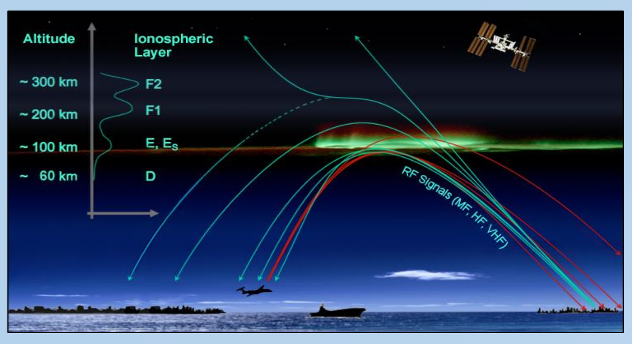
High frequencies wave propagation in Earth ionosphere

Foucault E., Blelly P.-L., Marchaudon A.,
IRAP, CNRS, Toulouse, France.

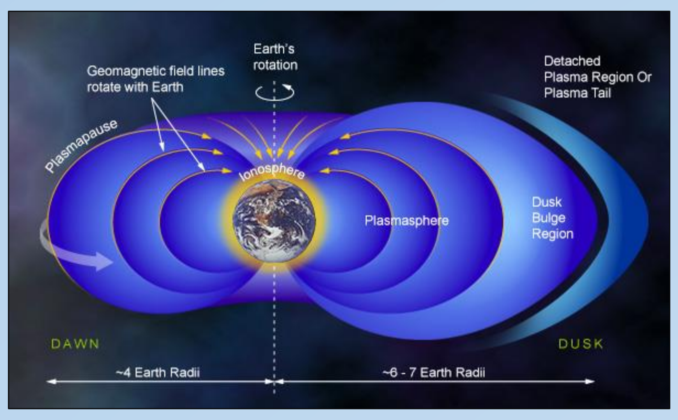
Motivation

Background:

The ionosphere (altitude 60-200km) (3) is defined as the region of the atmosphere that affects the propagation of radio waves. It is composed of plasma content (ions and electrons) created by the ionization of the atmospheric neutral compounds. It can be used as a mirror for ground-ground over-the-horizon communication in HF range. To do so the electronic content must be well known along the propagation path. Most ionosphere models are often empirical models which are not able to reproduce rapid spatio-temporal variations generally encountered in the high-latitude ionosphere. We present a new approach based on simulation of the propagation of HF radio waves in a realistic medium based on a first-principle ionosphere model developed at IRAP (TRANSCAR/IPIM family model)(1). By comparing the simulated results of waves propagation with observed data from HF ionospheric radars of the SuperDARN chain, the main ionospheric parameters (e.g. density and temperature of electrons/ions) will be adjusted in the model through a recursive loop in order to fit as best as possible the observations.
First a new ray tracing tool has been developed and the first tests of our code using realistic IPIM simulation of the ionosphere are presented in this poster.



Example of HF propagation, using ionosphere refraction: Trans-horizon communications.



Earth plasmasphere

IPIM : A new interhemispheric 16-moment model of the plasmasphere-ionosphere system
- parallel transport along magnetic field lines and perpendicular transport through convection and corotation.
- Based on physical processes (Photoionization, chemistry, transport…)
- Electrodynamics

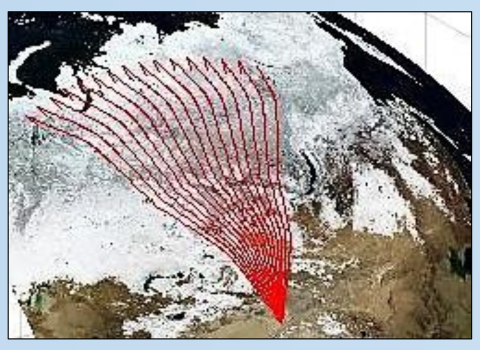
Objectives:

- Development of a ray tracing tool
- Development of a new simplified 3D model of the ionosphere
- Coupling the ionosphere model with the ray tracing tool to constraint our model with observed data

