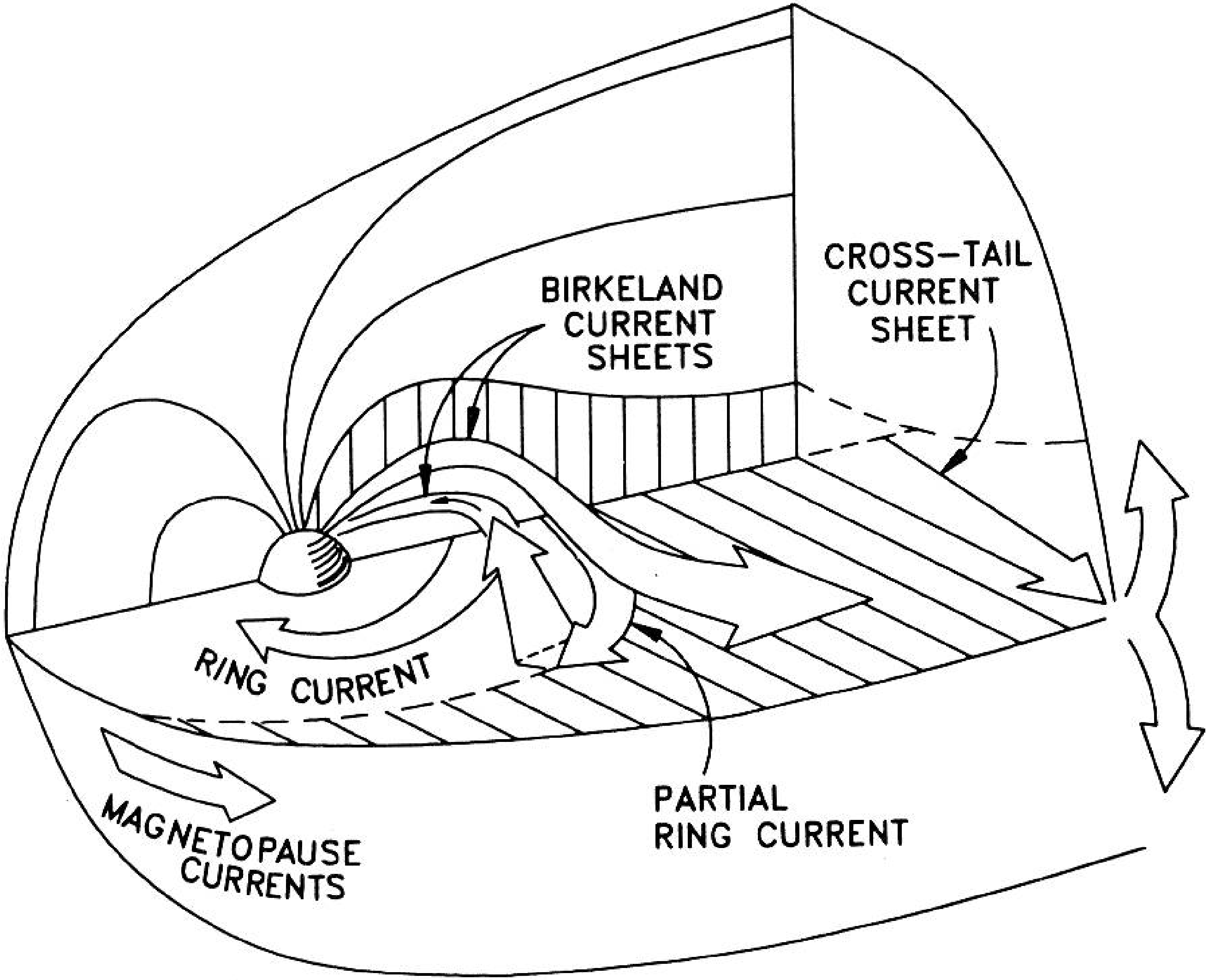


http://roma2.rm.ingv.it/

Kp	0	1	2	3	4	5	6	7	8	9
ap	0	4	7	15	27	48	80	132	207	400



Magnetospheric Current Systems



[Stern, 1994, doi:10.1029/94JA01239]

What is an Ionospheric Storm?

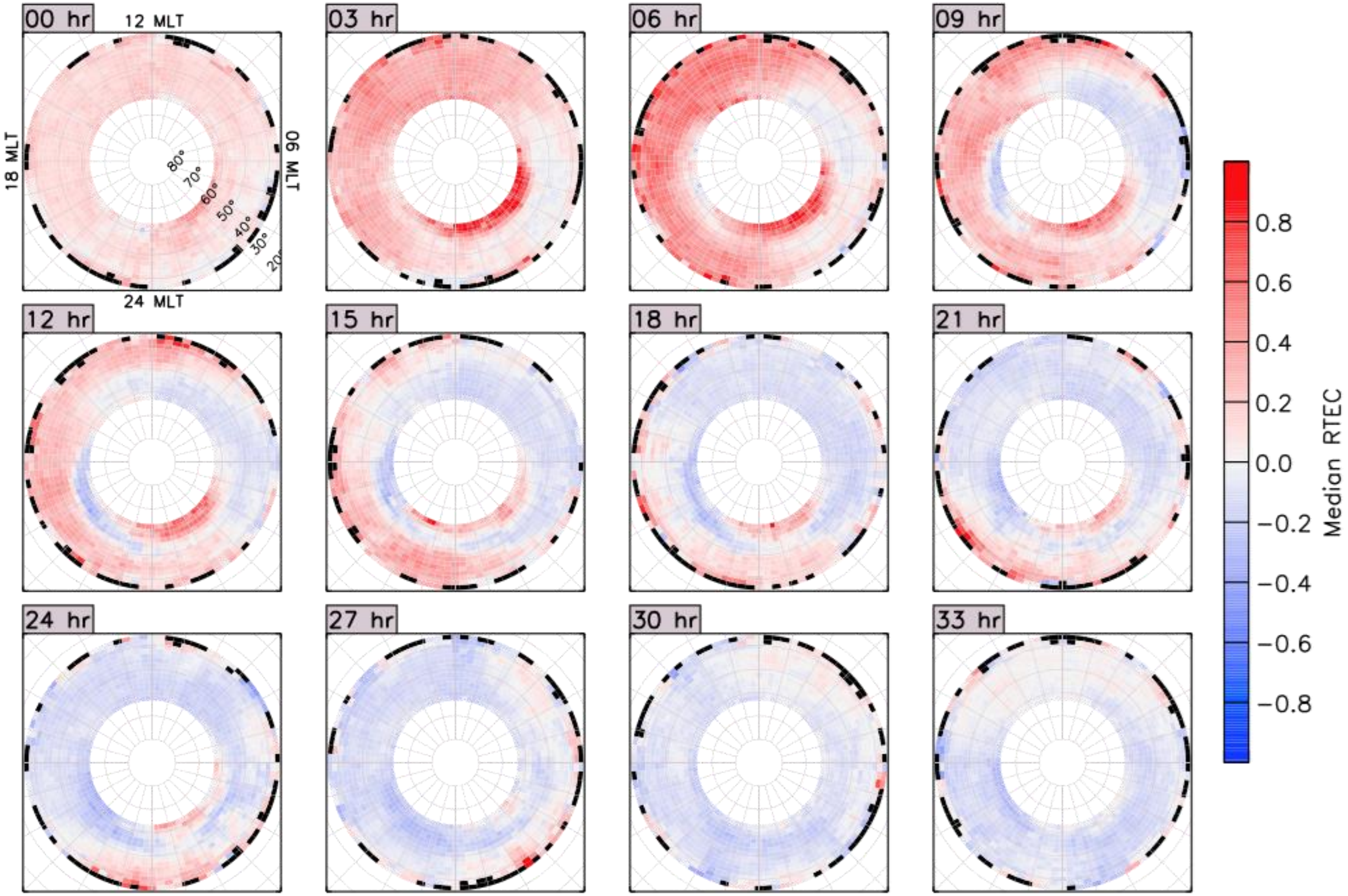
- An ionospheric storm is the specific response of the ionosphere to dynamic features in the solar wind that trigger geomagnetic disturbances throughout the coupled magnetosphere ionosphere system.

