Modeling Diurnal HF Signal Absorption in the Ionosphere: D, E, and F-Layer Effects from Citizen Science-Based GRAPE Receiver Observations

Gamal Zayed [1,4], Nathaniel Frissell [2,4], Kuldeep Pandey [3,4]

[1]The American University in Cairo (AUC)
[2]Department of Physics and Engineering, The University of Scranton, Scranton, PA, United States
[3]New Jersey Institute of Technology, Newark, PA, United States
[4]Ham Radio Science Citizen Investigation (HamSCI), Scranton, PA, United States

The European Space Weather Week (ESWW) Workshop 2025, Umeå, Sweden

gamal.zayed@aucegypt.edu

Objectives

- *Regenerating* a successful reception on April 8, 2001, 7 UTC @5,10 and 15 MHz
  from WWV, Colorado to W2NAF Spring Brook, Scranton
- *Understanding* the Total Absorption Loss profile for each HF ray.
- A dream: *Developing* PyLAP (D-Region & during eclipses) -> a good model for signal strength.

A Good Learner is a Good Developer!

Special Thanks

Special thanks to Prof. Nathaniel A. Frissell (W2NAF), lead of the Ham Radio Science Citizen Investigation (HamSCI).

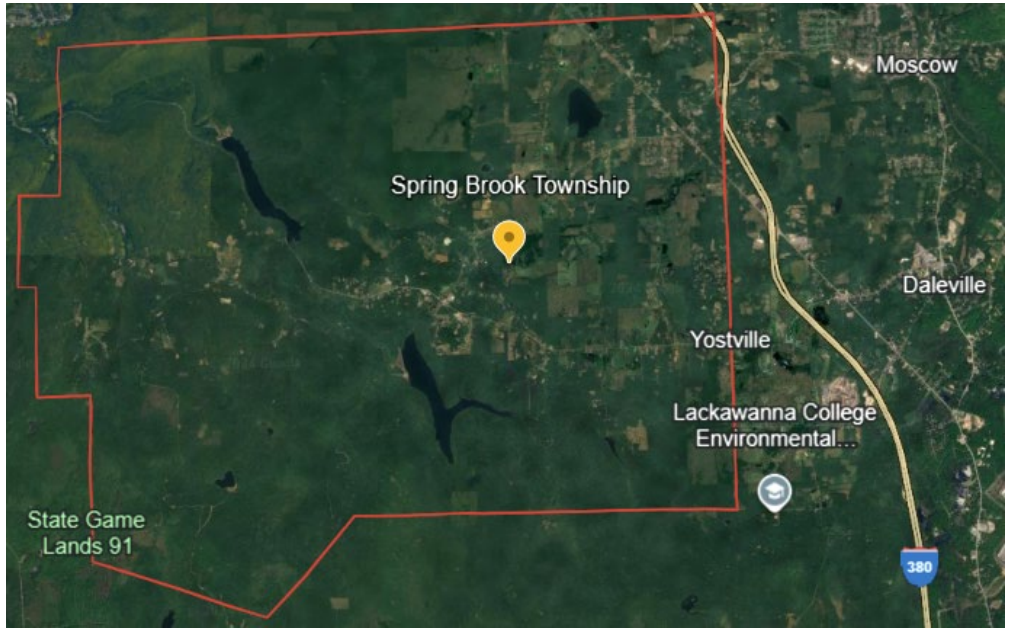
Special thanks to David McGaw N1HAC (Dartmouth College), Mr. Gary Mikitin (AF8A), Radio Operators Expert, and Mr. Bill Liles (NQ6Z), HamSCI Community Diversity Recruitment Chair, and Case Western Reserve University in collaboration with the University of Scranton for their invaluable contributions. Special thanks for the financial support of U.S. National Science Foundation Grant AGS-2404997 and Amateur Radio Digital Communications (ARDC).

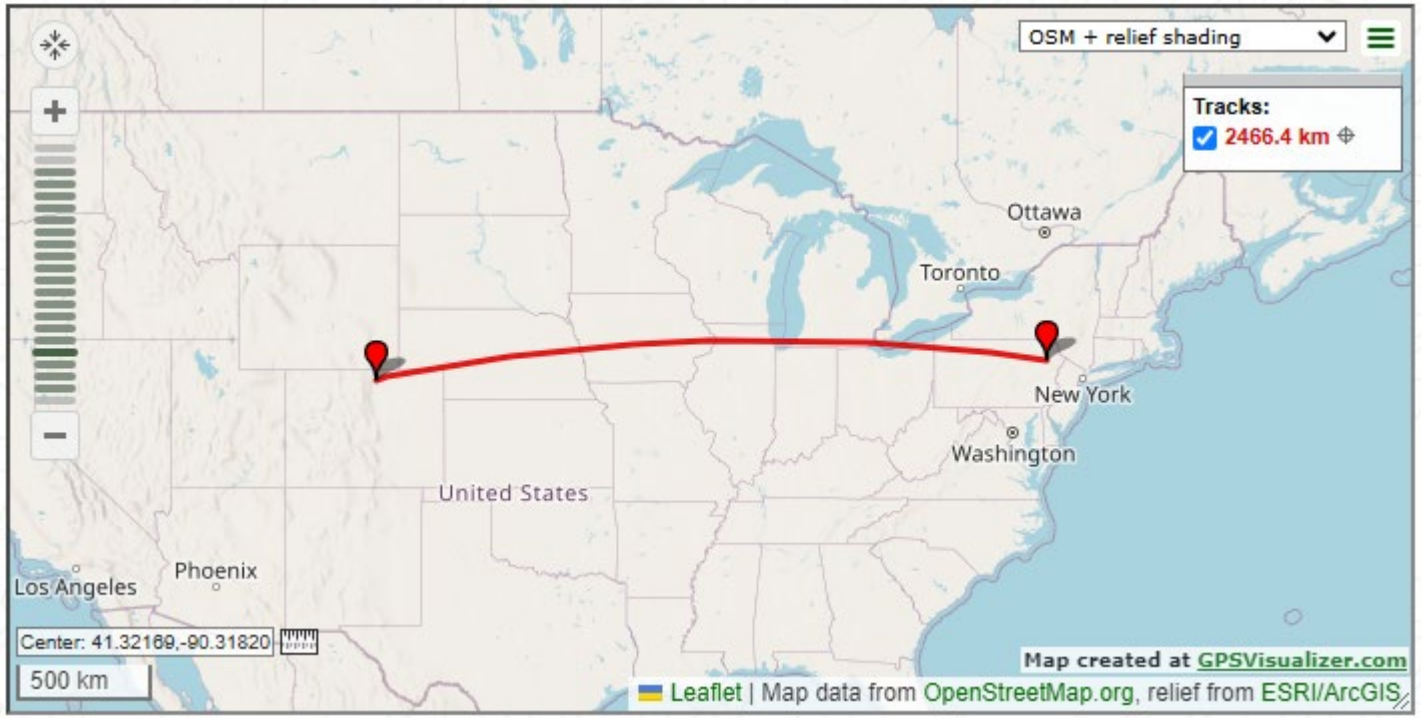
From WWV (Fort Collins, Colorado)

- Latitude: 40.6758
- Longitude: -105.0389

WWV - Callsign Lookup by QRZ Ham Radio, [15]

To Spring Brook, Pennsylvania (PA), USA





[16] https://www.gpsvisualizer.com/display/map/20241101135441-47194-map.html

Calculate the great circle distance between two points

This calculator will find the distance between two pairs of coordinates to a very high degree of precision (using the thoroughly nasty Vincenty Formula, which accounts for the flattened shape of the earth). The "Draw map" button will show you the two points on a map and draw the great circle route between them.

