DISPEC

Scientific exploitation of space Data for improved Ionospheric SPECification

SDA2 : "Modeling Trans-ionospheric Radio Signal Propagation"

Fabbro Vincent , Xavier Bauman (ONERA) & DISPEC team

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Funded by
the European Union

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SDA2. Modeling Trans-ionospheric Radio Signal Propagation

Context

- The need for modeling radio signal propagation through the ionosphere remains high and is becoming more challenging due to new requirements for accuracy and rapid availability.
- Further investigation into the ionosphere's complexity and dynamics requires unprecedented detail to evaluate plasma irregularity effects.
- Modeling signal propagation is extremely complex and demands high computational performance, especially when the ionosphere is considered as a anisotropic, inhomogeneous plasma without simplifications (or neglecting the Earth magnetic field).

SDA2. Modeling Trans-ionospheric Radio Signal Propagation

Context

- Ionospheric medium characterization : IRTAM / NeQuick / IRI

Assimilative IRTAM 3D (IRI-based Real-Time Assimilative Model). [Galkin et al., 2022] uses real-time measurement feeds from GIRO (Global Ionosphere Radio Observatory)

Note : A python version pyIRTAM exists available on GitHub [Forsythe et al., 2024]

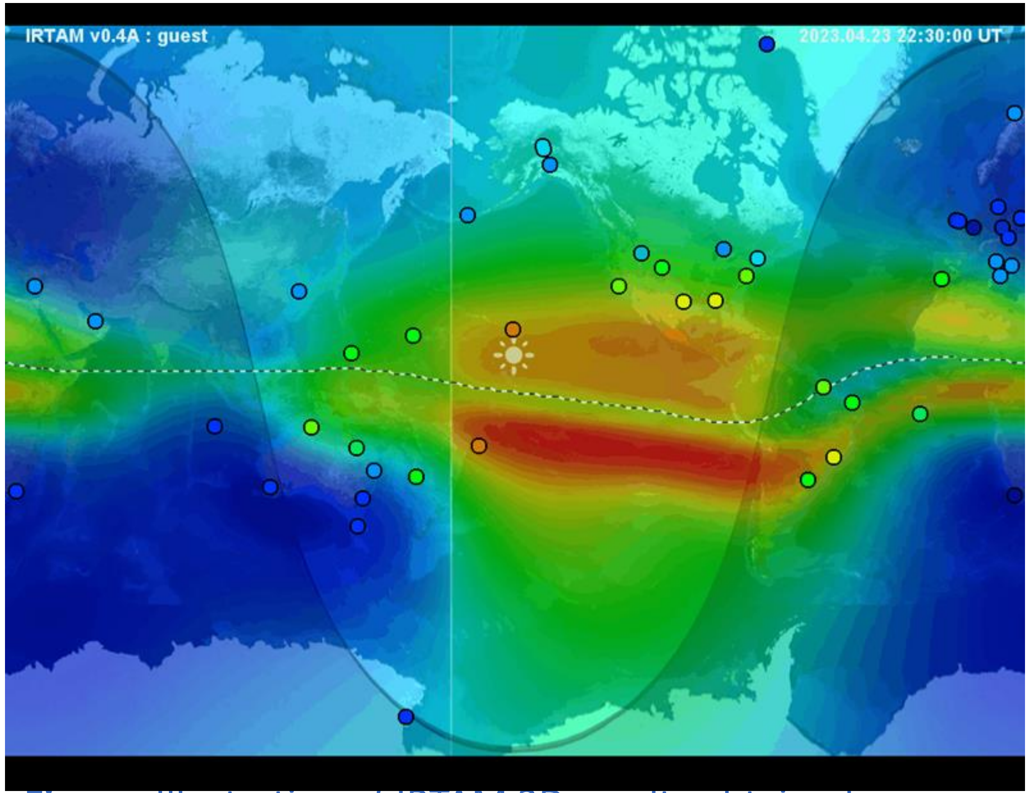

Figure: Illustration of IRTAM 3D results obtained using the GAMBIT tool.

SDA2. Modeling Trans-ionospheric Radio Signal Propagation

- Propagation modeling : **Haselgrove equation resolution model**

  - **Basic principle:** Hamiltonian formulation of the wave equation -> coupled equation systems giving the trajectory and wave vector of the wave at each point of the trajectory.

