Preliminary Analysis of the Effect of Earth's Magnetic Field on HF Propagation Part 1: A Comparison of Non-Magnetic Ray-Tracing Models

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Abstract

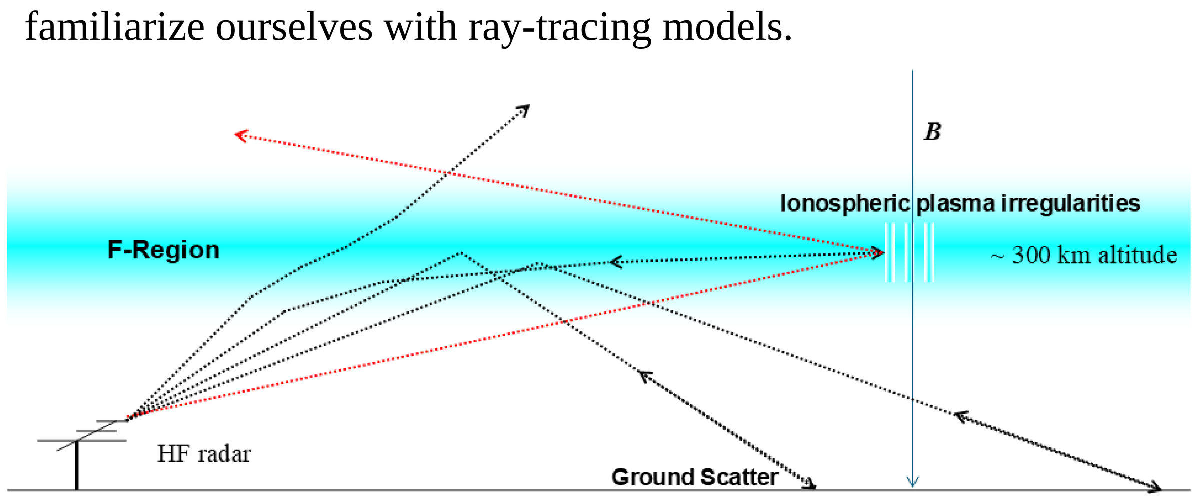
The SuperDARN radar system is a network of HF radars designed to study the Earth's ionosphere. The SuperDARN community has developed HF ray-tracing codes to assist in the interpretation of the data. One widely used version developed by de Larquier et al. [2011] uses a simplified form of the Appleton-Hartree equation that only considers the electron density when calculating the refractive index of the medium. This neglects the effects of the Earth's magnetic field and the existence of the extraordinary wave. There are some models (e.g. PHaRLAP) that use the complete solution to the Appleton-Hartree equation in their calculations, but many of them are closed source and not optimized for SuperDARN operations. In this study, we are formulating a new HF ray-tracing code that incorporates the full Appleton-Hartree equations. As a first step, a comparison will be made between the de Larquier and PHaRLAP models to examine the extent to which the effects of the ordinary vs extraordinary waves are manifested in SuperDARN data.

Background

The main data received by the SuperDARN radars relates to backscatter from the ionosphere and the ground. Both of these results are only possible because of the plasma that makes up the ionosphere without the radio waves would pass through into outer space. While speculation on an electrical phenomenon in the upper atmosphere goes back to Gauss in the mid-1800s, one of the first examples of the ionospheres effect on radio waves was when Marconi sent radio signals across the Atlantic Ocean in the early 1900s. It then wasn't till after WWI that most of the initial research into the ionosphere, and its effects on radio waves truly started. One of the most noticed phenomena that lead to ionospheric theories was interference in long range radio transmissions that was theorized, and later proven, to be caused by reflected radio waves from the ionosphere. The most common way to describe the effects the ionosphere had on radio waves is through the refractive index of the ionosphere. The first attempt at defining the refractive index of the ionosphere was an equation for an isotropic, it didn't include the Earth's magnetic field, model that based the refractive index on the plasma frequency of the ionosphere, which is based on the electron density, and the frequency of the radio wave. A couple years later an anisotropic, includes Earth's magnetic field, version was produced that has since come to be known as the Appleton-Hartree equation, or Appleton–Lassen equation. This equation defines the refractive index with respect to the plasma frequency, the electron gyro frequency, the electron collision frequency, and the radio wave frequency (it also deals with the angle between the direction of propagation and the Earth's magnetic field). It is the refraction defined by this refractive index that allows for the backscatter data collected by the SuperDARN radars.

As the rays curve through the ionosphere if they do not pass through the ionosphere they will eventually either hit the ground or a field aligned plasma irregularity in the ionosphere. When this happens, the ray will reflect back to the radar as ground or ionospheric backscatter. Ray-tracing models are then used to help understand and analysis what this data is and where it comes from.