  [Thomas et al., 2016, doi:10.1002/2015JA022182]

- Storm time variations in electron densities are typically characterized as
  - Positive: Increase in electron density
  - Negative: Decrease in electron density

  [Matsushita, 1959]

Ionospheric Storm Response



[Thomas et al., 2016, doi:10.1002/2015JA022182]

September 2017 Storms

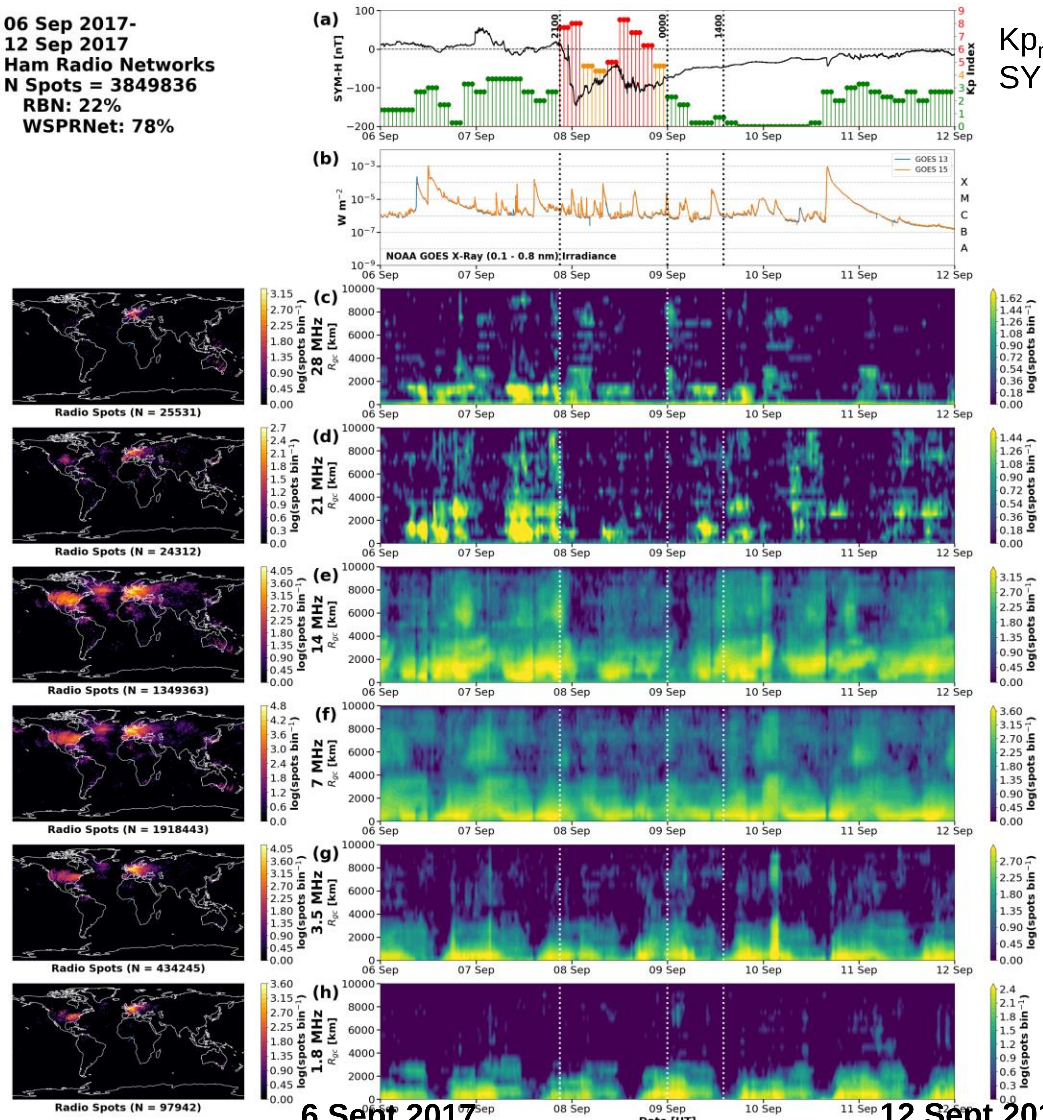
- Numerous solar flares and CME-induced interplanetary shocks occurred September 4-14, 2017, disrupting HF (3-30 MHz) communications.

Global Response to Geomagnetic Storm

8 Sept 2100 UT
- Storm Onset

9 Sept 0000 UT
- Geomagnetic Quiet

9 Sept 1400 UT
- Radio Recovery



Kp_{max} = 8+
SYM-H_{min} = -146 nT

28 MHz
21 MHz
14 MHz
7 MHz
3.5 MHz
1.8 MHz

6 Sept 2017 — 12 Sept 2017

[*Frissell et al.*, 2019, doi:10.1029/2018SW002008]