  - **Initial parameters:** frequency, azimuth, elevation -> require a search method to reach the receiver.

  - **Numerical resolution methods:** Runge-Kutta-4 or Runge-Kutta-Dormand-Prince to better control the integration error.

  - **Limitation:** Assume a slow variation of the ionosphere -> unsuitable for studying short-lived phenomena such as bubbles.

$$H = \frac{1}{2}\Re\left[\left(\frac{c}{\omega}\right)^2 \left(k_r^2 + k_\theta^2 + k_\varphi^2\right) - n^2\right]$$

$$\begin{cases} \dfrac{dr}{dP} = -\dfrac{1}{c}\dfrac{dH}{dk_r} \Big/ \dfrac{dH}{d\omega} \\ \dfrac{d\theta}{dP} = -\dfrac{1}{rc}\dfrac{dH}{dk_\theta} \Big/ \dfrac{dH}{d\omega} \\ \dfrac{d\varphi}{dP} = -\dfrac{1}{rc\sin(\theta)}\dfrac{dH}{dk_\varphi} \Big/ \dfrac{dH}{d\omega} \end{cases}$$

$$\begin{cases} \dfrac{dk_r}{dP} = \dfrac{1}{c}\dfrac{dH}{dr} \Big/ \dfrac{dH}{d\omega} + k_\theta \dfrac{d\theta}{dP} k_\varphi \sin(\theta)\dfrac{d\varphi}{dP} \\ \dfrac{dk_\theta}{dP} = \dfrac{1}{r}\left(\dfrac{1}{c}\dfrac{dH}{d\theta} \Big/ \dfrac{dH}{d\omega} - k_\theta \dfrac{dr}{dP} + k_\varphi r\cos(\theta)\dfrac{d\varphi}{dP}\right) \\ \dfrac{dk_\varphi}{dP} = \dfrac{1}{r\sin(\theta)}\left(\dfrac{1}{c}\dfrac{dH}{d\varphi} \Big/ \dfrac{dH}{d\omega} - k_\varphi \sin(\theta)\dfrac{dr}{dP} - k_\varphi r\cos(\theta)\dfrac{d\theta}{dP}\right) \end{cases}$$

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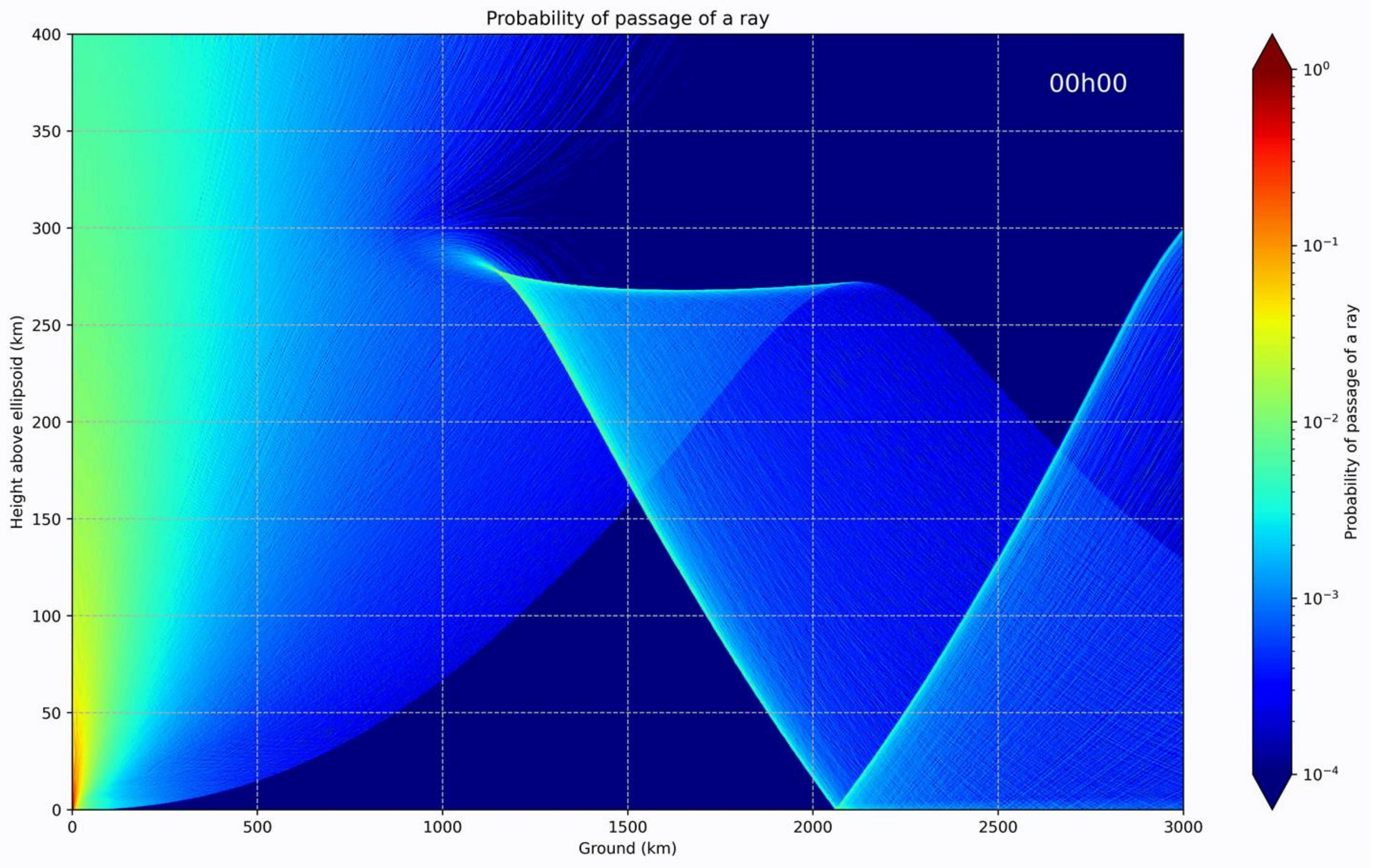


