DISPEC

Scientific exploitation of space Data for improved Ionospheric SPECification

SDA2 : "Modeling Trans-ionospheric Radio Signal Propagation"

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Outline

- Motivation
- Methodology
  - Propagation models
  - Evaluation of accuracy and uncertainty
- Proposed Demonstrator
- Conclusions and further work

Motivation

Improving Modeling Trans-ionospheric Radio signal Propagation

- 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).

We want to master the accuracy and limits of propagation models to estimate their impact on RF systems

Methodology

Different types of propagation models proposed:

- **Haselgrove equations 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.

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

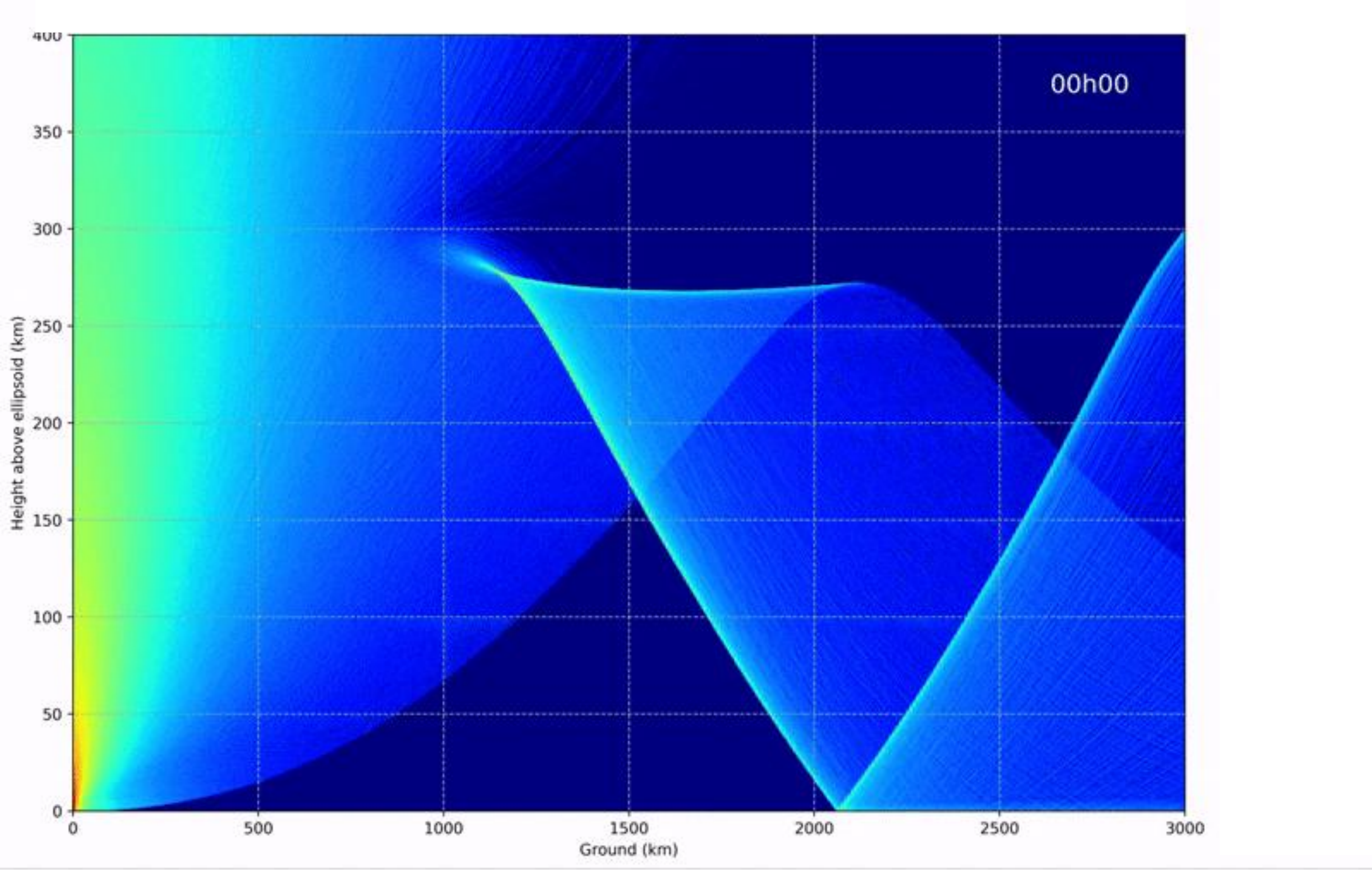
$$\begin{cases} \dfrac{dr}{dP} = -\dfrac{1}{c}\dfrac{dH}{dk_r} / \dfrac{dH}{d\omega} \\ \dfrac{d\theta}{dP} = -\dfrac{1}{rc}\dfrac{dH}{dk_\theta} / \dfrac{dH}{d\omega} \\ \dfrac{d\varphi}{dP} = -\dfrac{1}{rc\sin(\theta)}\dfrac{dH}{dk_\varphi} / \dfrac{dH}{d\omega} \end{cases}$$