500 km × 30 min bins

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Z-Score

$$z = \frac{x - \mu}{\sigma}$$

Quiet Time Baseline

- 2016-2017
- -25 < SYM-H < 25 nT
- K_p < 3
- n = 283 days

7, 14 MHz

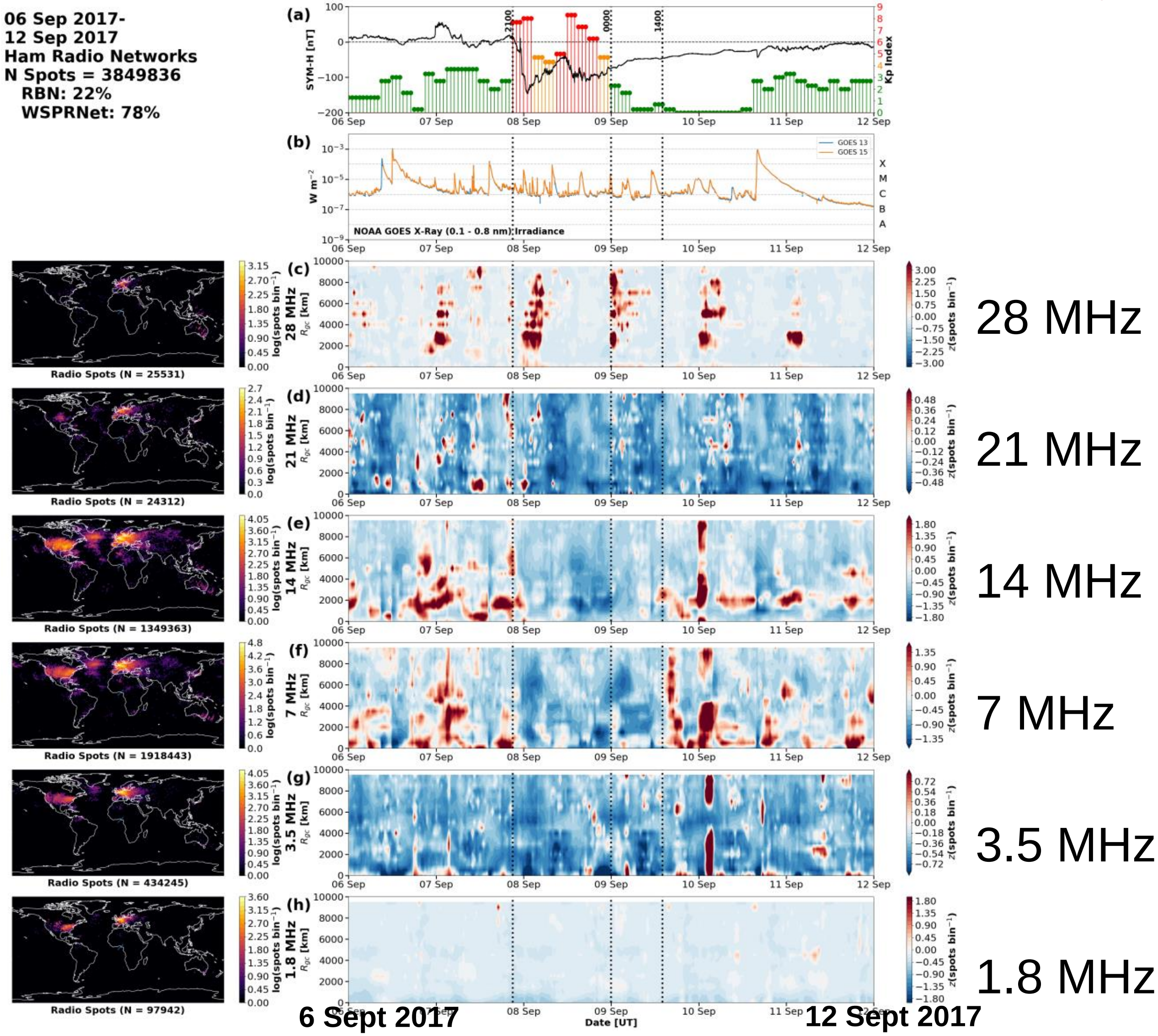
- Clearly below average during storm

1.8, 3.5, 21 MHz

- Inconclusive

28 MHz

- Above average… more work to be done here…



500 km × 30 min bins

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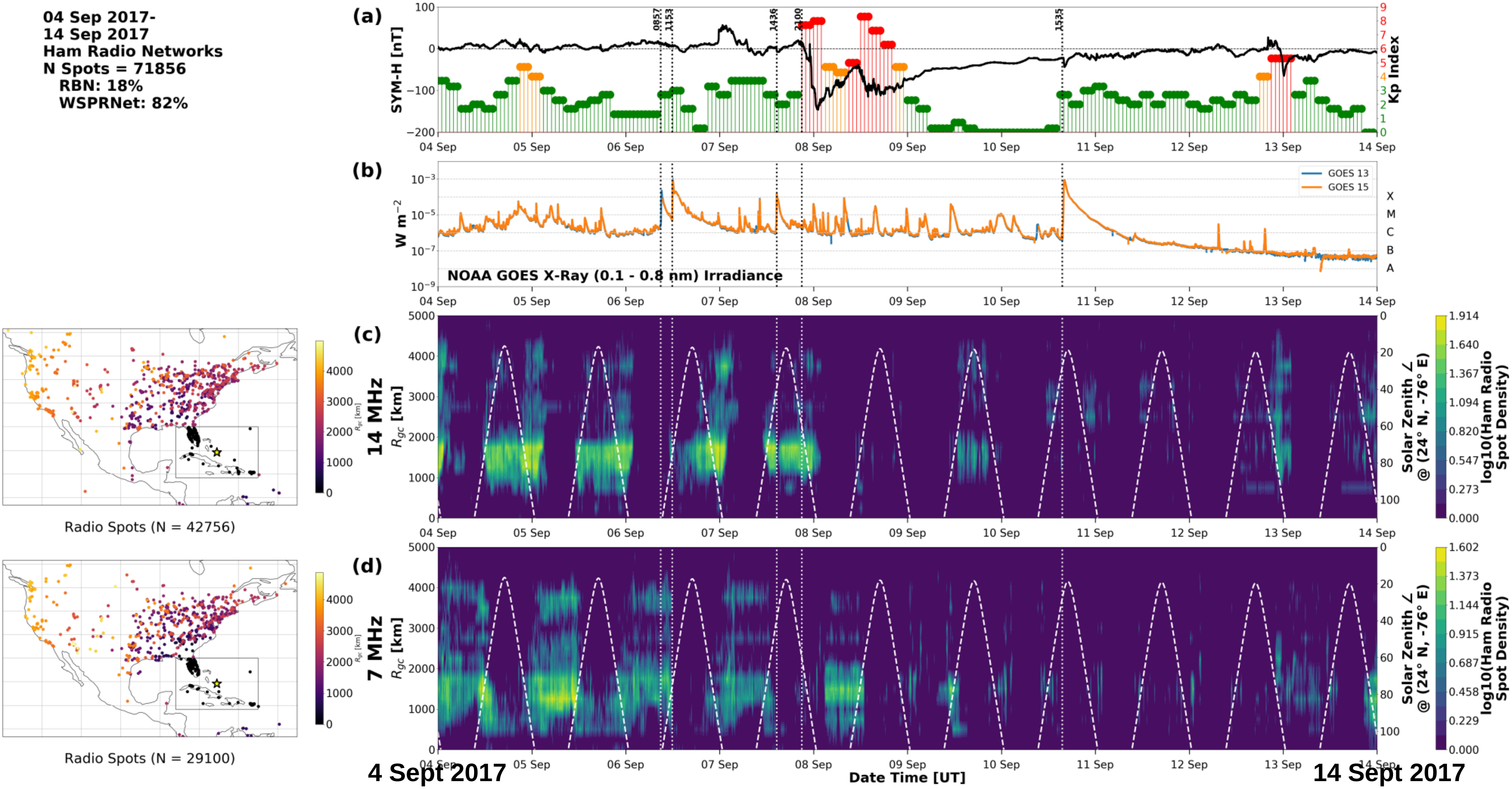
Caribbean Response



[*Frissell et al.*, 2019, doi:10.1029/2018SW002008]

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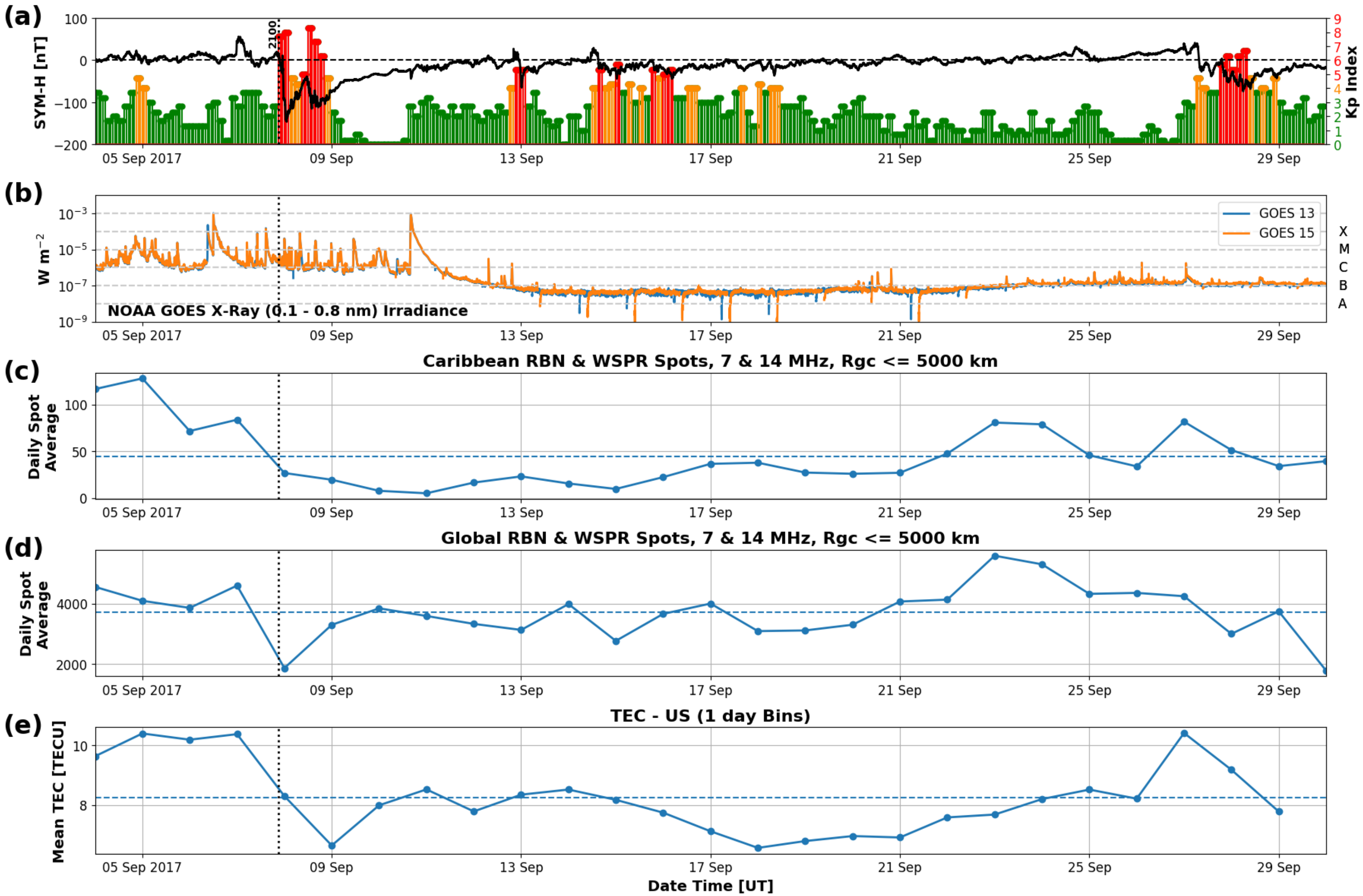
Comparison to Mean US TEC



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Ionospheric Storms Summary

- **Severe geomagnetic storm 7-10 September 2017**
  - Kp_{max} = 8+ and SYM-H_{min} = -146 nT
  - wiped out ionospheric communications first on 14 MHz and then on 7 MHz starting at ~1200 UT 8 September.