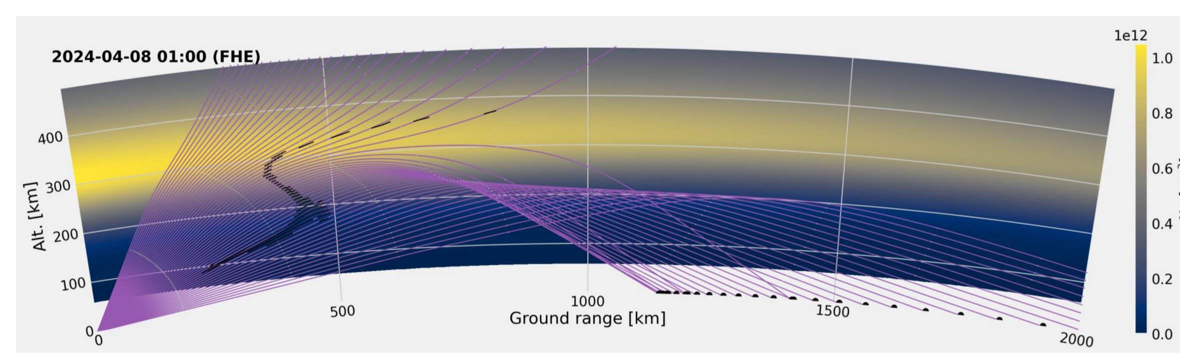
While the final plan of the study is to see the effects the Earth's magnetic field has on the path of the rays, for this poster we plan to look at the difference between two ray-tracing methods that ignore the Earth's magnetic field to act as a starting point and to help familiarize ourselves with ray-tracing models.



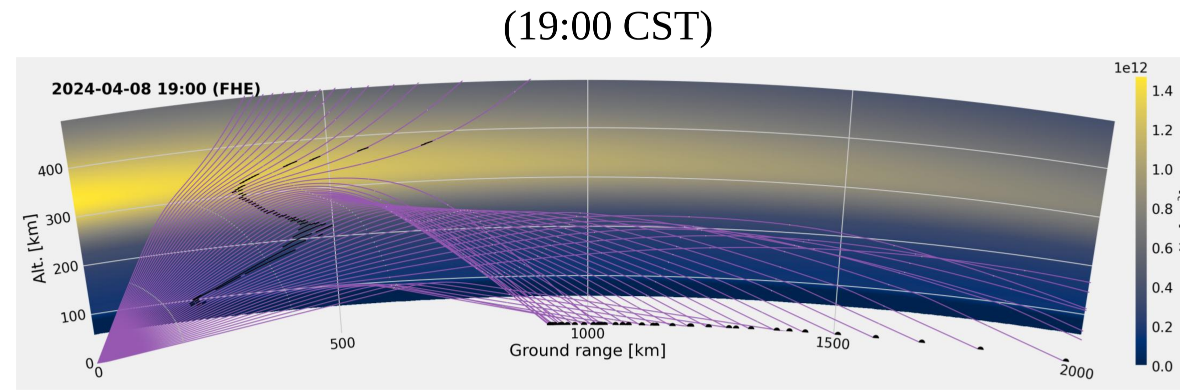
de Larquier Model

The de Larquier model is a 2-D numerical ray-tracing, NRT, model originally created by a former VT graduate student working with the SuperDARN group Sébastien de Larquier. This model was designed as an ancillary tool to help aid in the study of other phenomena in SuperDARN data. To accomplish this an adaptive step-size Runge-Kutta method was used to solve the Euler-Lagrange equation whose solution would produce the path that minimizes the sum of the refractive index along the path. This was done under the assumption that the ray would follow the path that minimizes the phase path.

The phase path can then be described as the integral from a to b of the refractive index. This formulation meant a decision needed to be made on what to use as the refractive index. It was decided that using the simplified version of the Appleton-Hartree equation, $n^2 = 1 - \frac{{f_N}^2}{f^2}$, where f_N is the plasma frequency of the ionosphere and f is the frequency of the radio wave. To accomplish this the International Reference Ionosphere, IRI, model of the atmosphere was used to determine the needed electron densities to calculate the plasma frequencies.



de Larquier 2-D ray trace of April 8, 2024, at 01:00 UTC (19:00 CST)