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

Methodology:

Different types of propagation models proposed:

- **Haselgrove equations model**



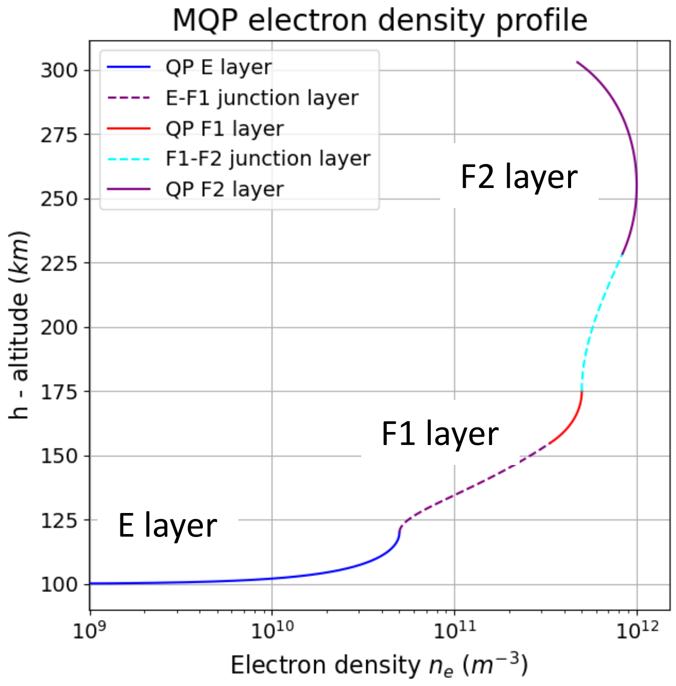
Methodology:

Different types of propagation models proposed:

- **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

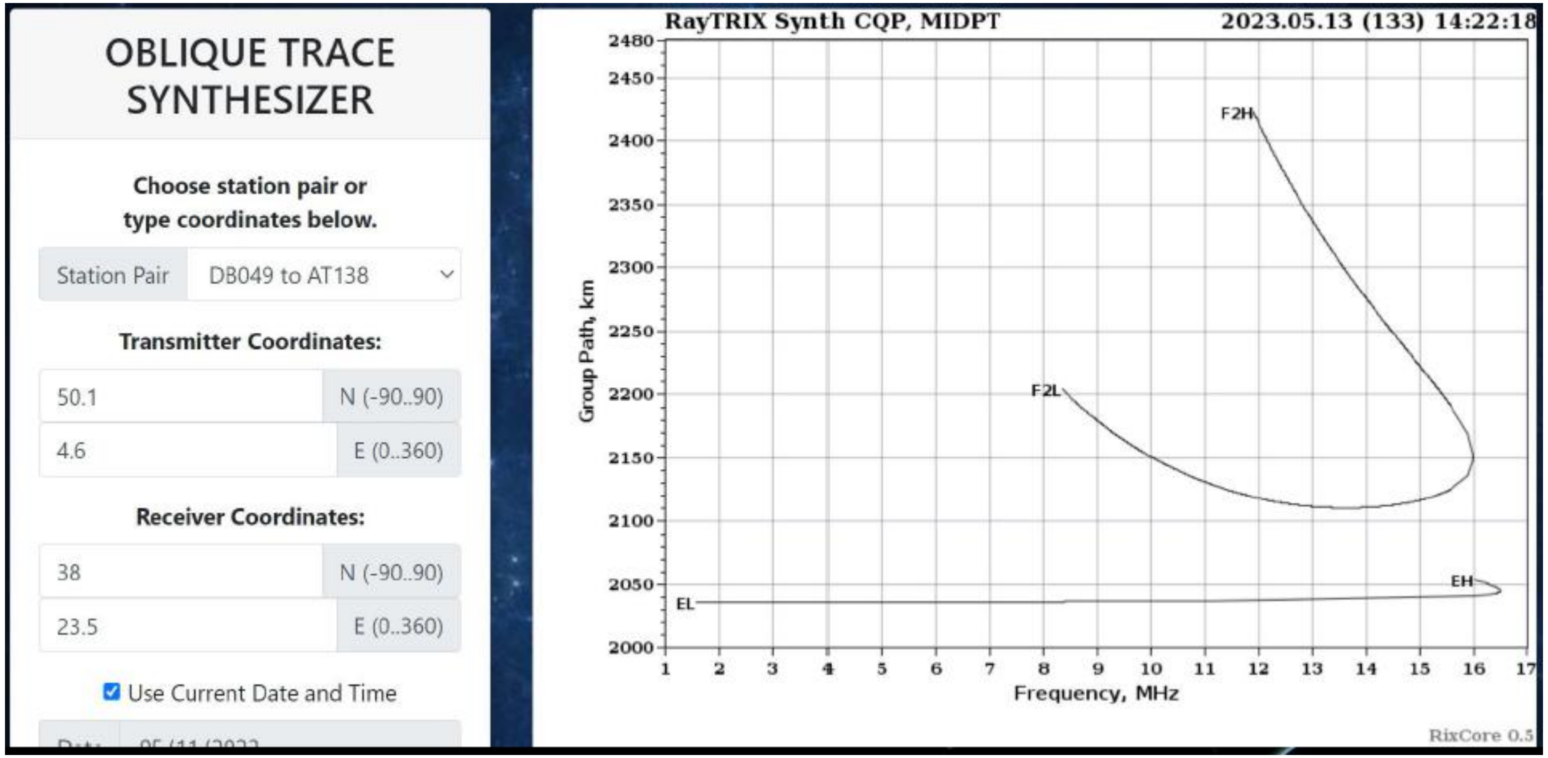
$$\mathrm{f}(r)^2 = f_{Pi}^2\left[1 \mp \frac{(r - r_{mi})^2}{y_{mi}^2}\frac{r_{bi}^2}{r^2}\right]$$