TRAVELING IONOSPHERIC DISTURBANCES

Traveling Ionospheric Disturbances

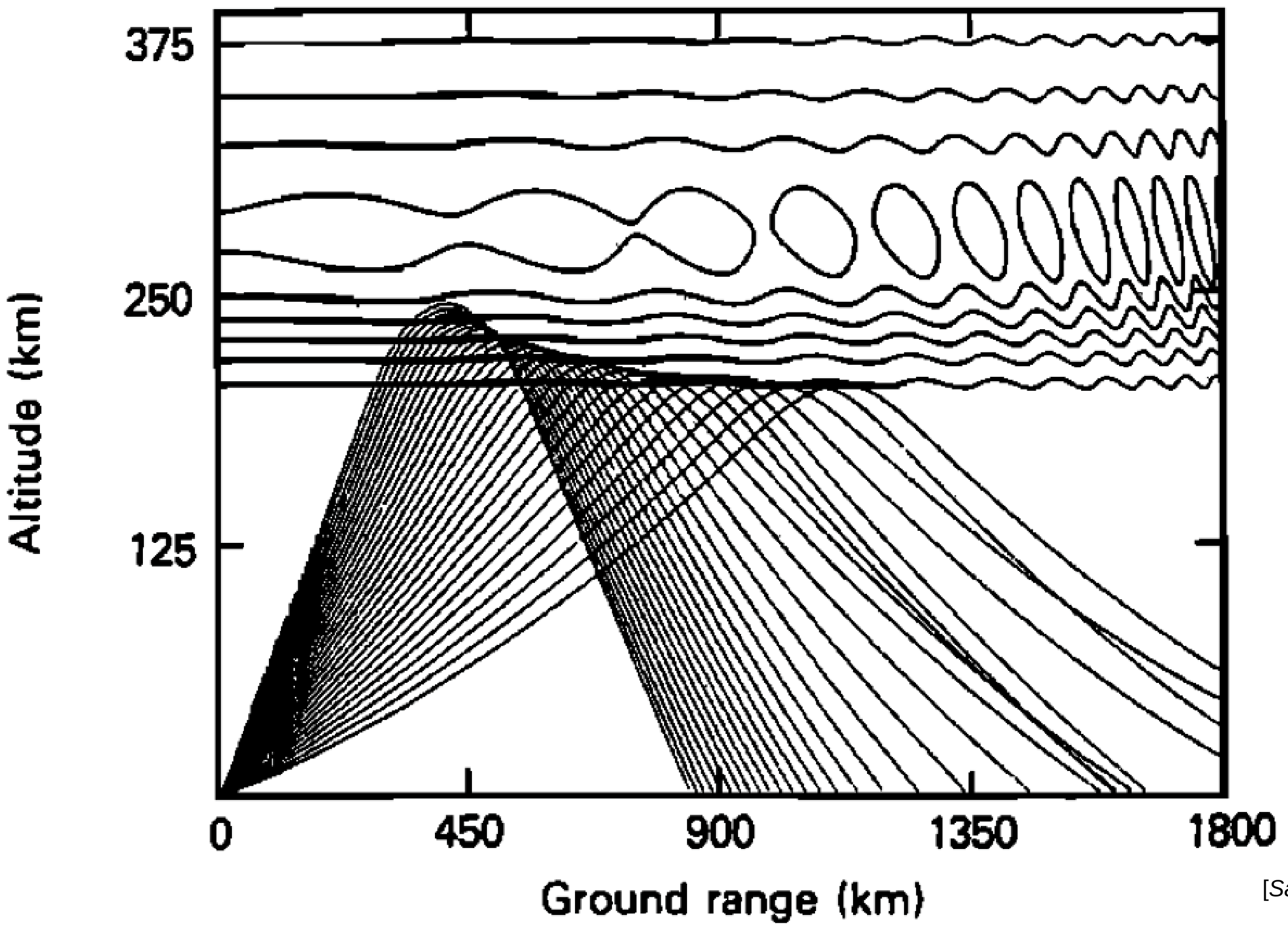
- **TIDs are Quasi-periodic Variations of F Region Electron Density**
  - **Medium Scale (MSTID)**
    - $T \approx 15 - 60$ min
    - $v_H \approx 100 - 250$ m/s
    - $\lambda_H \approx$ Several Hundred km (< 1000 km)
    - Often Meteorological Sources
  - **Large Scale (LSTID)**
    - $\lambda_h > 1000$ km
    - $30 < T$ [min] < 180
    - Often Auroral Electrojet Enhancement, Particle Precipitation
- **Often associated with Atmospheric Gravity Waves**

[*Francis*, 1975; *Hunsucker* 1982; Ogawa et al., 1967; *Ding* et al., 2012; *Frissell et al.*, 2014; 2016]

- **Typically thought to be caused by**
  - **Auroral/Space Weather Activity**
  - **Lower/Middle Atmospheric Disturbances**

Traveling Ionospheric Disturbances

MSTIDs are a type of HF Fading



[*Samson et al.*, 1990]

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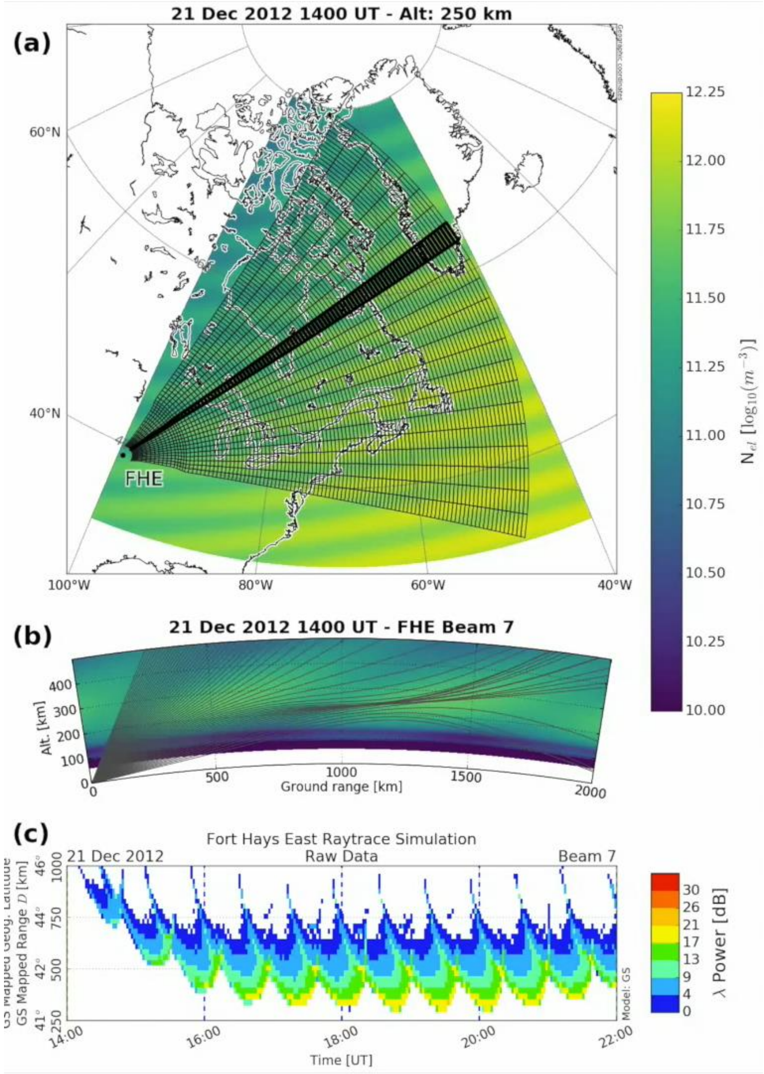
Traveling Ionospheric Disturbances



Ray trace simulation illustrating how SuperDARN HF radars observe MSTIDs.

(a) Fort Hays East (FHE) radar field of view superimposed on a 250 km altitude cut of a perturbed IRI. FHE Beam 7 is outlined in bold.