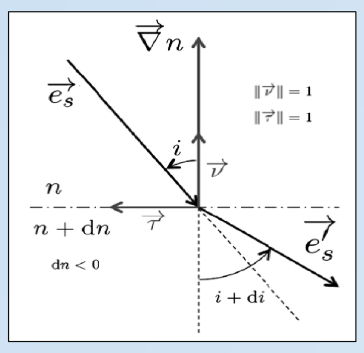
Ray tracing tool

- Aim:
  - Calculating HF wave propagation path in a refractive medium
  - Ray bending estimation
- Algorithm:
  - Based on Fermat Principle
  - Ionosphere and ground backscatter modelling
  - Geocentric problem
  - Entries: $(r, \varphi, \theta, \alpha, \beta)$. Where : r the distance to Earth center, φ the geocentric longitude, θ the geocentric latitude, α the azimuth angle and β the elevation angle
  - Outputs: $(r, \varphi, \theta, \alpha, \beta, t)_S$, where S is the curvilinear abscissa
  - Runge-Kutta scheme (Order 1 to 5), using variable integrating step
  - Based on the Eikonal equation (derived from the Fermat Principle (2)) along the trajectory :

$\vec{\nabla} n = \frac{d}{ds}(n\vec{e_s})$, where $n = \sqrt{1 - \frac{w_p^2}{\omega_f^2}}$, with w_p and ω_f respectively the plasma and radio wave pulsations.



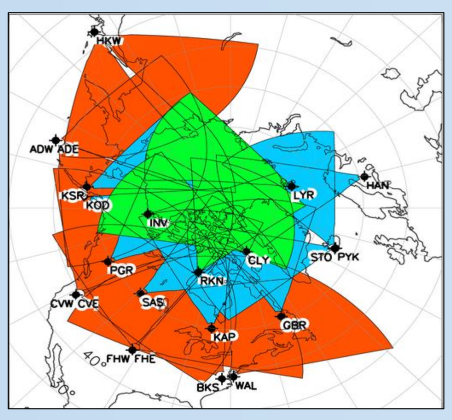
Propagation SuperDARN-like, 16 Beam at 12MHz, in a simulated ionosphere with a n_e peak at 2.10^{11} m^{-3}



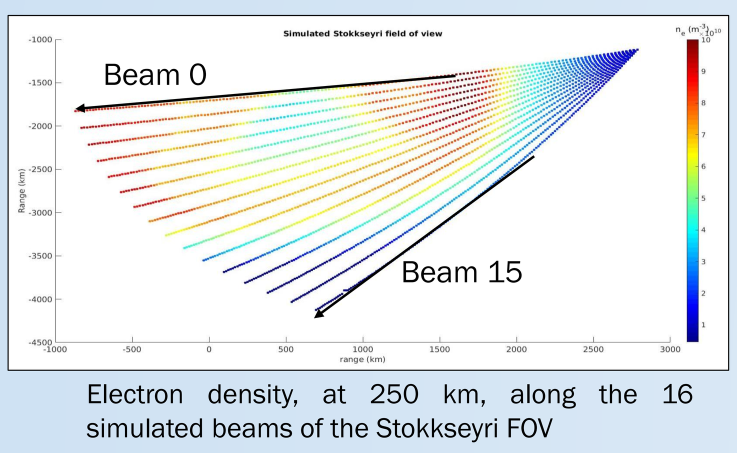
Local base, based on the refractive index *n*

Simulation

Simulation parameters used to test the ray tracing tool:
- Stokkseyri, Iceland, field of view (63,86 N, −22,02 E), SuperDARN HF radar
- Spring Equinox, the March 20th 2015, at 06:00 UT
- Reconstruction of the Stokkseyri Field-of-View (FOV) by simulating 160 magnetic flux tubes along each of the 16 beams (coverage: 4000 km in range)
- Each flux tube has been convecting 4 hours : first backward without simulation and then forward with simulation in order to arrive in the Stokkseyri FOV at 06:00 UT. Convection is obtained from SuperDARN global convection maps