Lat., Lon. 1: 40.6758, -105.0385

Lat., Lon. 2: 41.3076, -75.5975

—>

2466.436 k
1532.572 r
1331.769 r

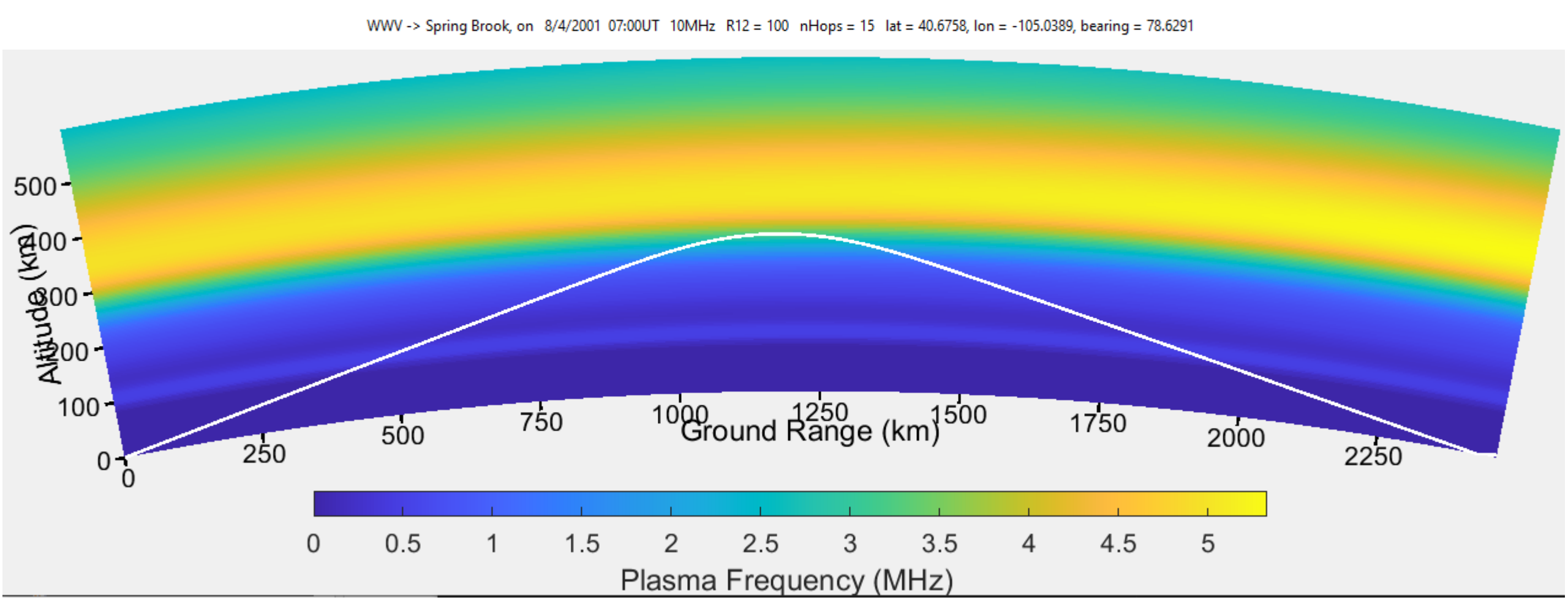
78.629° initial bearing (approximate)

Draw map

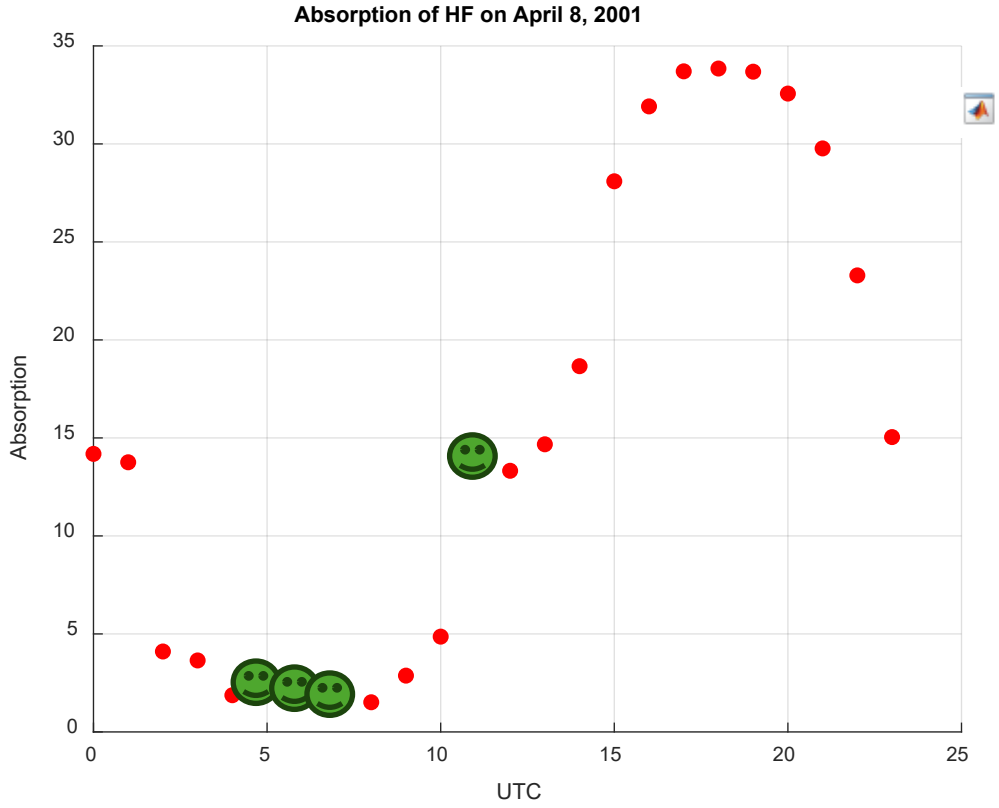
output format: Leaflet map

units: km

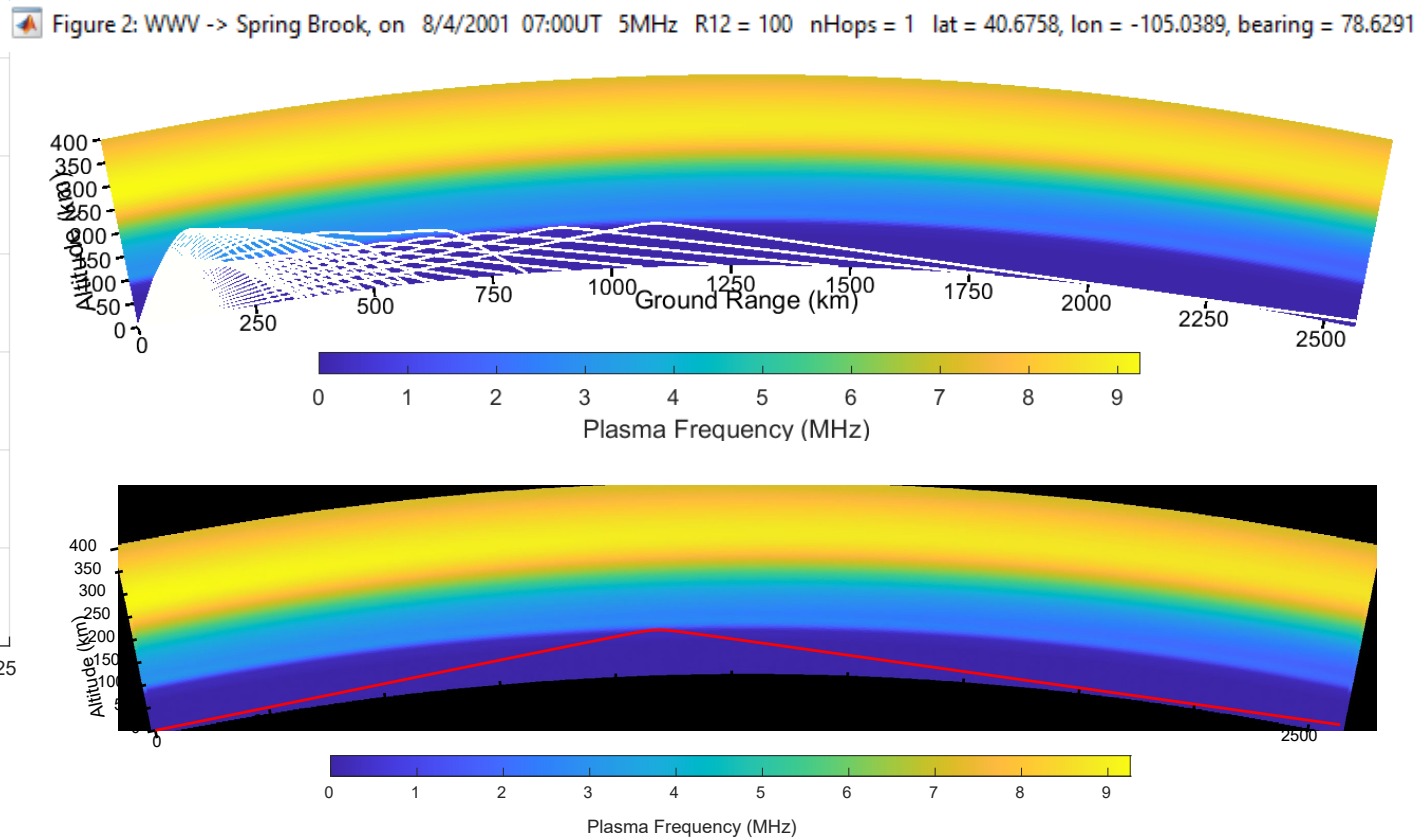
Picking the 10 degree-elevation ray



```
73 de HamSCIHamSCI: Searching for the nearest front ray ...
Sorry, the hour 23 0 does not have a successful ray
 However, we reached the nearest worst-case ray#1 degrees at elevation of 0 degrees. Arriving 116.986880 kms away from W2NAF
```