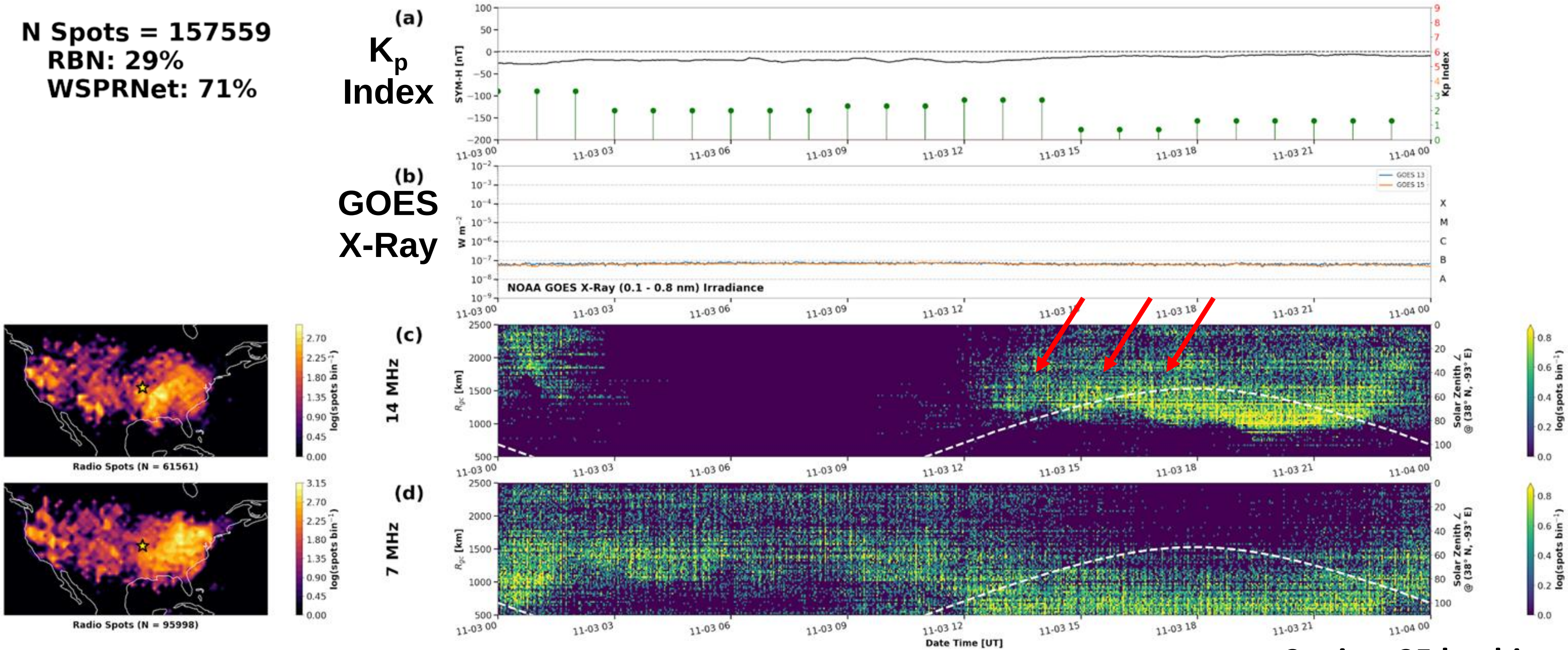
(b) Vertical profile of 14.5 MHz ray trace along FHE Beam 7. Background colors represent perturbed IRI electron densities. The areas where rays reach the ground are potential sources of backscatter.

(c) Simulated FHE Beam 7 radar data, color coded by radar backscatter power strength. Periodic, slanted traces with negative slopes are the signatures of MSTIDs moving toward the radar.

[Frissell et al., 2016]

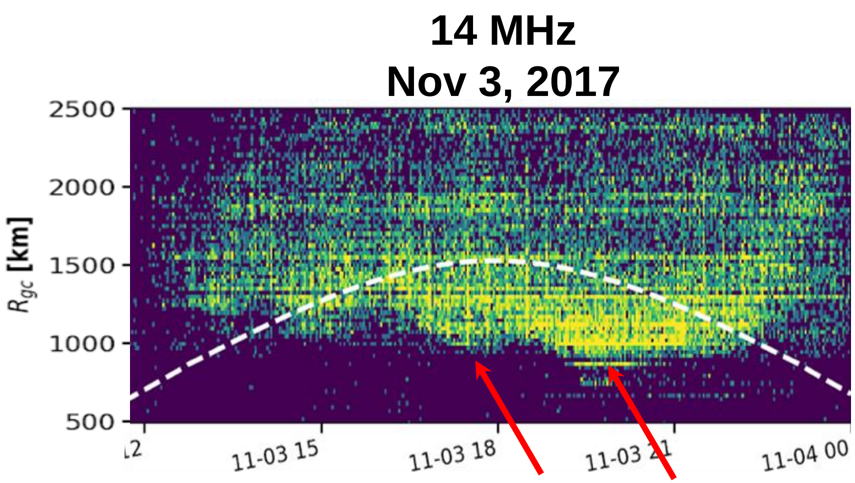
Ham Radio TIDs

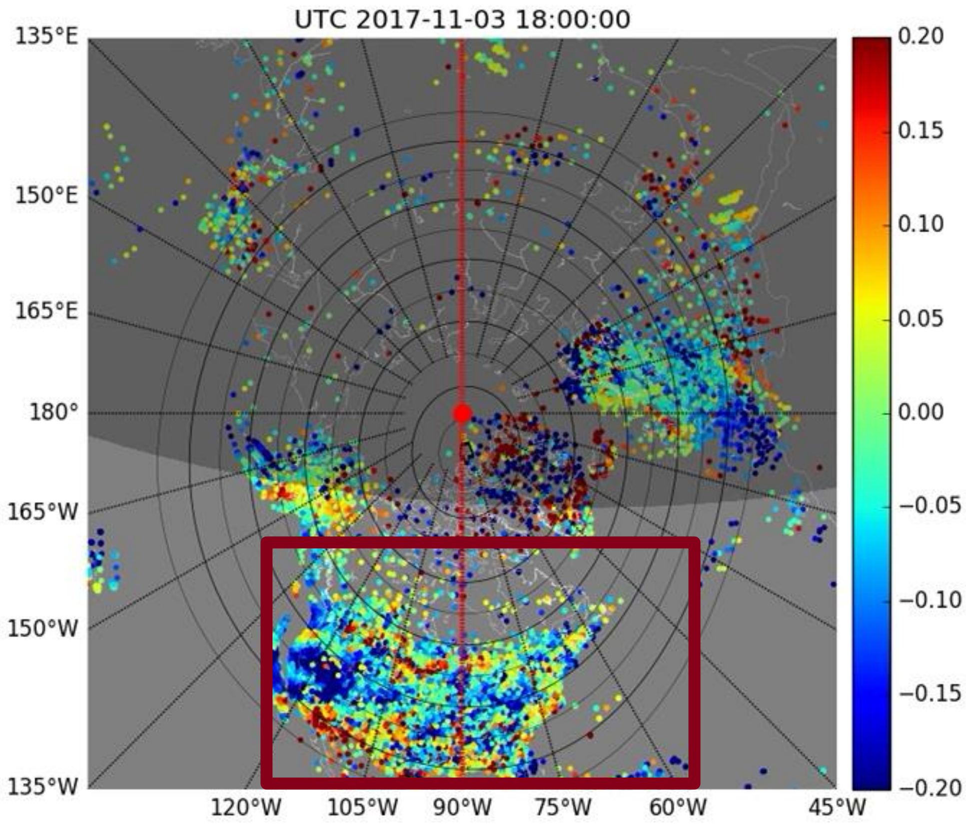
N Spots = 157559
RBN: 29%
WSPRNet: 71%



2 min x 25 km bins

GNSS TEC Comparison 18:00 - 21:00





- Radio range is shortest when TEC is red (higher TEC)
- Higher electron densities → More HF refraction, communication range decreases