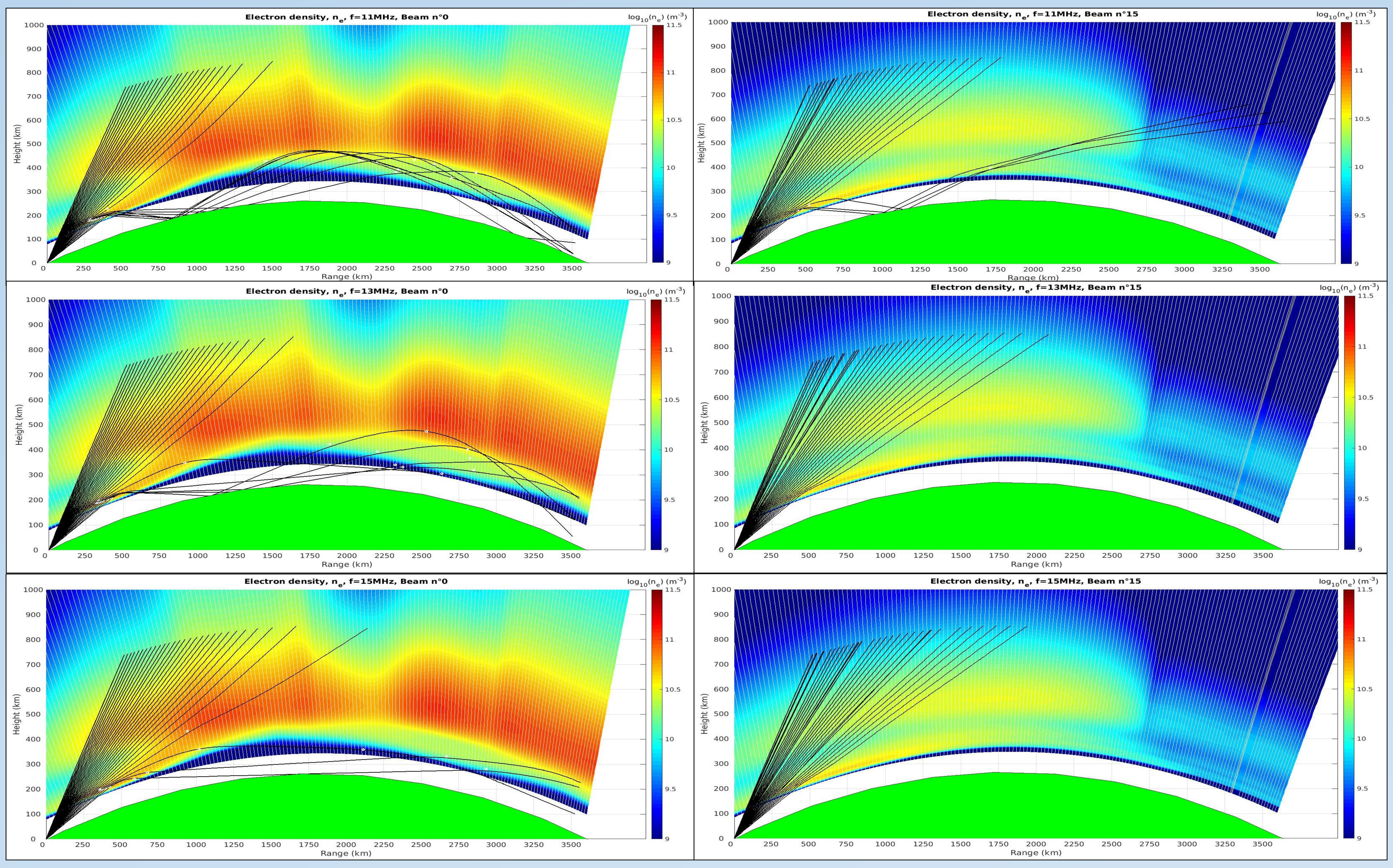
North hemisphere SuperDARN FOV



Electron density, at 250 km, along the 16 simulated beams of the Stokkseyri FOV

Ray tracing tool validation

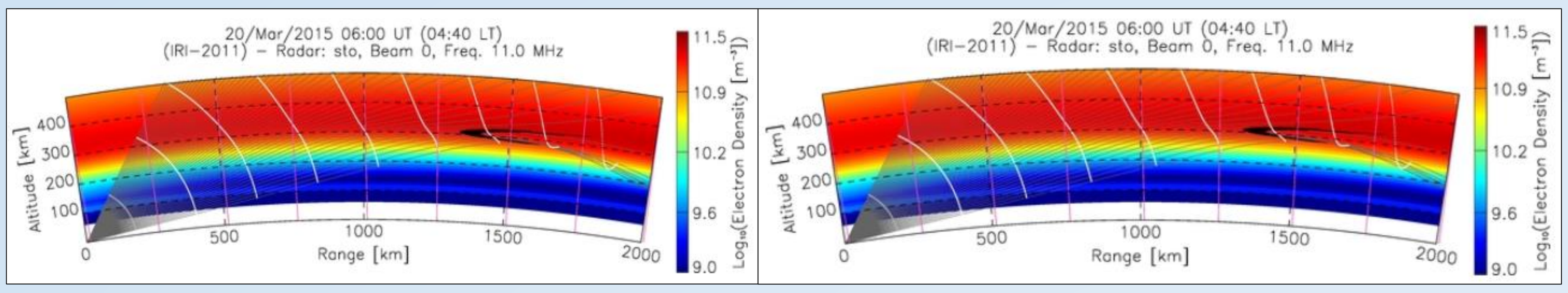
We present below the results of our propagation tool in the IPIM simulated ionosphere at the location of the Stokkseyri radar, the 20th March 2015 at 6h UT. Propagation paths for beams 0 and 15 are presented. Electron density ranges from 10^9 to 3.10^{11}. Strong ray bending is observed for low elevation on beam 0. Lesser ionosphere interaction is found for beam n°15, it can be link to a lower electron density peak, leading to very little variation in the refractive index *n*. With no strong gradient along the trajectory, the radio waves can leave the ionosphere with very few bending. In this case, the propagation do not gives information on the medium as there is no ionospheric backscatter. Lower frequencies can be used to probe this environment. Ionospheric backscattering is verified while the propagation path is perpendicular to the magnetic field lines. A part of the signal is then refracted.