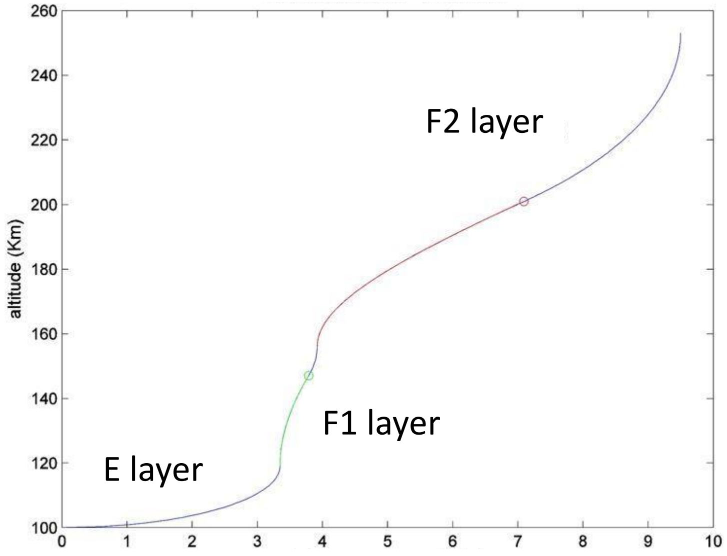
SDA2. Modeling Trans-ionospheric Radio Signal Propagation

- Propagation modeling : **MQP model (Multi Quasi Parabolic)**

  - **Basic principle:** Description of vertical ionospheric density profile by segments of quasi-parabola. Then, analytic formulations available to compute the ray trajectory (i.e. group distance).
  - **Initial parameters:** frequency, azimuth, elevation -> require a search method to reach the receiver.
  - **Limitations:**
    - Approximation of electron density profile by MQP
    - No variability of the profile vs distance, nor lateral dimension
    - Assumes approximation of the refractive index

$$\mathrm{f}(r)^2 = f_{Pi}^2\left[1 \mp \frac{(r - r_{mi})^2}{y_{mi}^2}\frac{r_{bi}^2}{r^2}\right]$$

MQP modeling – 5 layers



Plasma frequency (MHz)