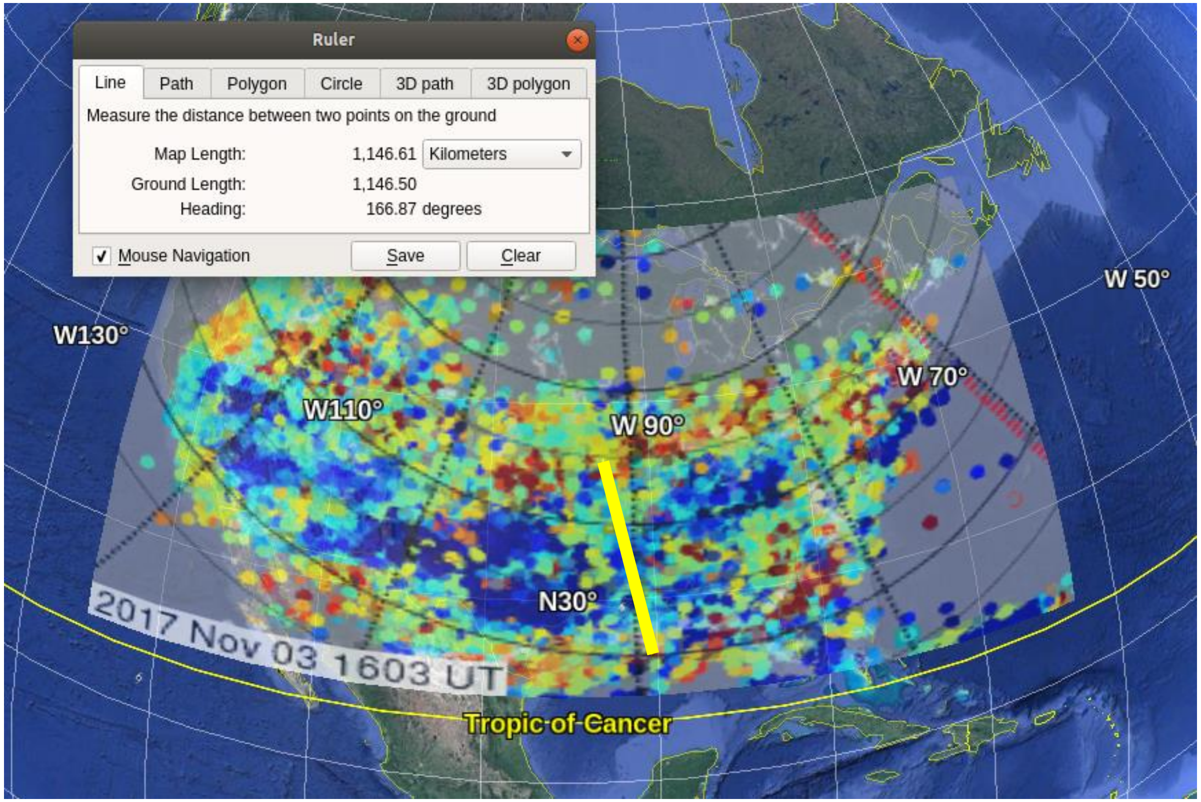
Estimated GNSS TEC LSTID Parameters

$\lambda_h \approx$ 1,100 km

$v_p \approx$ 950 km/hr

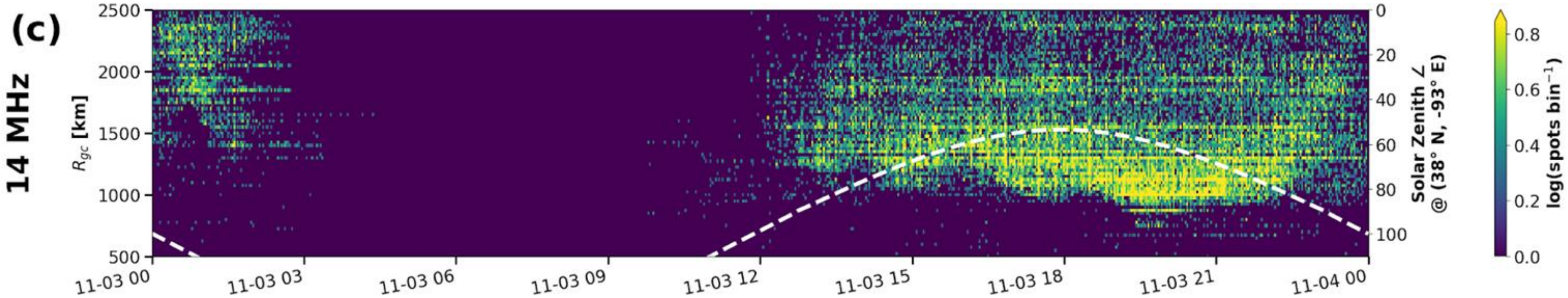
$T \approx$ 70 min

$\Phi_{Azm} \approx 135°$



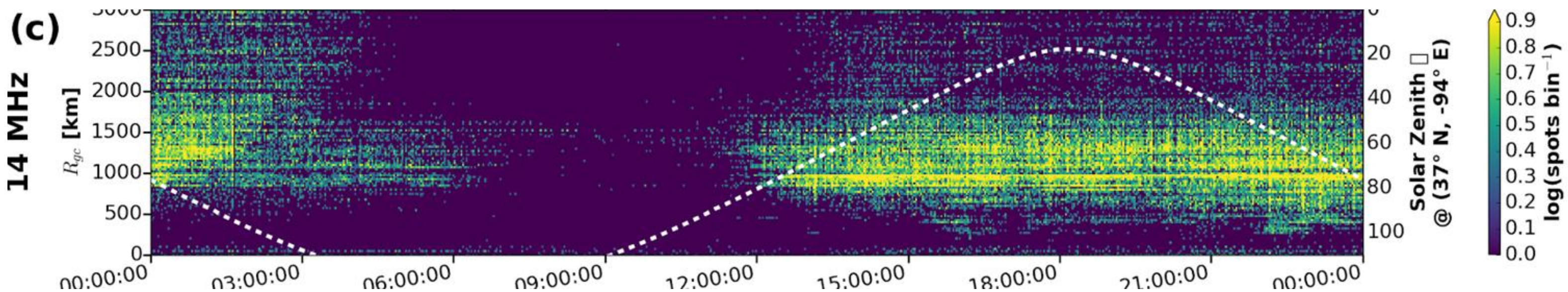
14 MHz Plot Comparisons

03 Nov 2017-
04 Nov 2017
Ham Radio Networks
N Spots = 157559
RBN: 29%
WSPRNet: 71%



3 Nov 2017 **4 Nov 2017**

16 May 2017-
17 May 2017
Ham Radio Networks
N Spots = 169822
RBN: 12%
WSPRNet: 88%



16 May 2017 **17 May 2017**

2 min x 25 km bins

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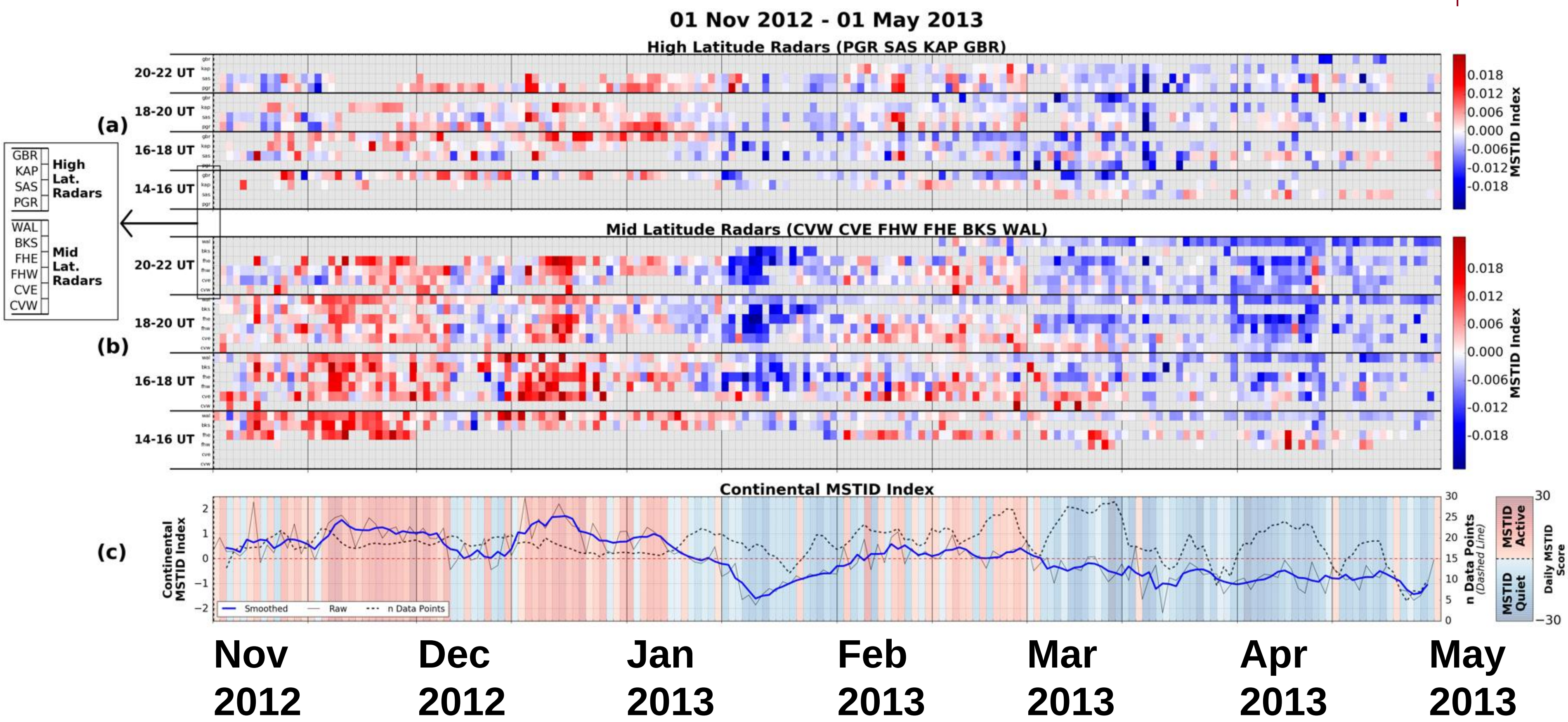
MSTIDs Nov 2012 – May 2013