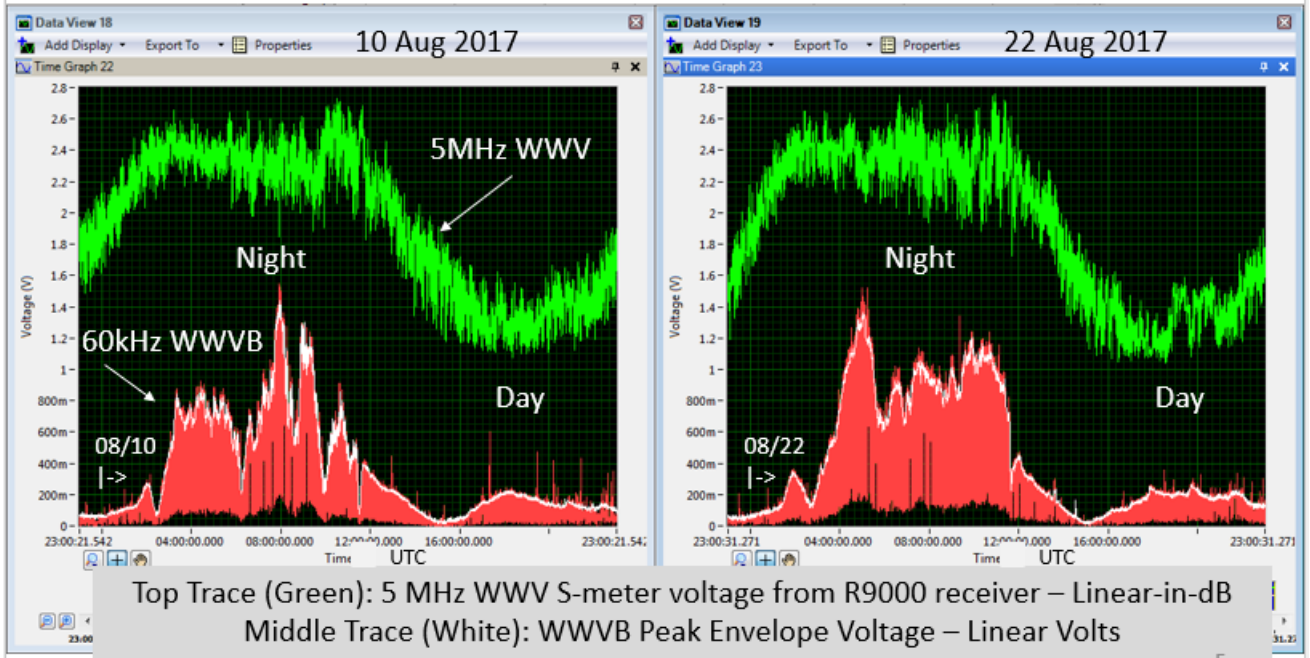
Total Absorption vs UTC @5 MHz



Real WWV -> San Antonio

- [Steve Cerwin, 2027 Solar Eclipse Data]

24 Hour Recordings of WWVB and 5 MHz WWV
Before and After the Day of the 2017 Eclipse.
WWV and WWVB to WA5FRF.
Ft. Collins, CO to San Antonio, TX Path. 23-23 UTC.



Top Trace (Green): 5 MHz WWV S-meter voltage from R9000 receiver – Linear-in-dB
Middle Trace (White): WWVB Peak Envelope Voltage – Linear Volts
Bottom Trace: (Red): WWVB Demodulated Envelope Voltage – Linear Volts

5

HamSCI Personal Space Weather Station

- The HamSCI Personal Space Weather Station (PSWS, hamsci.org/psws) is a NSF-funded Distributed Array of Small Instruments (DASI) project.
- We use observations from PSWS software defined radio (SDR) instrument known as the WSPR Daemon-Grape, which uses the RX-888 HF SDR, KA9Q-Radio & WSPRDaemon Software, and a GPS-disciplined oscillator to make precision frequency measurement.
- The system is capable of receiving multiple bands simultaneously from 0.5-60 MHz.

HamSCI Personal Space Weather Station SDR High Frequency Receiver, [36]

WWV TRANSMITTER

WWV Transmitter near Fort Collins, CO, [32]

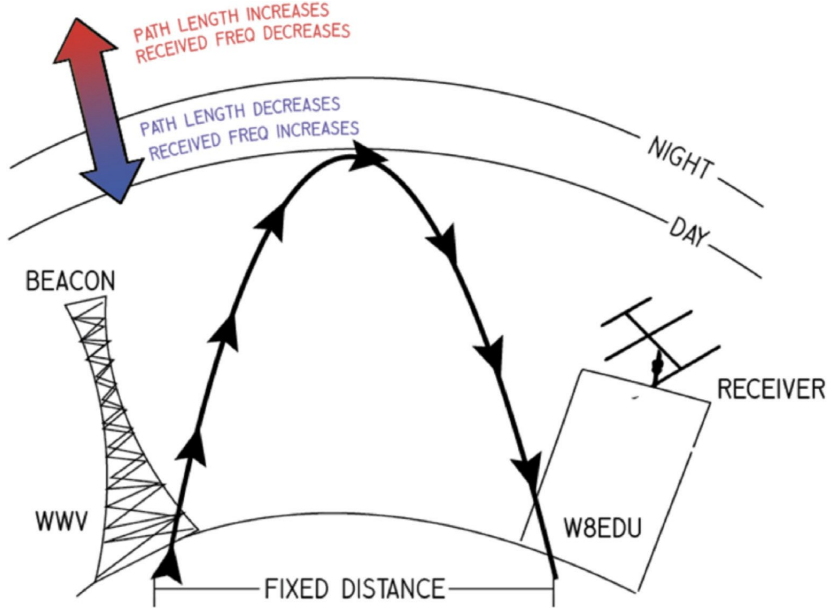


Illustration of HF Doppler Shift. From Collins, [33]

- The NIST WWV Transmitter (Figure 2) near Fort Collins, CO transmits precise carriers on 5, 10, 15, and 20 MHz, We use these as signals of opportunity.

- As these signals propagate from transmitter to receiver through the ionosphere, ionospheric variability can change the propagation path lengths and impart Doppler shifts (Figure 3) and amplitude variations to the carrier signal.

- In our experiment, we place our receiver near Scranton, PA (Figure 4).