Methodology:

Different types of propagation models proposed:

- **MQP model (Multi Quasi Parabolic)**



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/

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

Methodology:

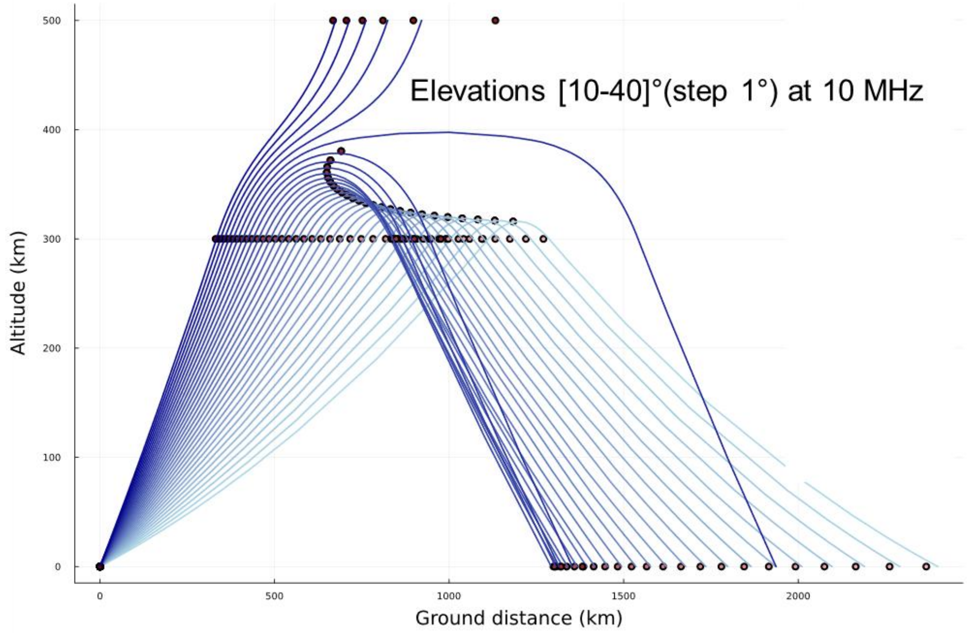
Evaluation of accuracy and uncertainty

- Comparisons in **canonical configurations**

The two propagation modelling techniques are compared in different **canonical configurations** to quantify their limits and accuracy.

This first step quantifies the errors inherent to each method, which will be used to establish basis criteria.

These will be used as references for comparisons with HF propagation measurements.



- Comparisons to **data**

The HF propagation modelling will be applied considering as input scaled ED profiles and the propagation results compared to the **HF measurements**.

The data selected for validation are oblique HF band ionosphere-sounding.

Deviations will be compared to model accuracy criteria and analysed.

DISPEC Demonstrator

SDA2:

- Two possible workflow (1) Comparisons in canonical configurations and (2) Comparisons to data

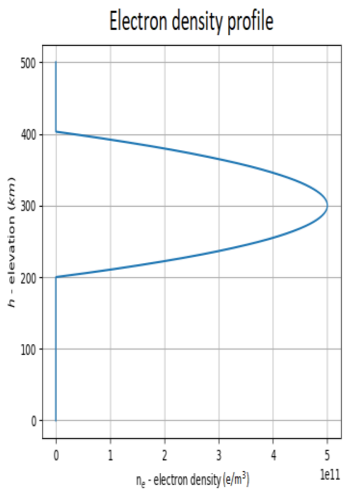
Workflow 1: Comparisons in canonical configurations