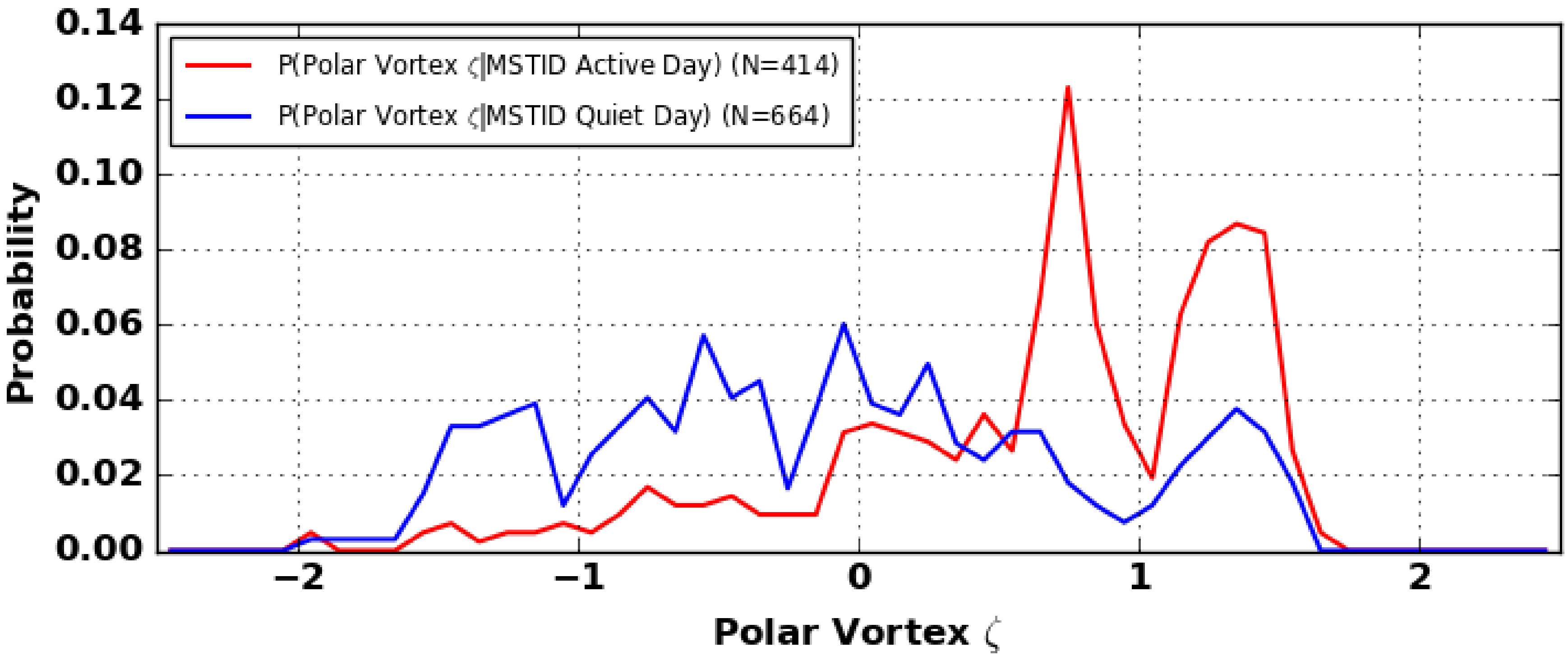


MSTID Active

MSTID Quiet

[Frissell et al., 2016]

Correlation with Polar Vortex!



MSTID Active

MSTID Quiet

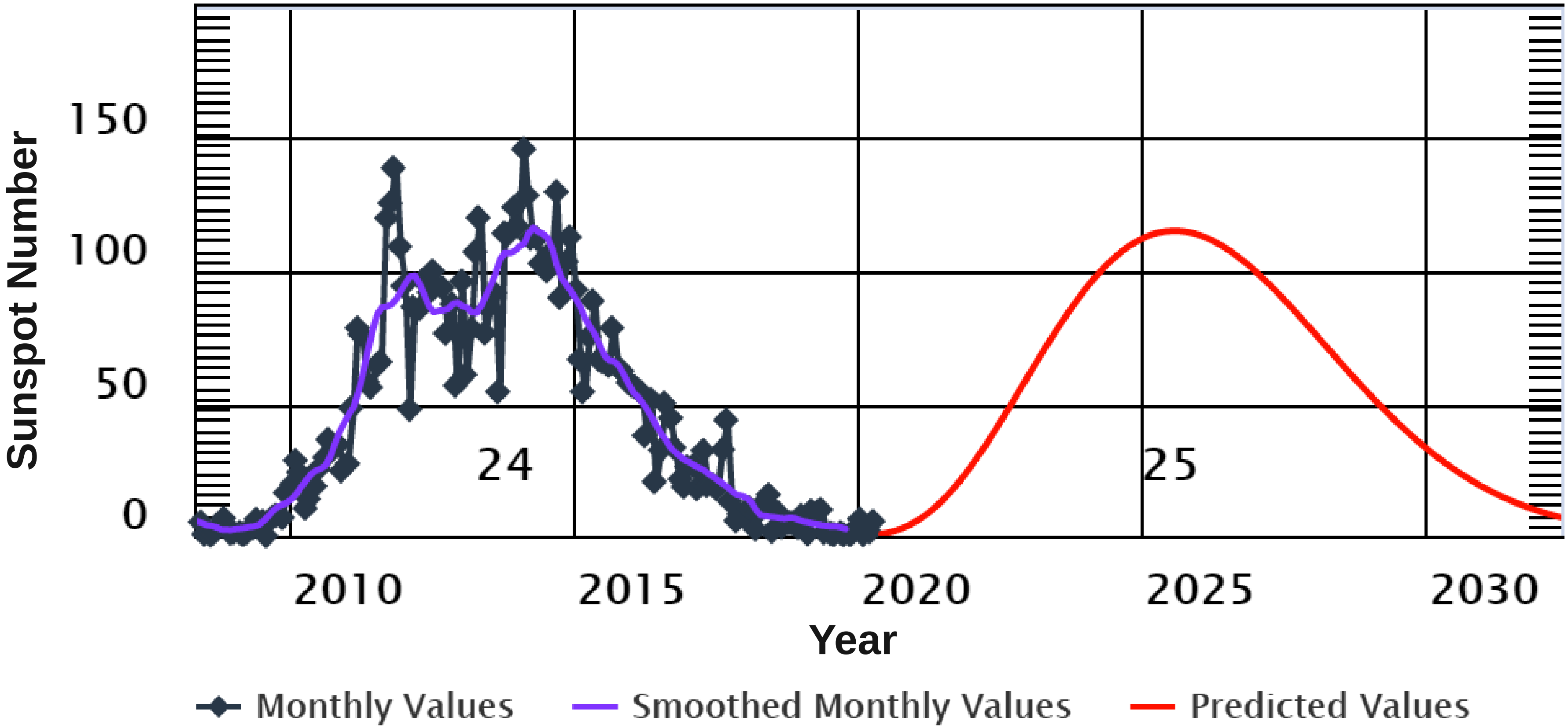
SOLAR CYCLE FORECAST

Solar Cycle Forecast

- The forecast comes from the Solar Cycle Prediction Panel representing NOAA, NASA and the International Space Environmental Services (ISES).
- This amounts to the 'official' forecast for the solar cycle.
- The Prediction Panel forecasts the sunspot number expected for solar maximum and has predicted **Cycle 25** to reach a **maximum of 115** occurring **in July 2025**.
- The error bars on this prediction mean the panel expects the cycle maximum could be between 105-125 with the peak occurring between November 2024 and March 2026.