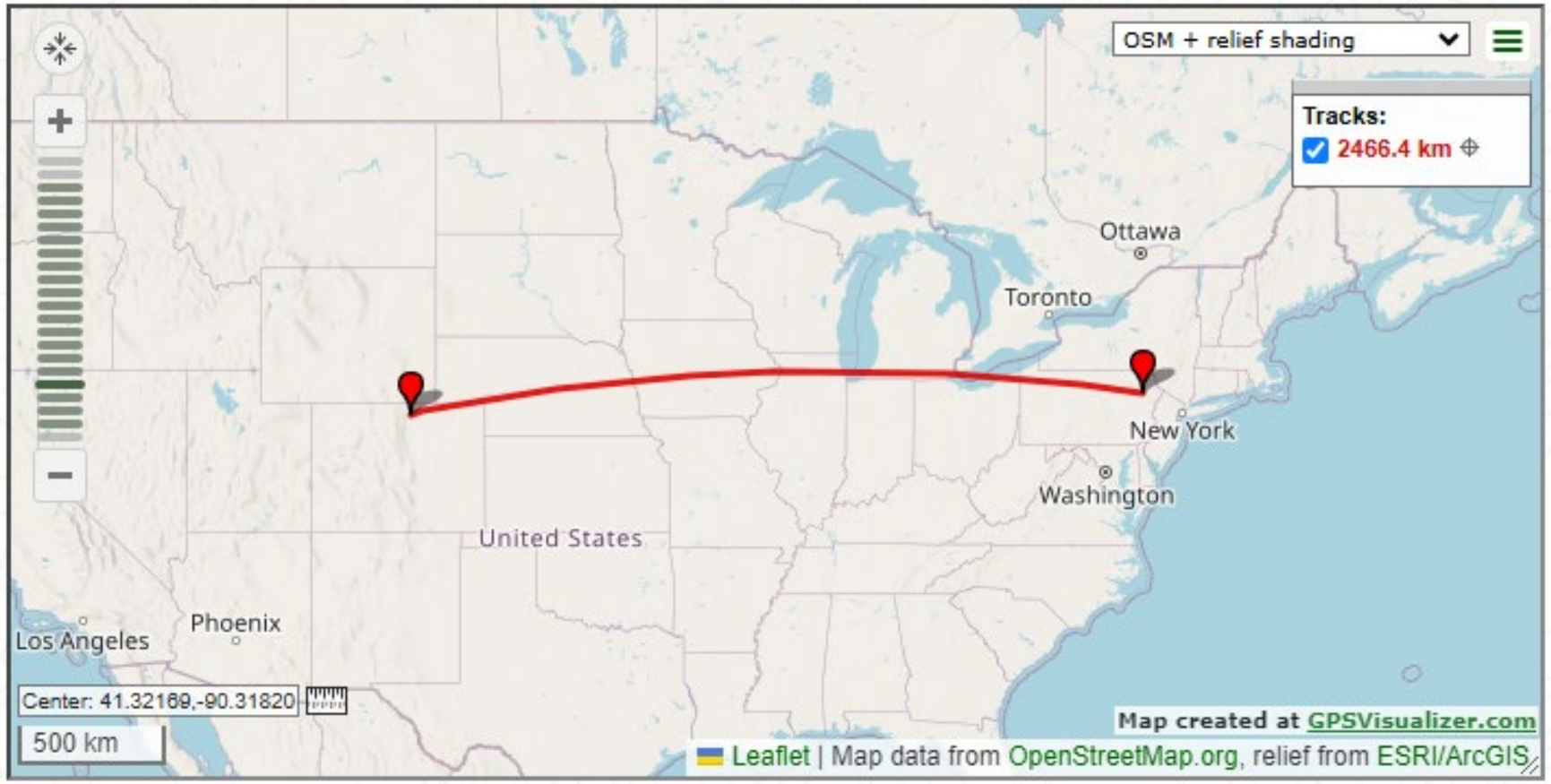


Figure 4: Transmitter-Receiver relative locations per Earth's elliptical model

PHaRLAP via International Reference Ionosphere

- Used IRI-2020 to model ionospheric ray data and absorption at 20, 15, 10 and 5 MHz
- Used ray tracing visualization for “successful” reception and absorption at W2NAF, PA
- Used PHaRLAP ray tracing and IRI-2020 to model HF rays and received signal power absorption at 20, 15, 10, 5 MHz as in Figures 5, 6, 7 and 8, respectively.
- Investigated criteria for determining the “successful” rays modeled with ray tracing.
- Compared with modeled absorptions for better understanding.

RAY TRACE ERROR DETECTION

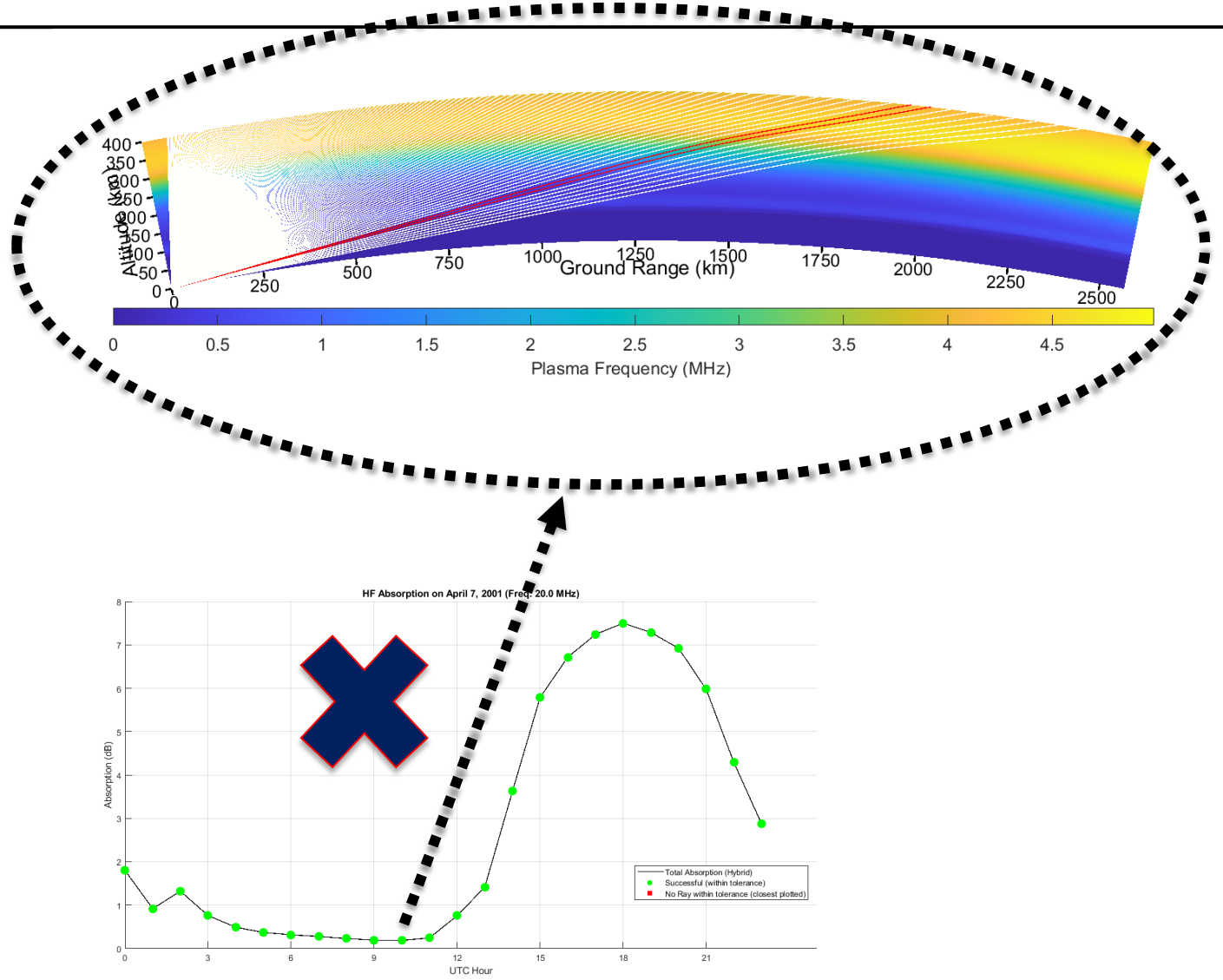
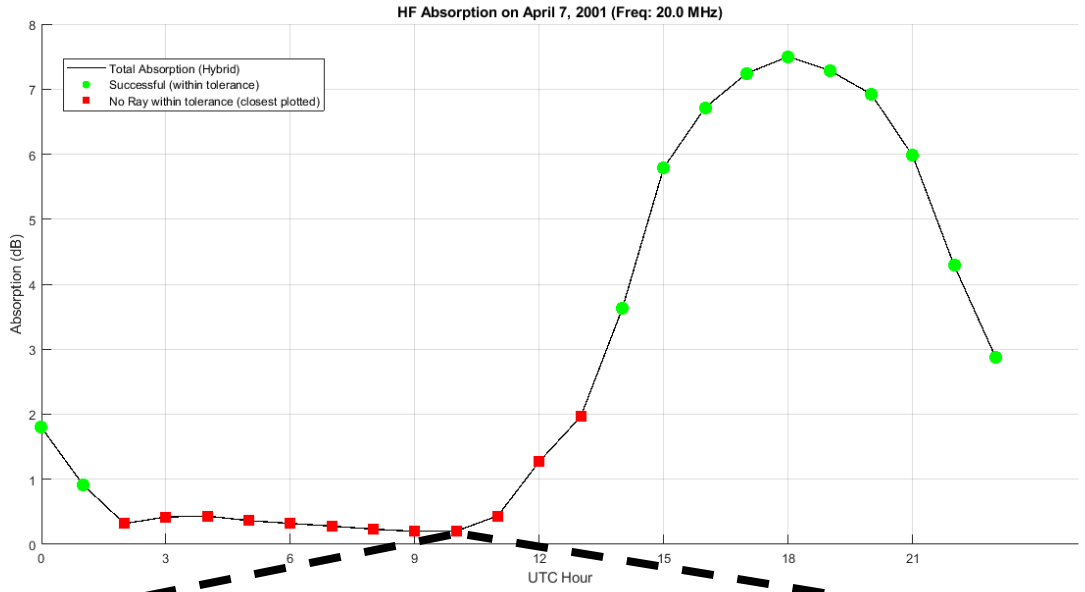


Figure 5: Visualization for ray debugging

HANDLED!