Ray tracing results for beam n°0 (left) and beam n°15 (right). Propagation paths are plotted on black, magnetic field lines in white. Ionospheric backscatter are plotted with white dots. From top to bottom emitted waves frequency is 11, 13, 15 MHz

Virginia Tech ray tracing tool

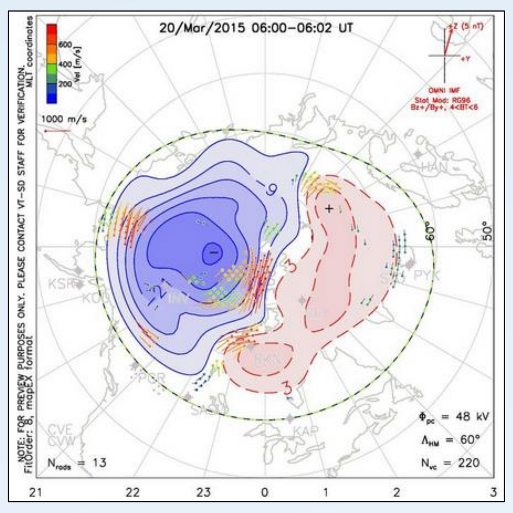
Virginia Tech scientific group provides an interactive ray tracing tool, I've shown below the results of the propagation in the same ionosphere but given by the IRI model. Same ionosphere is found for the two beams and a higher electron density is found. It ranges from 1.10^6 to 3.10^{11} m^{-3} for the two beams. Ray bending appears for low elevations, also ionospheric backscattering is also obtained between 200 and 300 km altitude at 1500 km range.



SuperDARN wave propagation (Virginia Tech ray tracing tool (4)), resulting from iono probing along beam n°0 (left) and beam n°15 (right) at 11MHz, the March 20th 2015. Propagation paths are plotted in black, magnetic lines in pink and ionospheric backscatter in bold black.

Summary

- Acquired:
  - HF wave propagation in a refractive medium
  - Fermat principle verified
  - Backscattering localization
  - **Ray tracing tool validation**
- Later work:
  - Integration of Faraday rotation, scintillation interaction…
  - Convection speed estimation using Doppler effect
  - VHF propagation integration
  - Development of a new simple ionosphere model (based on IPIM model)
    - Keeping all the most important features of the original model (chemistry, transport, electrodynamics)
    - Operational model with faster numerical resolution
    - Constrained by observational data (SuperDARN) through ray tracing tool



North hemisphere convection map, 20th March 2015 6:00 UT

Bibliography

1) Marchaudon, A., and P.-L. Blelly (2015), A new interhemispheric 16-moment model of the plasmasphere-ionosphere system: IPIM, *J. Geophys. Res. Space Physics*, 120, 5728–5745, doi:10.1002/2015JA021193.
2) Grandin, M., P.-L. Blelly, O. Witasse, and A. Marchaudon, (2014), Mars Express radio-occultation data: A novel analysis approach, *J. Geophys. Res. Space Physics*, 119, doi:10.1002/2014JA020698
3) P.-L. Blelly and D. Alcaydé, Ionosphere. In: Y. Kamide/A. Chian, Handbook of the Solar-Terrestrial Environment, pp.189-220 (2007). DOI: 10,1007/11367758_8
4) de Larquier, S., J. M. Ruohoniemi, J. B. H. Baker, N. Ravindran Varrier, and M. Lester (2011), First observations of the midlatitude evening anomaly using Super Dual Auroral Radar Network (SuperDARN) radars, *J. Geophys. Res.*, 116, A10321, doi:10.1029/2011JA016787.