Source: NOAA Space Weather Prediction Center
Downloaded May 2, 2020
https://www.swpc.noaa.gov/products/solar-cycle-progression

NOAA-ISES Sunspot Progression



Source: NOAA Space Weather Prediction Center
Downloaded May 2, 2020
https://www.swpc.noaa.gov/products/solar-cycle-progression

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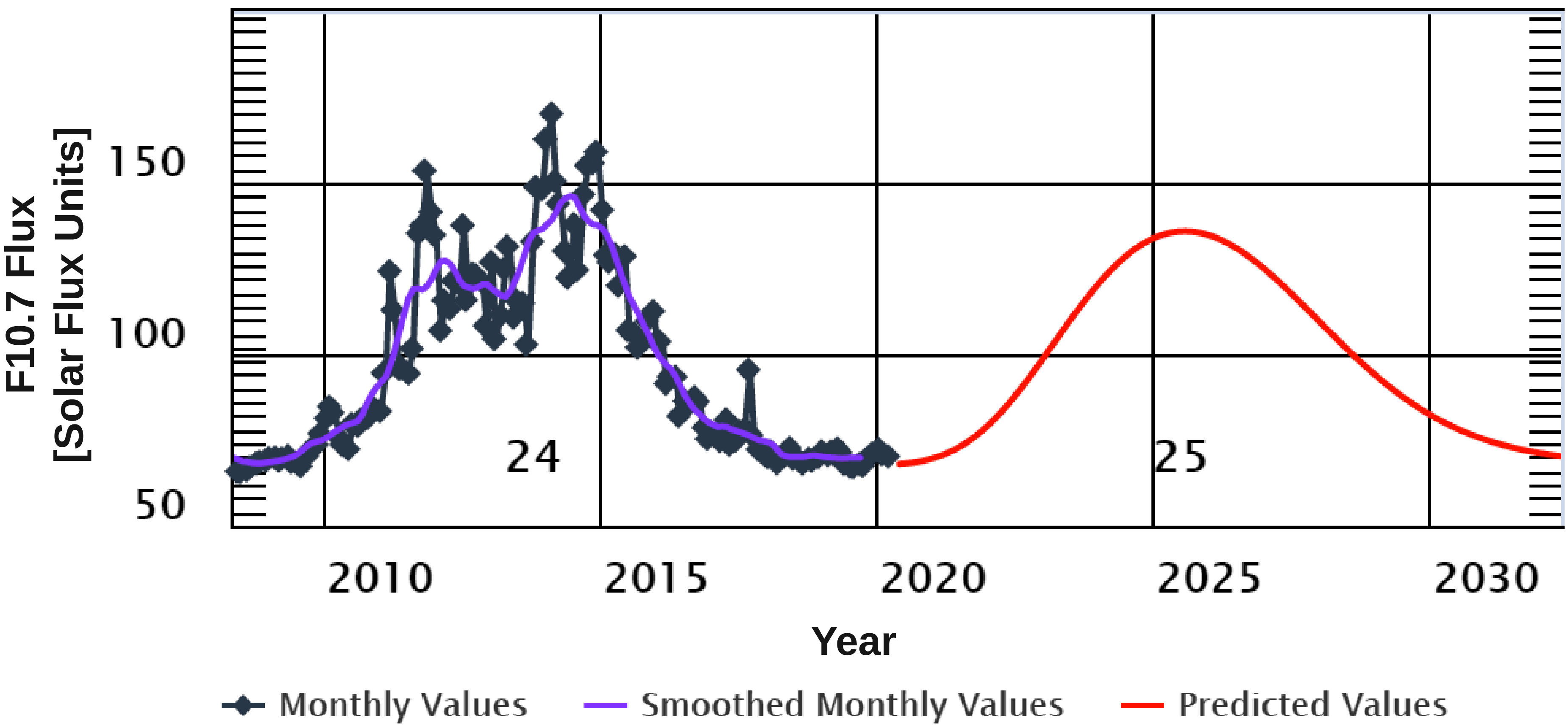
NOAA-ISES F10.7 Progression



Source: NOAA Space Weather Prediction Center
Downloaded May 2, 2020
https://www.swpc.noaa.gov/products/solar-cycle-progression

The Big Take Away

- The ionosphere and HF propagation are highly variable! (Contesters certainly know this…)
- Models often portray the ionosphere as a smoothed, monthly median model.
- This is not reality, and understanding what causes all of the short-term variability is still an area of very active research.
- But, we can understand certain phenomena, which can help with contesting strategy.
- And the part that we don't understand is part of what keeps contesting fun!

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THANK YOU!

References

- Ding, F., Wan, W., Ning, B., Zhao, B., Li, Q., Zhang, R., Xiong, B., and Song, Q. (2012), Two-dimensional imaging of large-scale traveling ionospheric disturbances over China based on GPS data, J. Geophys. Res., 117, A08318, doi:10.1029/2012JA017546.
- Francis, S. H. (1975), Global propagation of atmospheric gravity waves: A review, J. Atmos. Terr. Phys., 37, 1011–1054, doi:10.1016/0021-9169(75)90012-4.
- Frissell, N. A., Baker, J. B. H., Ruohoniemi, J. M., Gerrard, A. J., Miller, E. S., Marini, J. P., West, M. L., & Bristow, W. A. (2014), Climatology of medium-scale traveling ionospheric disturbances observed by the midlatitude Blackstone SuperDARN radar, Journal Of Geophysical Research: Space Physics, http://dx.doi.org/10.1002/2014JA019870.
- Frissell, N. A., J. B. H. Baker, J. M. Ruohoniemi, R. A. Greenwald, A. J. Gerrard, E. S. Miller, and M. L. West (2016), Sources and characteristics of medium-scale traveling ionospheric disturbances observed by high-frequency radars in the North American sector, J. Geophys. Res. Space Physics, 121, 3722–3739, doi:10.1002/2015JA022168.
- Frissell, N. A., Katz, J. D., Gunning, S. W., Vega, J. S., Gerrard, A. J., Earle, G. D., et al. (2018). Modeling amateur radio soundings of the ionospheric response to the 2017 great American eclipse. Geophysical Research Letters, 45, 4665– 4674. https://doi.org/10.1029/2018GL077324
- Frissell, N. A., Vega, J. S., Markowitz, E., Gerrard, A. J., Engelke, W. D., Erickson, P. J., et al. (2019). High-frequency communications response to solar activity in September 2017 as observed by amateur radio networks. Space Weather, 17, 118–132. https://doi.org/10.1029/2018SW002008
- Hunsucker, R. D. (1982), Atmospheric gravity waves generated in the high-latitude ionosphere: A review, Rev. Geophys., 20(2), 293–315, doi:10.1029/RG020i002p00293.
- Ogawa, T., K. Igarashi, K. Aikyo, and H. Maeno (1987), NNSS satellite observations of medium-scale traveling ionospheric disturbances at southern high-latitudes, J. Geomagn. Geoelectr., 39, 709–721.
- Matsushita, S. (1959), A study of the morphology of ionospheric storms, J. Geophys. Res., 64(3), 305–321, https://doi.org/10.1029/JZ064i003p00305.
- Rideout, W., Coster, A. Automated GPS processing for global total electron content data. GPS Solut 10, 219–228 (2006). https://doi.org/10.1007/s10291-006-0029-5
- Stern, D. P. (1994), The art of mapping the magnetosphere, J. Geophys. Res., 99(A9), 17169–17198, doi: 10.1029/94JA01239.
- Thomas, E. G., Baker, J. B. H., Ruohoniemi, J. M., Coster, A. J., and Zhang, S.-R. (2016), The geomagnetic storm time response of GPS total electron content in the North American sector, J. Geophys. Res. Space Physics, 121, 1744– 1759, https://doi.org/10.1002/2015JA022182.
- Tsugawa, T., Otsuka, Y., Coster, A. J., and Saito, A. (2007), Medium-scale traveling ionospheric disturbances detected with dense and wide TEC maps over North America, Geophys. Res. Lett., 34, L22101, doi:10.1029/2007GL031663.

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