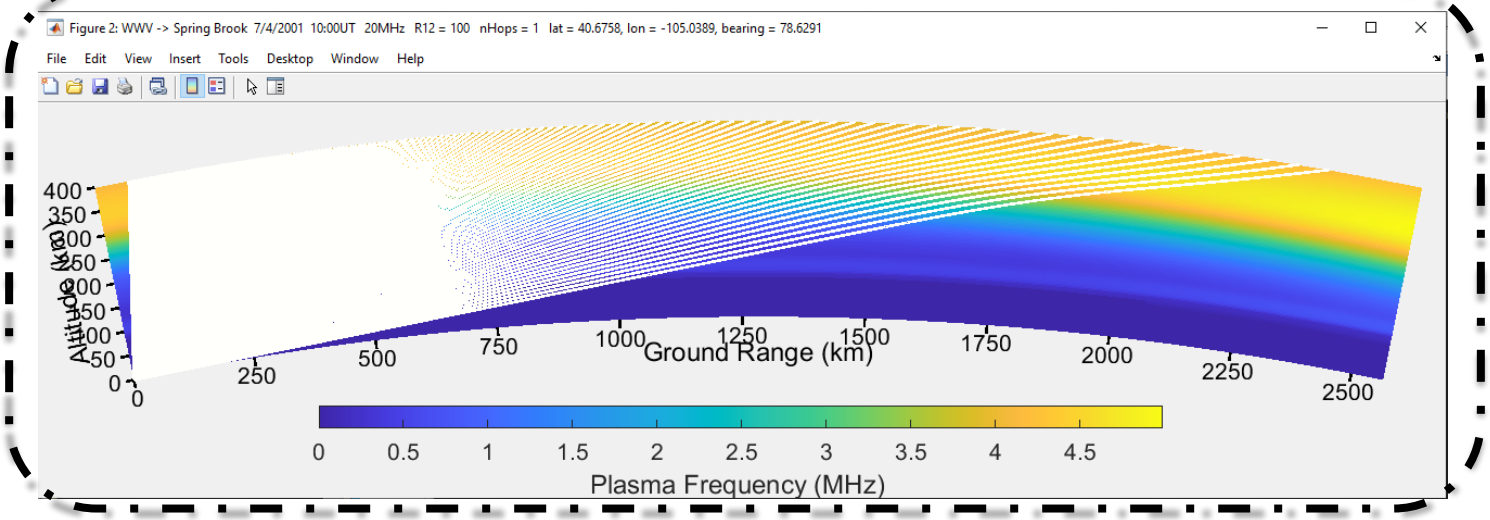


Figure 6: Corrections using Ray Labels

HF Absorption on April 7, 2001 (20, 15, 10 and 5 MHz)

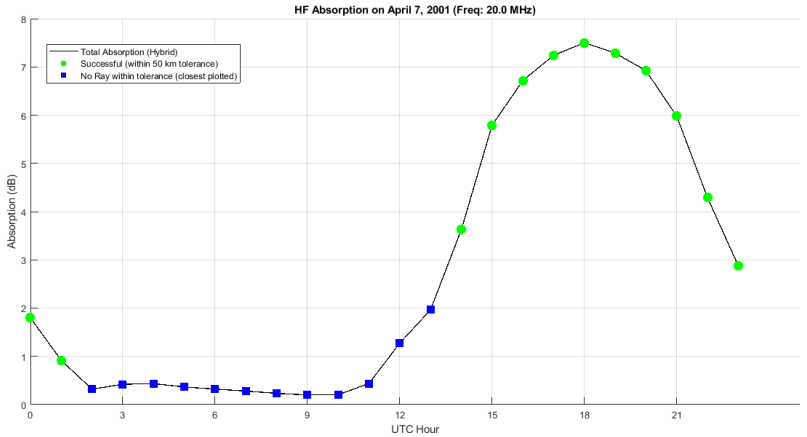
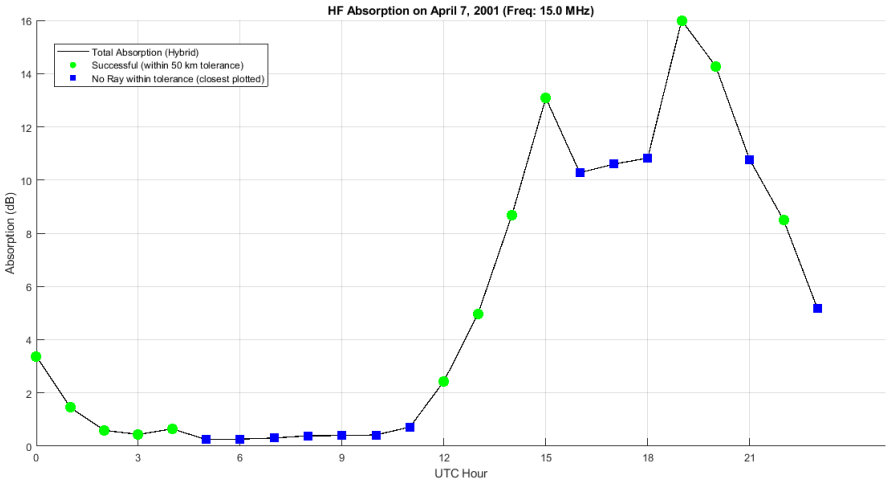