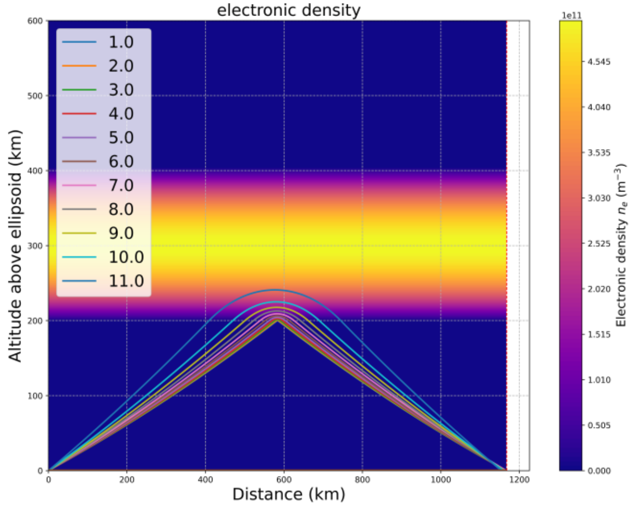
Input : [text] Ne(h) theoretical : QP, MQP, IRI
link geometry,
frequencies

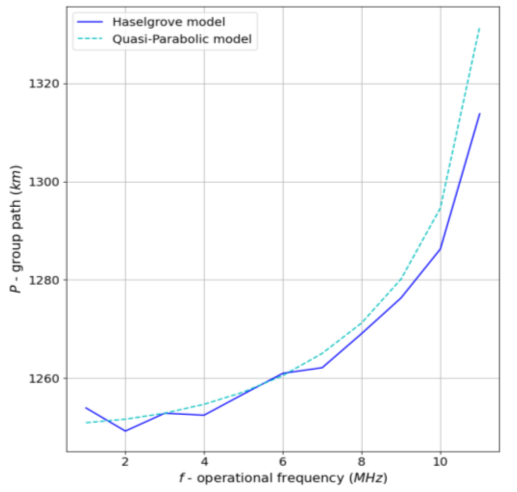
Haselgrove propag. Model (asym, O and X mode)

MQP propag. Model (asym mode)

Comparisons :
Plot : ray trajectories, oblique ionogram
Text : delay vs freq, Differences : relative error, RMSE, Biais







	Ground path (D)	Group path (P)
Relative error (%)	0,29	0,30
RMSE (km)	1,55	1,89
Bias (km)	-2,61	-3,32

DISPEC Demonstrator

SDA2:

- Two possible workflow (1) Comparisons in canonical configurations and (2) Comparisons to data

Workflow 2: Comparisons to data (vertical + oblique sounding)

Input:
IRI (long term), IRI (with scaled parameters) and sensitivity study

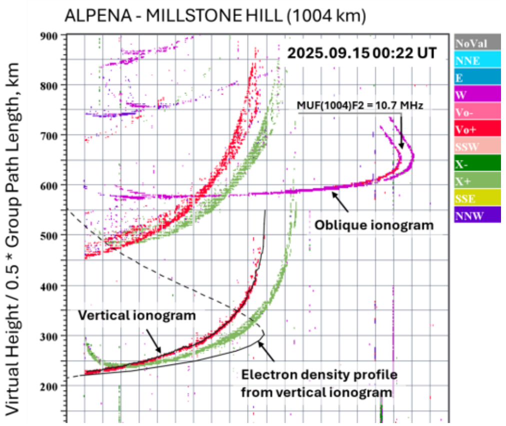
link geometry, frequencies

Haselgrove propag. model

MQP propag. model

Comparisons :
Plot : Oblique ionogram (all modeled)
+ **Modeled MUF vs measured MUF**

Text : MUFs, OI, MUF skill score and OI skill scores.



Comparison and study of :

- Measured MUF **vs** simulated MUF (Haselgrove, 3 modes: asym., **ordinary** and **extraordinary**) **vs** simulated MUF (MQP, 1 mode: asym)

→ MUF Skill score

- Measured O.I. **vs** simulated O.I. (Haselgrove , 3 modes: asym., **ordinary** and **extraordinary**) **vs** simulated O.I. (MQP , 1 mode: asym)

→ OI Skill score

Note: skill score = relative error, RMSE, Biais

Conclusions and further work

- Development / adaptation of different propagation models, in order to evaluate **accuracy and uncertainty of propagation modeling**
- Definition of a **demonstrator** and development (on going work)
- **Further work:**
  - Finalization of the demonstrator
  - Comparison study in canonical configurations
  - Sensitivity study of output with key parameters of EDP
  - Comparisons vs oblique ionogram measurements
- **DISPEC demonstrator** will provide open access to:
  - Comparisons between the different propagation models
  - Comparisons with MUF data in specific conditions.

Thank you for your attention!

WEB: https://dispec.eu

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