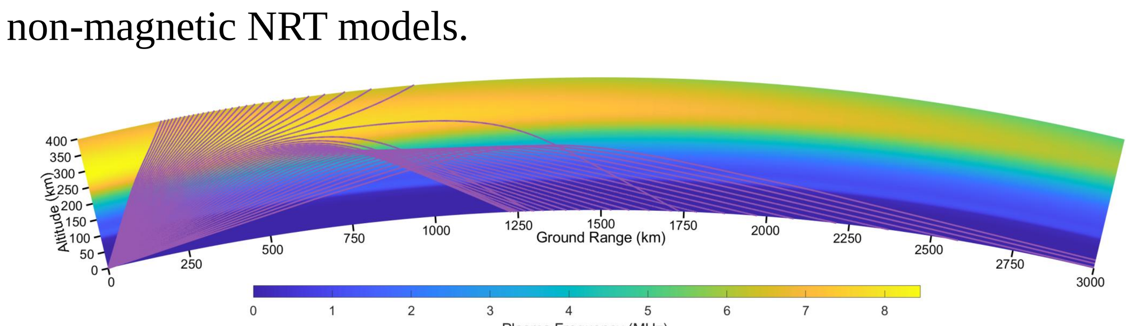


de Larquier 2-D ray trace of April 8, 2024, at 19:00 UTC (13:00 CST)

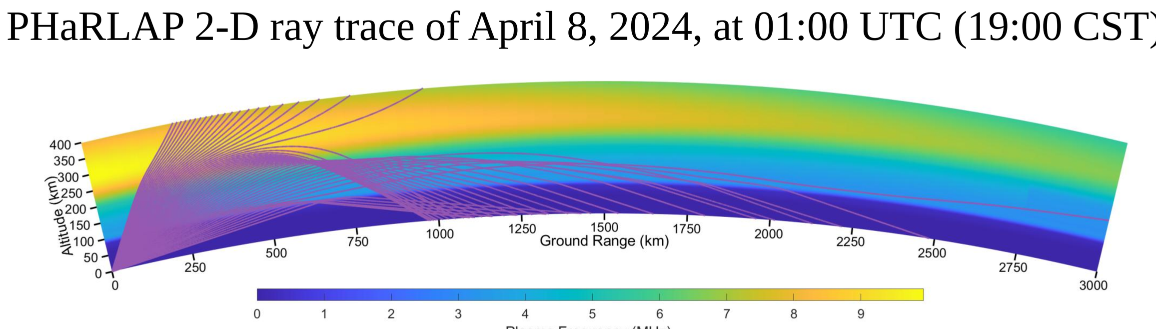
PHaRLAP

PHaRLAP is a Matlab toolbox distributed by the Australian Department of Defense that can be used to produce different ray-tracing plots for any user supplied plasma. PHaRLAP is closed source meaning that what is distributed to the public is a set of Matlab functions that act as black boxes, takes in a set of inputs and through an unknown algorithm returns a set of outputs, to produce ray-tracing plots. For PHaRLAPs 2-D NRT model the inputs are similar to those of the de Larquier model. It needs an initial location, in this case as a set of latitudes and longitudes instead of a SuperDARN radar code. A bearing, in this case a magnetic direction instead of a radar beam. A date and time, and unlike the de Larquier model, which assumes the desire to use IRI, information on the ionosphere, however, while PHaRLAP doesn't assume you want to use IRI it does provide functions that will use IRI to calculate the needed information about the ionosphere and return it in the needed format.

PHaRLAP also has a ray-tracing model that would include the Earth's magnetic field and produce traces for the O and X mode, but it is only available, as far as I could tell, for use with 3-D ray-tracing. Due to time constraints, it was decided to only compare the two 2-D non-magnetic NRT models.



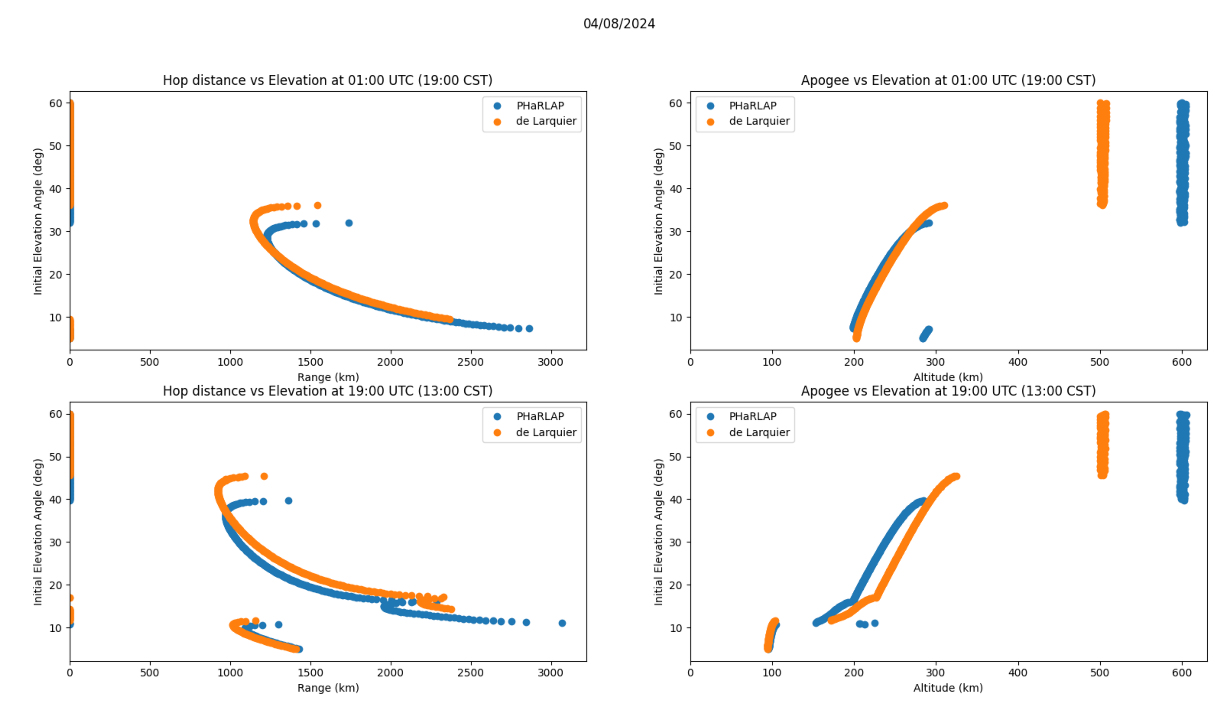
PHaRLAP 2-D ray trace of April 8, 2024, at 01:00 UTC (19:00 CST)