Figure 7: HF Absorption on April 7, 2001, at 20 MHz



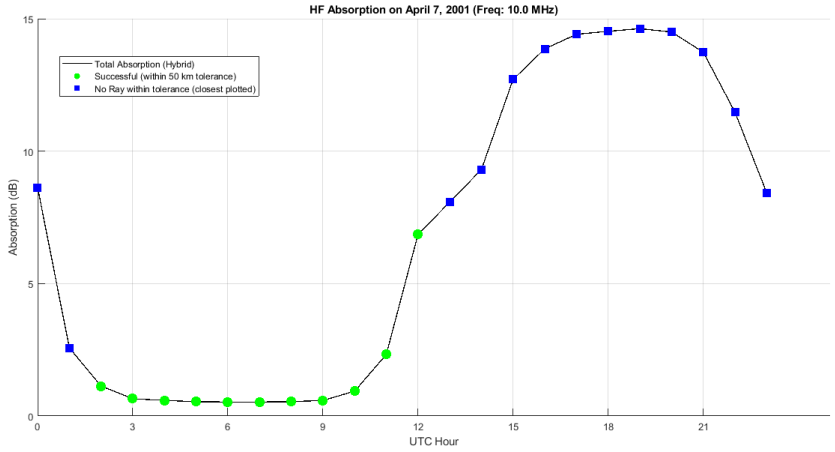


Figure 9: HF Absorption on April 7, 2001, at 10 MHz

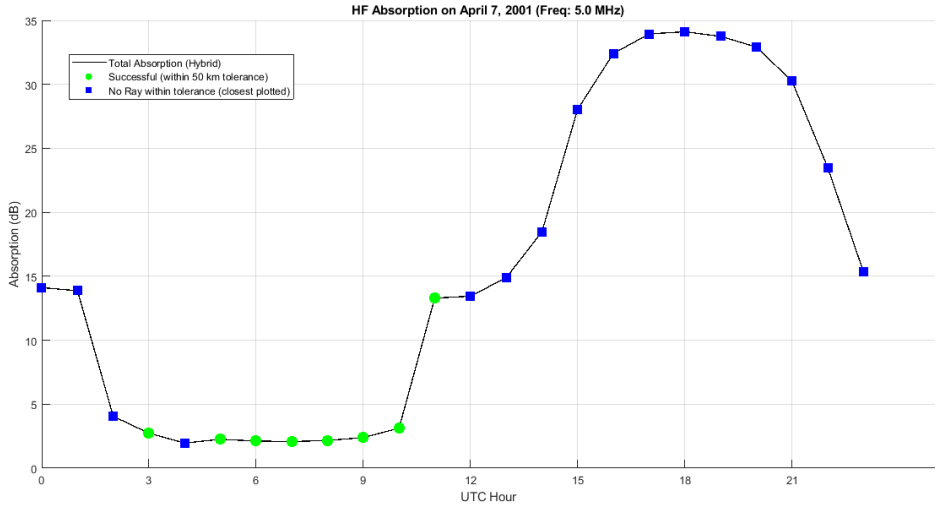
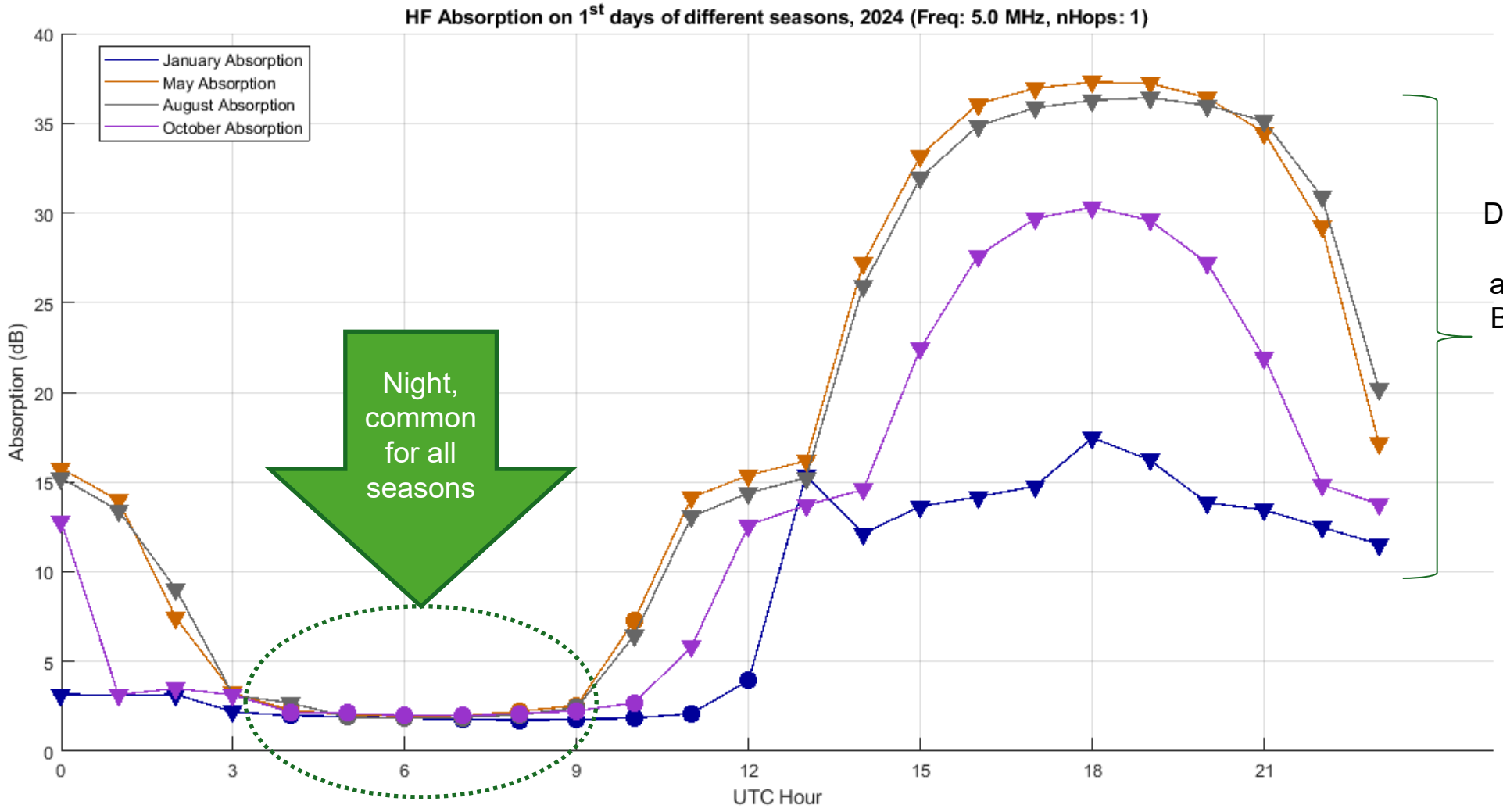


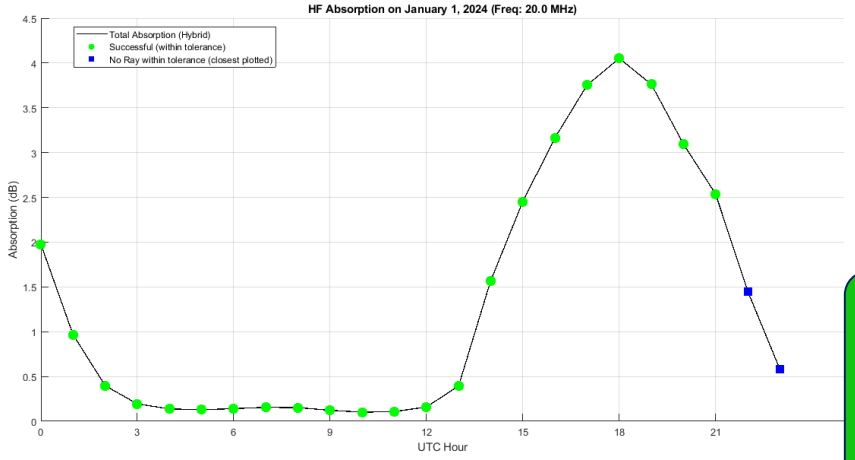
Figure 10: HF Absorption on April 7, 2001, at 20 MHz

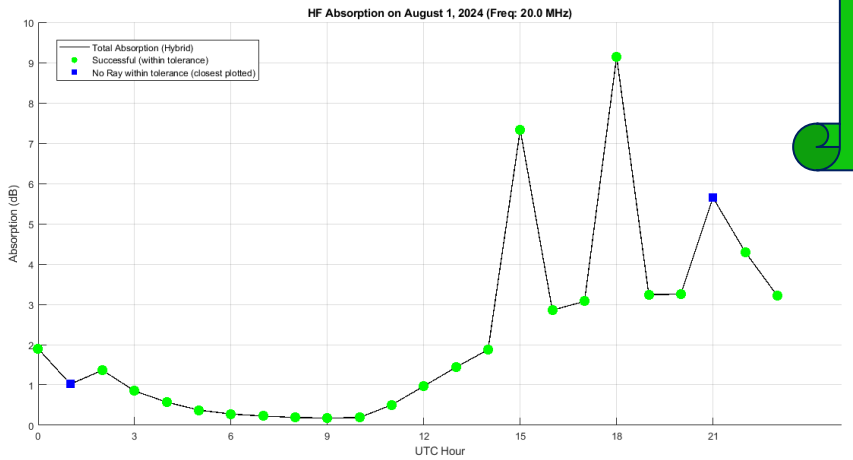
HF absorptions vs seasons (5 MHz)



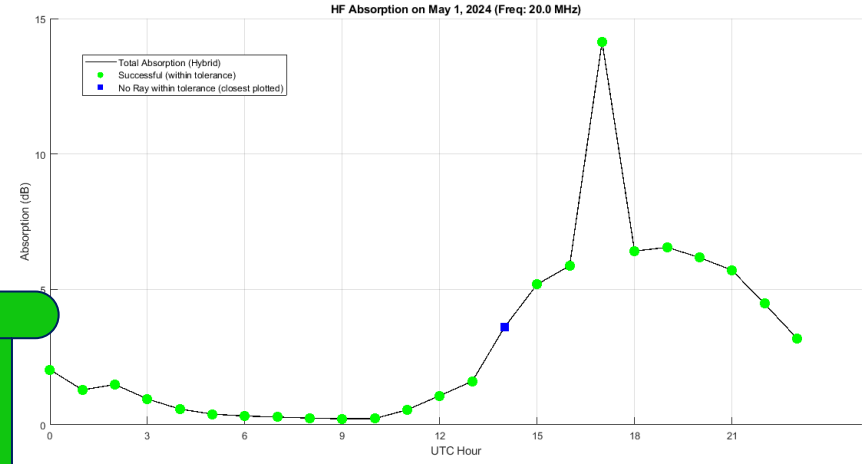
Disparity appears at daylight among seasons. Best for January (Winter), worst for May and August (Summer).