SDA2. Modeling Trans-ionospheric Radio Signal Propagation

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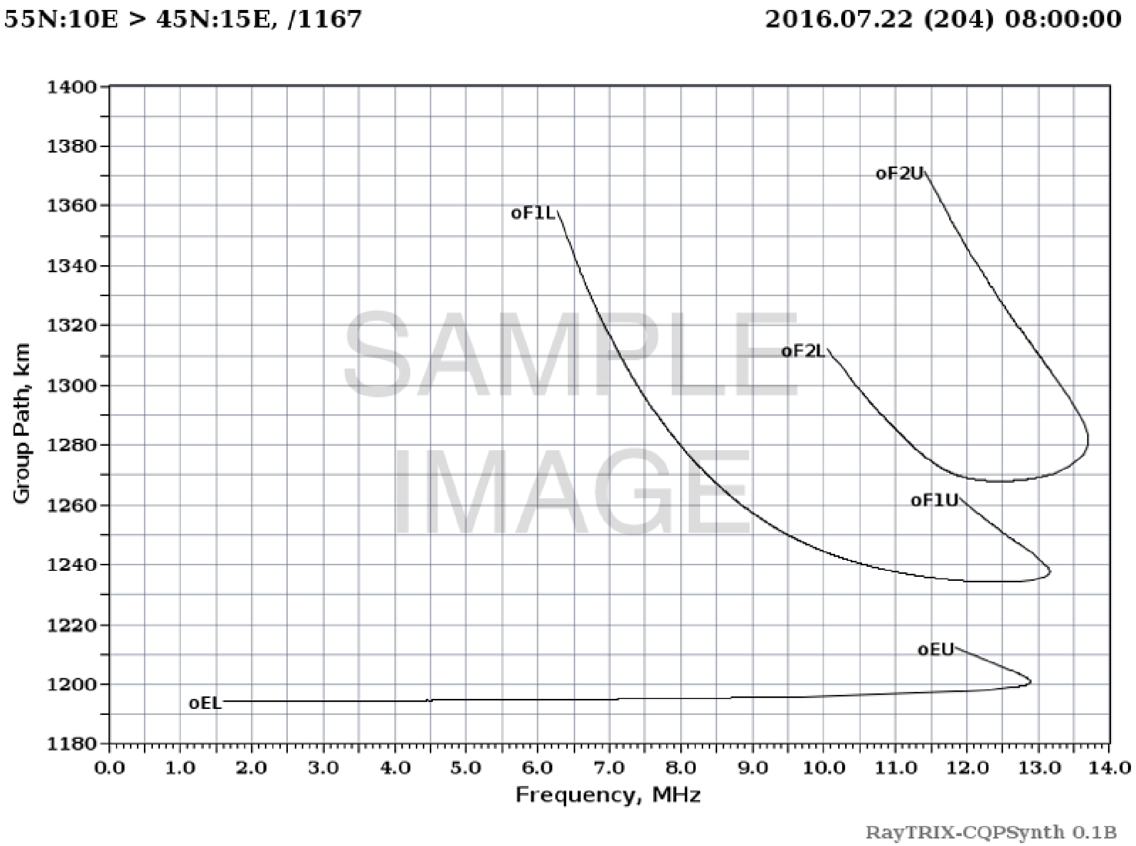
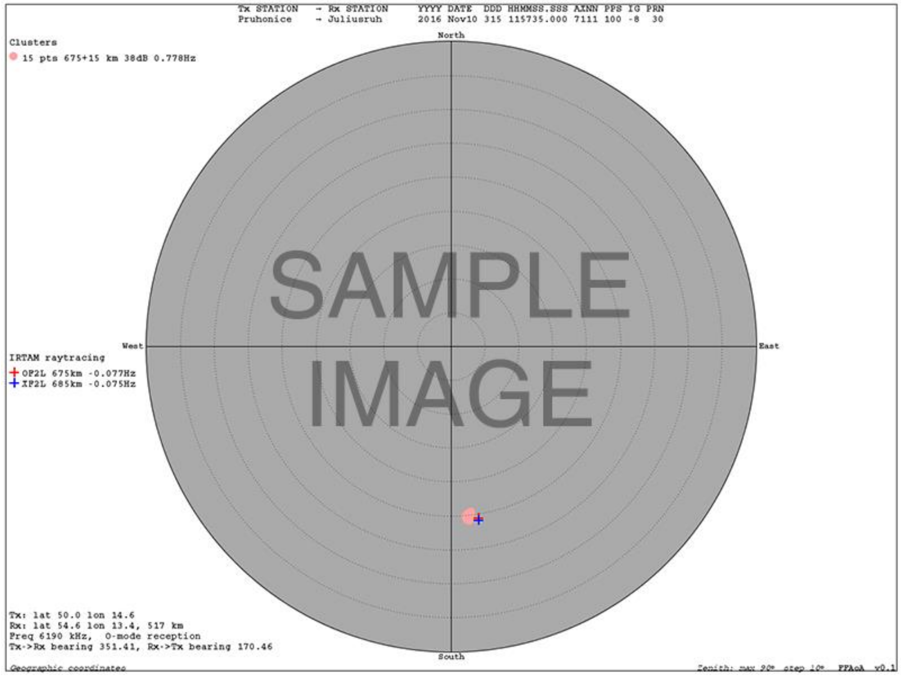