PHaRLAP 2-D ray trace of April 8, 2024, at 19:00 UTC (13:00 CST)

Results

To aid in comparing the differences between the two models some additional plots were generated. It was decided to look at hop distance and apogee height, because these are commonly looked at features, versus initial elevation angle. To do this a common date, time, location, and bearing were chosen, in this case Fort Hays east on April 8, 2024, at 01:00 UTC (19:00 LT) and 19:00 UTC (13:00 LT). Then both the de Larquier model and PHaRLAP were run with as close to the same IRI parameters I could determine, and initially elevation angles between 5 and 60 at 0.1-degree intervals. Each model was also set to only produce a single hop, i.e. stop when the ray reaches the ground. The apogee height and hop distance were then taken and plotted versus the initial elevation angle as seen below.



Discussion

To start this discussion with the elephant in the room, the zero hop distance. This does not represent an actual hop distance of 0 km, this is a fill value that allows for easier visualization of where no hop distance was calculated by the model. These points represent one of two things, the ray passed through the ionosphere and into outer space and therefore never scattered off the Earth, or the hop distance was outside of the simulation distance. This second reason is more common in the de Larquier model which has a stricter distance cutoff.

The next striking feature is the vertical lines on the apogee plot. These represent each model's max height. Since rays that pass through the ionosphere continue without a convenient criterion for the model to stop at, each one chose a certain height as the upper bound of the ray. If the ray reached this height it was considered to have passed through the ionosphere and the model stopped. This then produces an apogee for these rays at or around the stop height. With these values plotted it allows us to tell which zero hop distance rays passed through the ionosphere and which ones exceeded the simulation distance, by comparing the zero hop to the lines of max height.

Comparing the other features of the plot it appears that the de Larquier model produces values higher and further than PHaRLAP. This is made more interesting by the fact that each plot otherwise has a very similar shape between models. Assuming the IRI models used are the same, you would expect each model to produce the same results. The fact that they don't implies that each model handles something differently. Looking at the inputs to PHaRLAP it appears that a collision frequency is produced by its IRI function and passed to the 2-D NRT. I believe this is the cause of the differences in the plots since without the source code I cannot tell what other differences there are in the algorithms, and the differences seem to be small enough to be caused by this.

Conclusion

While we were unable to get to the original purpose of the study, because of time constraints, we were able to lay some groundwork for the next steps. By investigating and comparing these two 2-D NRT we were able to gain insight into how ray-tracing models work. From here we can better understand what might change as we add in the Earth's magnetic field to a model. This study has also provided us with some experience on how to compare different ray-tracing models which can be utilized in the future as the ray-tracing models get more different from each other and more complicated.

Acknowledgments

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"The results published in this paper were obtained using the HF propagationtoolbox, PHaRLAP, created by Dr Manuel Cervera, Defence Science and TechnologyGroup, Australia (manuel.cervera@dst.defence.gov.au). This toolbox is available from https://www.dst.defence.gov.au/opportunity/pharlap-provision-high-frequency-raytracing-laboratory-propagation-studies."
"We like to acknowledge the IRI Working Group with all its members for their work on IRI. The results in this paper use IRI-2020. The IRI model code in Fortran is available from the IRI homepage at irimodel.org."

References:

de Larquier, Sébastien, "THE MID-LATITUDE IONOSPHERE UNDER QUIET GEOMAGNETIC CONDITIONS: PROPAGATION ANALYSIS OF SUPERDARN RADAR OBSERVATIONS FOR LARGE IONOSPHERIC PERTURBATIONS", 2013