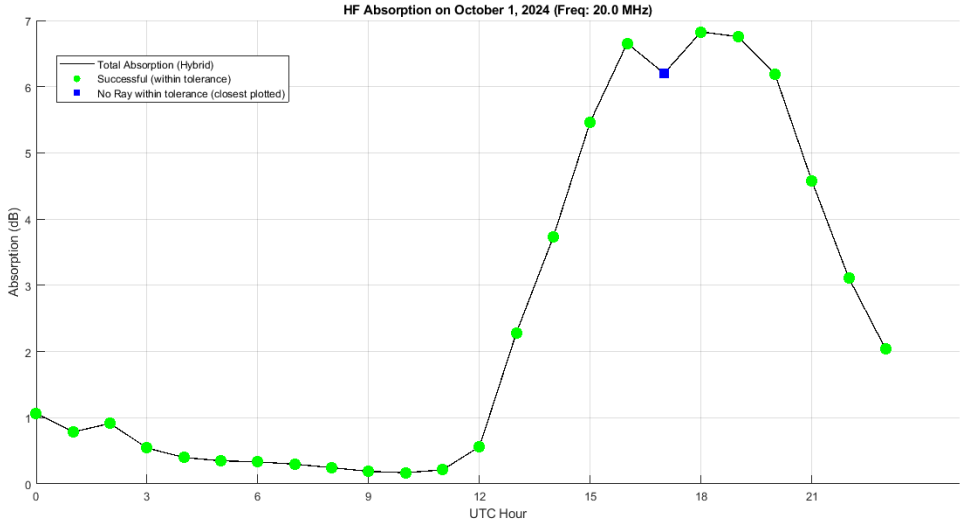
HF Absorption on first day of January, May, August and October, 2024 at 20 MHz





Figures 11-14: January & October best seasons for HF Absorption 1st of January, May, August and October 2024 at 20 MHz





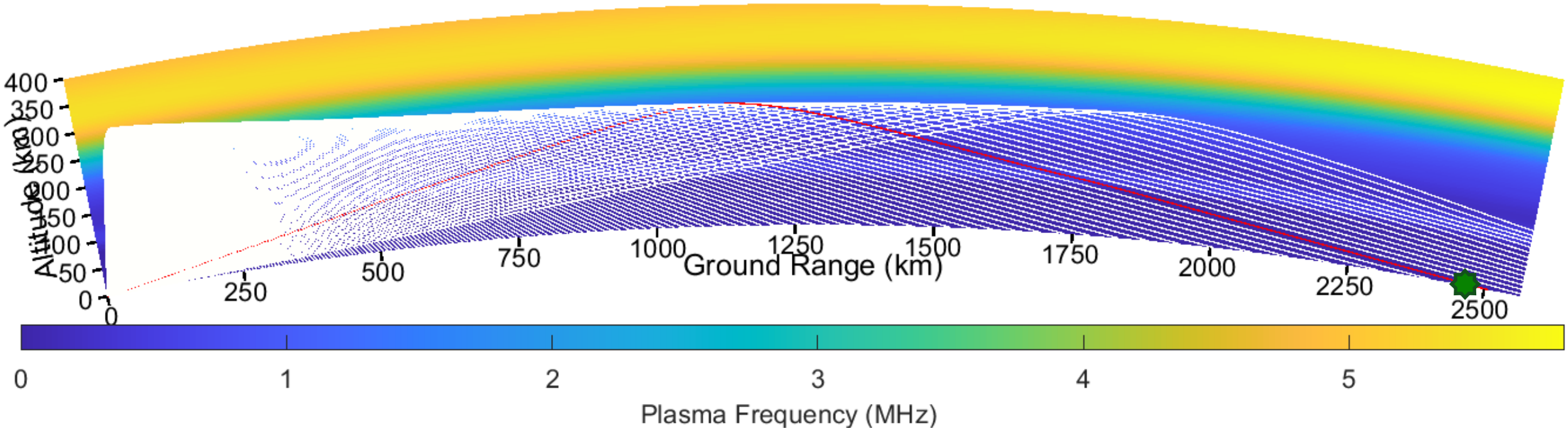


Figure 15: Successful reception at W2NAF from WWV at 5MHz (star (✹) at receiver's location)

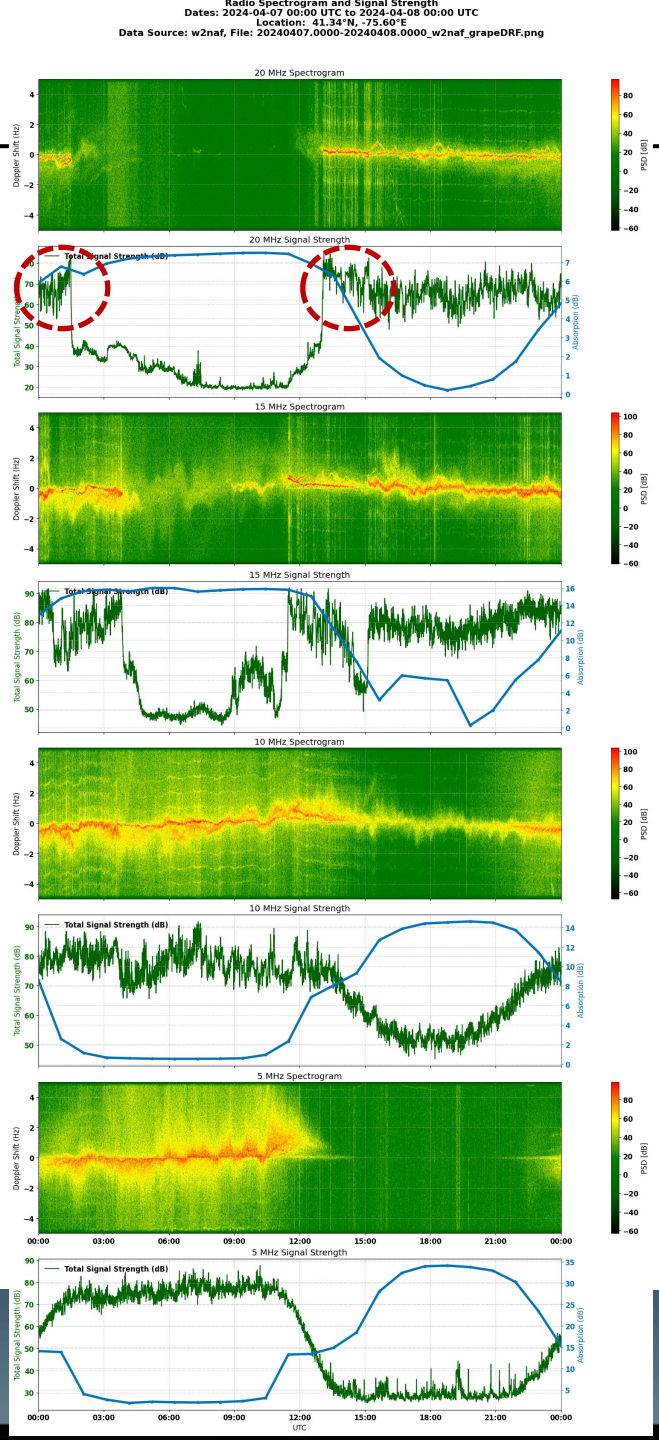
GRAPE DIGITAL RF

- Used the Grape Digital RF (grapeDRF) Linux-based environment to plot PSWS Doppler shift spectrogram and Signal Strength observations on April 7, 2024.
- Used HamSCI HF Doppler observations collected with a WSPR Daemon-Grape Personal Space Weather Station.
- Compared with modeled absorptions for better understanding.

Placing Absorptions on Signal Strength Curves

- Low frequencies show better matches of IRI-2020 simulated absorptions with Personal Space Weather Station observations.
- *Challenges:* To work on the mismatches at higher frequencies.

Model and Observation matching at lower frequencies



CHECK POINT TAKEAWAYS

- Investigated reception at W2NAF (Scranton, PA) from WWV (Fort Collins, CO)
- Used HamSCI HF Doppler observations collected with a WSPR Daemon-Grape Personal Space Weather Station.
- Used PHaRLAP ray tracing and IRI-2020 to model HF rays and received signal power absorption at 20, 15, 10, 5 MHz.
- Investigated criteria for determining the “successful” rays modeled with ray tracing.
- Compared with modeled absorptions ⟹ way to have our own power absorption.