This service uses a spherically stratified Composite-Q DP is matched to the Assimilative IRI profile at the midpoint, calculated using near-real-time GIRO data.

RayTRIX
Ray Tracing through Realistic Ionosphere Explorer

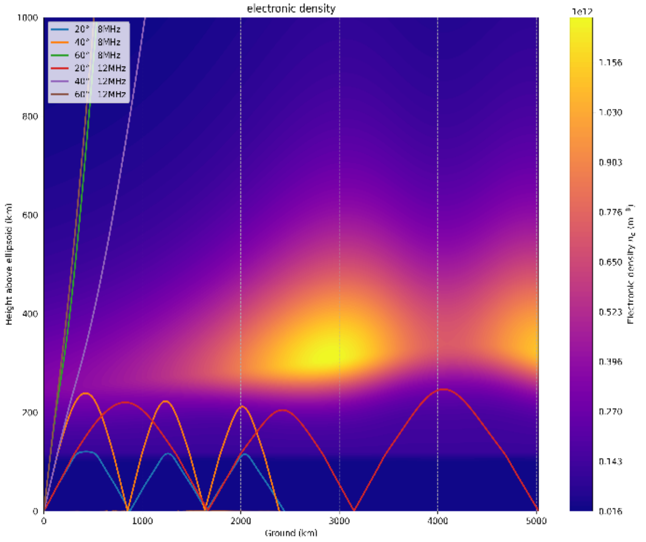
https://giro.uml.edu/rix/oi-synth/

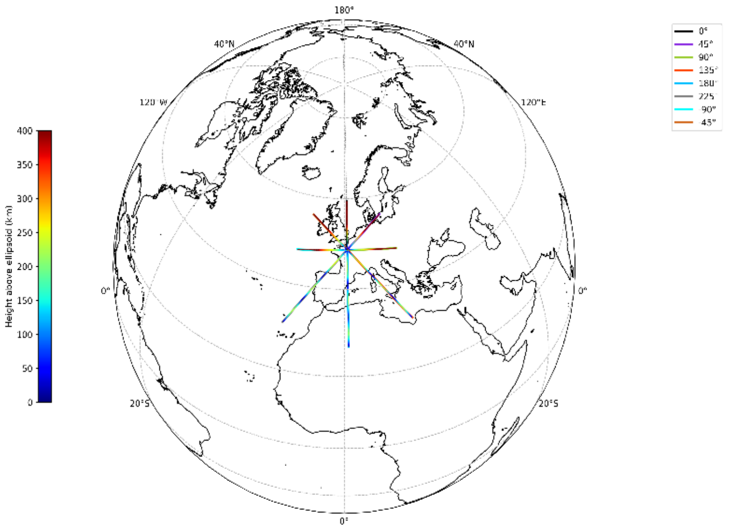


SDA2. Modeling Trans-ionospheric Radio Signal Propagation

- Review of Scientific models underpinning SDA2 (regarding their operational capability)
  1. LIMPID-HF 3D raytracer with quiet-time background ionosphere modeled by NeQuick or IRI,

Ionosphere modeled by NeQuick or IRI
resolution of Haselgrove equations (3D)