Future Work

- We aspire to model the absorption loss due to ground reflections:
  - Reflection Coefficient maps covering U.S.
  - Getting more into Brewster's angle involvement.
- We aspire to figure out a model for D-Region:
  - SAMI3 model does cover the D-Region!
  - Modeling the D-Region during eclipse (neither PHaRLAP nor SAMI3)

References

[1] Cervera, M. A., and T. J. Harris (2014), Modeling ionospheric disturbance features in quasi-vertically incident ionograms using 3-D magnetoionic ray tracing and atmospheric gravity waves, J. Geophys. Res. Space Physics, 119, 431–440, doi:10.1002/2013JA019247.

[2] Shehaj, E., Leroy, S., Cahoy, K., Geiger, A., Crocetti, L., Moeller, G., Soja, B., and Rothacher, M.: Global Navigation Satellite System (GNSS) radio occultation climatologies mapped by machine learning and Bayesian interpolation, Atmos. Meas. Tech., 18, 57–72, https://doi.org/10.5194/amt-18-57-2025, 2025.

[3] K. Collins, A. Montare, N. Frissell and D. Kazdan, "Citizen Scientists Conduct Distributed Doppler Measurement for Ionospheric Remote Sensing," in IEEE Geoscience and Remote Sensing Letters, vol. 19, pp. 1-5, 2022, Art no. 3504605, doi: 10.1109/LGRS.2021.3063361

[4] Carlton, A., Morgan, R., Lohmeyer, W., & Cahoy, K. (2018). Telemetry fault-detection algorithms: Applications for spacecraft monitoring and space environment sensing. Journal of Aerospace Information Systems, 15(5), 239-252. DOI: https://doi.org/10.2514/1.I010587

[5] W3USR, Scranton, PA, https://www.scranton.edu/academics/cas/physics-engineering/w3usr/index.shtml

[6] Zawdie, K. A., D. P. Drob, D. E. Siskind, and C. Coker (2017), Calculating the absorption of HF radio waves in the ionosphere, Radio Sci., 52, 767–783, doi:10.1002/2017RS006256.

[7] Pederick, L. H., and M. A. Cervera (2014), Semiempirical Model for Ionospheric Absorption based on the NRLMSISE-00 atmospheric model, Radio Sci., 49, 81-93, doi:10.1002/2013RS005274.

[8] Cahoy, K. L., D. P. Hinson, and G. L. Tyler (2006), Radio science measurements of atmospheric refractivity with Mars Global Surveyor, J. Geophys. Res., 111, E05003, doi:10.1029/2005JE002634.

[9] Zayed, G., Frissell, N., & Pandey, K. Challenges in Modeling HF Absorption: Exploring D, E and F-Layer Effects on Signal Attenuation Using Provision of High-frequency Raytracing Laboratory for Propagation studies.

[10] Zayed, G. (2024). Hybridization of WSPRlive Real-Time Beacons Dataset, Friis Propagation Model and Numerical Solution for Localization. In *HamSCI Workshop 2024*.

[11] G. Zayed, “Web Application for Ionospheric Data Pipeline: FastAPI and JSON with TypeScript-React Integration,” in *The First Computational Sciences and Artificial Intelligence (CSAI) Workshop*, 2023. DOI: 10.13140/RG.2.2.35818.73920.

[12] Zayed, G., Ismail, T., & Fahmy, Y. (2020, December). Visible light communications localization error enhancement using parameter relaxation. In *2020 16th international computer engineering conference (ICENCO)* (pp. 191-196). IEEE.

[13] Chris Smolinski, Pushing the RF Envelope: The Sky Loop Antenna. *Radio Hobbyist*, 2012. URL: https://www.radiohobbyist.org/blog/?p=564

[14] G. Zayed, Frissell, N., and Pandey, K., “High-Frequency Signal Strength Simulation at GRAPE Personal Space Weather Stations Using PHaRLAP Ray Tracing”, *HamSCI Workshop 2025*. HamSCI, Newark, NJ, 2025.

[15] Tarrío, P.; Bernardos, A.M.; Casar, J.R. “Weighted Least Squares Techniques for Improved Received Signal Strength Based Localization," *Sensors*, 2011.

[16] G. Zayed, Lesniowski, M., Harsha, P. Babu Sree, Downs, M., Metcalfe, D., and Karabulut, S. Kardelen, “Evaluation of Global Ionospheric TEC Using Simultaneous Observations from Amateur Radio Networks, International Space Station, and NeQuickG Model for Space Weather Prediction”, *HamSCI Workshop 2023*. HamSCI, Scranton, PA, 2023.

[17] Nuria González-Prelcic, Musa Furkan Keskin, Ossi Kaltiokallio, Mikko Valkama, Davide Dardari, Xiao Shen, Yuan Shen, Murat Bayraktar and Henk Wymeersch. The Integrated Sensing and Communication Revolution for 6G: Vision, Techniques, and Applications, arXiv, eess.SP. Eprint: 2405.01816. URL https://arxiv.org/abs/2405.01816

[18] Jiang, Suying & Wang, Wei & Miao, Yang & Fan, Wei & Molisch, Andreas. (2022). A Survey of Dense Multipath and Its Impact on Wireless Systems. IEEE Open Journal of Antennas and Propagation. 3. 1-1. 10.1109/OJAP.2022.3168400.

[19] Gerard Pleijlar, HyEndFed 5 Band Black Clamp MK3, *HyEnd Company*. URL: https://www.hyendcompany.nl/antenna/multiband_8040201510m/product/detail/3/HyEndFed_5_Band_Black_Clamp_MK3#prod

[20] DX Commander Amateur Radio Antennas, Classic Antenna Kits, *DX Commander*. URL: https://dxcommander.com/product-category/products/antenna-kits/classic/

[21] GAP Antenna Products, TITAN DX, *GAP Antenna Products, Inc.*, 2024. URL: https://gapantenna.com/shop/titan-dx/

[22] Doron Tal, 4X4XM, What are the modes of HF Radio Propagation?, QSL.net. URL https://www.qsl.net/4x4xm/FAQ/What-are-the-modes-of-HF-Radio-Propagation.htm

[23] https://www.gpsvisualizer.com/display/map/20241101135441-47194-map.html

[24] QRZ.com. "K6KPH: Maritime Radio Historical Society - Bolinas, CA. " California, United States. URL https://www.qrz.com/db/K6KPH

[25] https://www.gpsvisualizer.com/display/map/20241101072309-47194-map.html

[26] "Beacon Stations," WSPRlive, [online]. Available: https://wspr.live/gui/goto/IBxQFcJSR?orgId=1

[27] "Participants," WSPRlive, [Online]. Available: https://wspr.live/gui/goto/k27GRVJIg?orgId=1

[28] WSPRnet Spot Database, https://www.wsprnet.org/drupal/wsprnet/spots

[29] "Beacon Uptime (active hours)," WSPRlive, [Online]. Available: https://wspr.live/gui/goto/kFn_enJIR?orgId=1

[30] "Map," WSPRnet, [Online]. Available: https://www.wsprnet.org/drupal/wsprnet/map

[31] IntlWSPR Project, IU2PJI team, https://www.qrz.com/db/IU2PJI

[32] QRZ.com. "WWV: National Institute of Standards and Technology (NIST) - Fort Collins, CO. ", Colorado, United States. URL https://www.qrz.com/db/WWV

[33] "Spot Database," WSPRnet, [Online]. Available: https://www.wsprnet.org/drupal/wsprnet/spots

[34] https://www.gpsvisualizer.com/display/map/20241018114723-35166-map.html?center=-4.854,36.093245&zoom=2

[35] https://www.gpsvisualizer.com/map?output_calculators

[36] https://hamsci.org/wsprdaemon-grape-overview-specifications-sourcing

[37] https://www.qrz.com/db/WWV

[38] https://www.gpsvisualizer.com/display/map/20241101135441-47194-map.html

A Good Learner is a Good Developer!

Acknowledgments

The HamSCI Community is led by The University of Scranton Department of Physics and Engineering W3USR, in collaboration with Case Western Reserve University W8EDU, the University of Alabama, the New Jersey Institute of Technology Center for Solar Terrestrial Physics K2MFF, the MIT Haystack Observatory, TAPR, additional collaborating universities and institutions, and volunteer members of the amateur radio and citizen science communities.

We are grateful for the financial support of the United States National Science Foundation, NASA, and Amateur Radio Digital Communications (ARDC).

HamSCI silhouette photo by Ann Marie Rogalcheck-Frissell KC2KRQ.

Thank you!

Questions?