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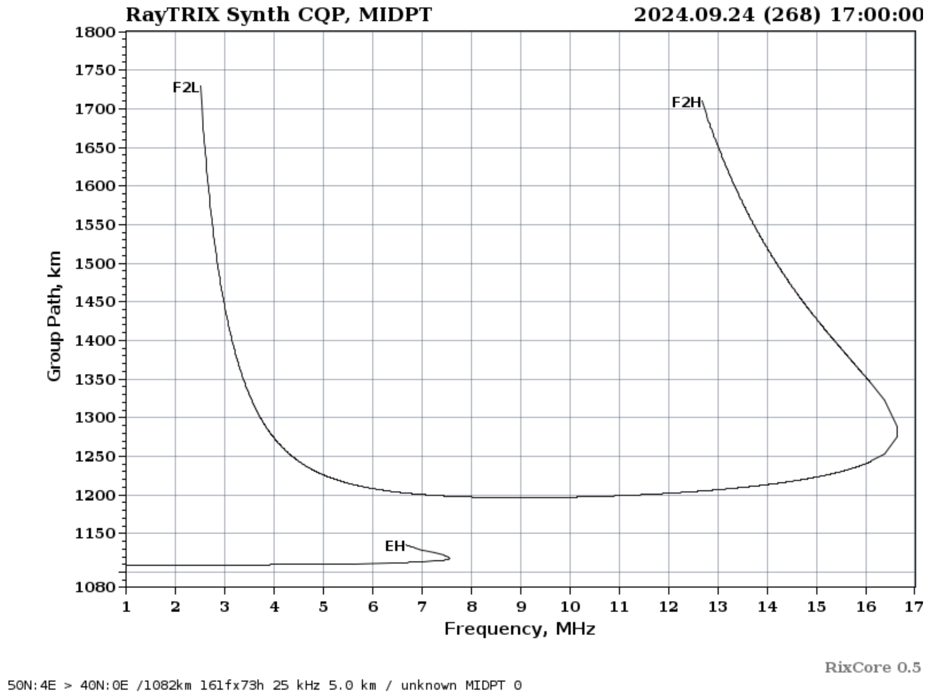
  1. LIMPID-HF 3D raytracer with quiet-time background ionosphere modeled by NeQuick or IRI,
  2. RayTRIX CQP (Composite Quasi-Parabolic), extended to 2 hops

Simplified electron density profile and propagation
Based on IRTAM background ionosphere
IRI is also possible



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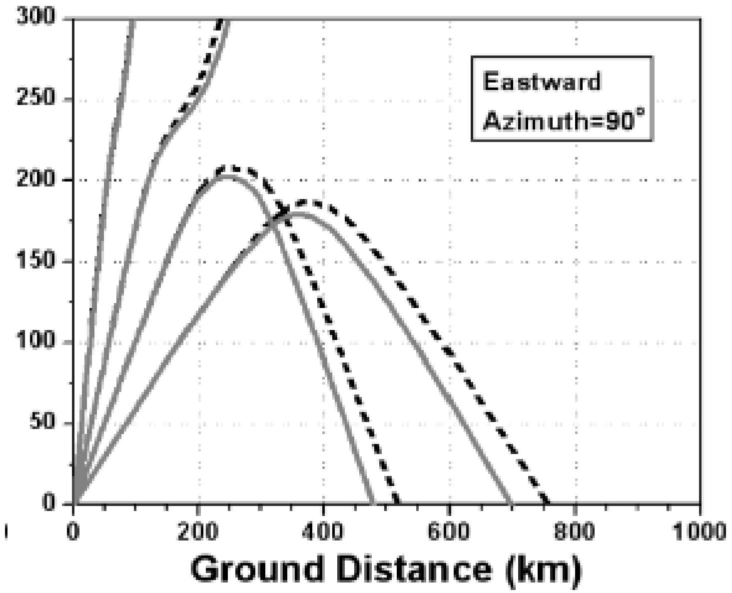
  3. HR2006 Numerical 3D raytracer (Parallelized and rewritten in GPU) with IRTAM background ionosphere

IRI-like profile formalism for background ionosphere
IRTAM is possible
Overlaying TIDs is also possible



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  Outputs: synthetized Doppler skymaps and oblique ionograms

- Tests to verify the results:
  - ✓ Validations : (1) vs (2) vs (3) on quiet-time background ionosphere (and no Earth magnetic field, neither collision profile), with 1 or 2 hops
  - ✓ Validations : (1) vs (2) vs (3) on quiet-time background ionosphere, with Earth magnetic field
  - ✓ (1) (2) (3) : Cross-validation versus D2D oblique sounding **data**

  (2) and (3) should demonstrate improved performance with **DISPEC high-level data products**

Thank you for your attention!

WEB: https://dispec.eu

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