COMPARISON OF METHODS FOR MODELING THE TRANS-IONOSPHERIC PROPAGATION OF RADIO SIGNALS

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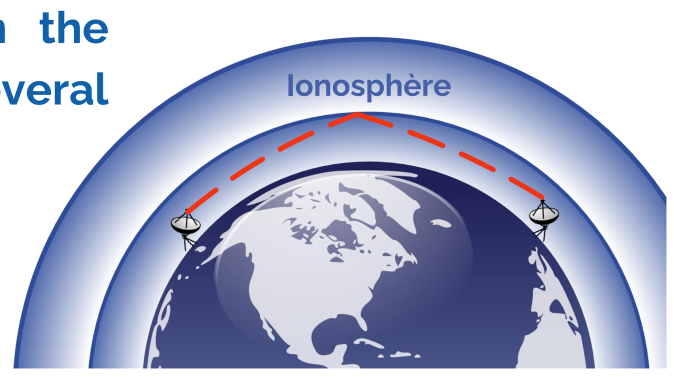
CONTEXT

In the HF band, radio waves are refracted in the ionosphere, enabling communications over several thousands of kilometers.

This phenomenon is exploited for communications when the operational context does not permit satellite-based communication.



To better understand this phenomenon, two simulation methods are being studied. The goal is to determine if these methods can produce comparable results under the same assumptions and to evaluate their accuracy in predicting propagation.

MULTI QUASI PARABOLIC (MQP) METHOD

Basic principle :

Vertical description of the ionospheric density profile by quasi parabolic segments. Analytic solutions available to compute the ray trajectory (i.e group distance)

Initial parameters :

Frequency, azimuth elevation -> requires a research method to reach the receiver

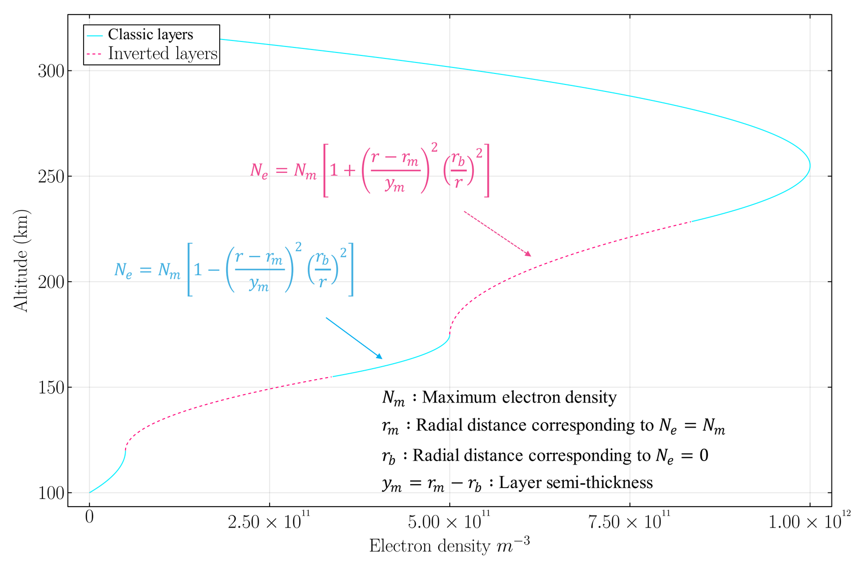


Figure 1: Profile generated by the MQP method.

Strenghts and limitations :

- ✓ Analytical solutions
- ✓ Fast computations
- ✗ Electron density profile approximated by MQP
- ✗ No variability of the profile with the distance
- ✗ Refractive index approximated
- ✗ Earth magnetic field neglected (isotropic medium)
- ✗ Collisions between particles neglected

HASELGROVE'S METHOD

Basic principle :

Hamiltonian formulation of the wave equation. Couple equation systems giving the trajectory and wave vector of the wave at each point of the trajectory

Numerical resolution methods : Tsitouras algorithm

$$\frac{d\vec{x}}{dP} = \frac{\partial H}{\partial \vec{k}} \qquad \frac{d\vec{k}}{dP} = -\frac{\partial H}{\partial \vec{x}}$$

P: Independant variable of integration

$\vec{k}$: Wave vector

H: Hamiltonian

$\vec{x}$: Position of the ray

Initial parameters :

Frequency, azimuth elevation -> requires a research method to reach the receiver

Strenghts and limitations :

- ✓ Earth magnetic field
- ✓ Works with any ionospheric profile
- ✗ More computational resources
- ✗ Potential numerical errors
- ✗ Assumes a slow variation of the ionosphere

These methods give very similar results except for specific solutions called Pedersen rays

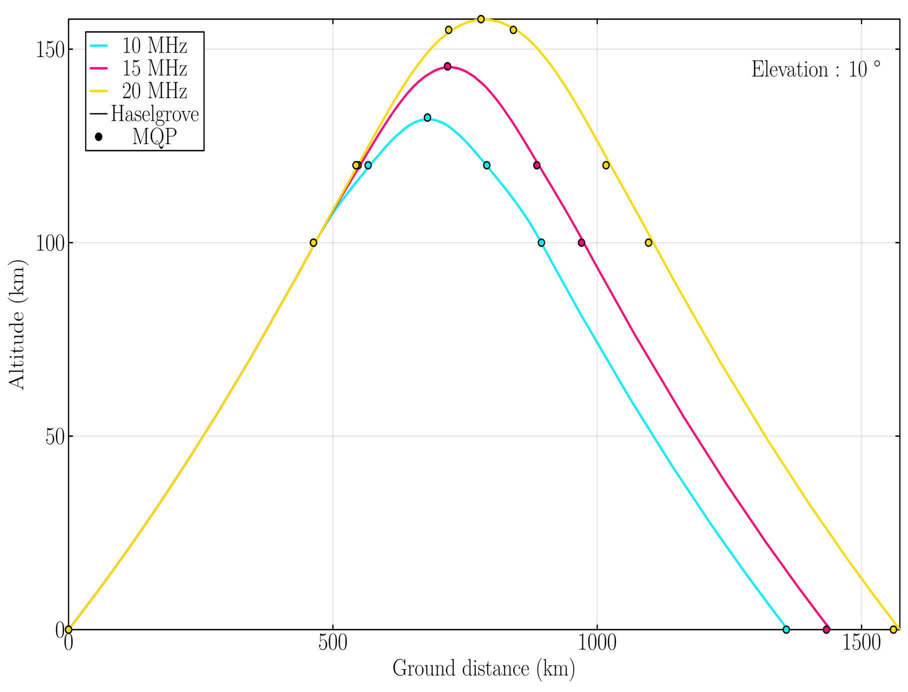


Figure 2: Ray tracing comparison for three different frequencies at 10° elevation.

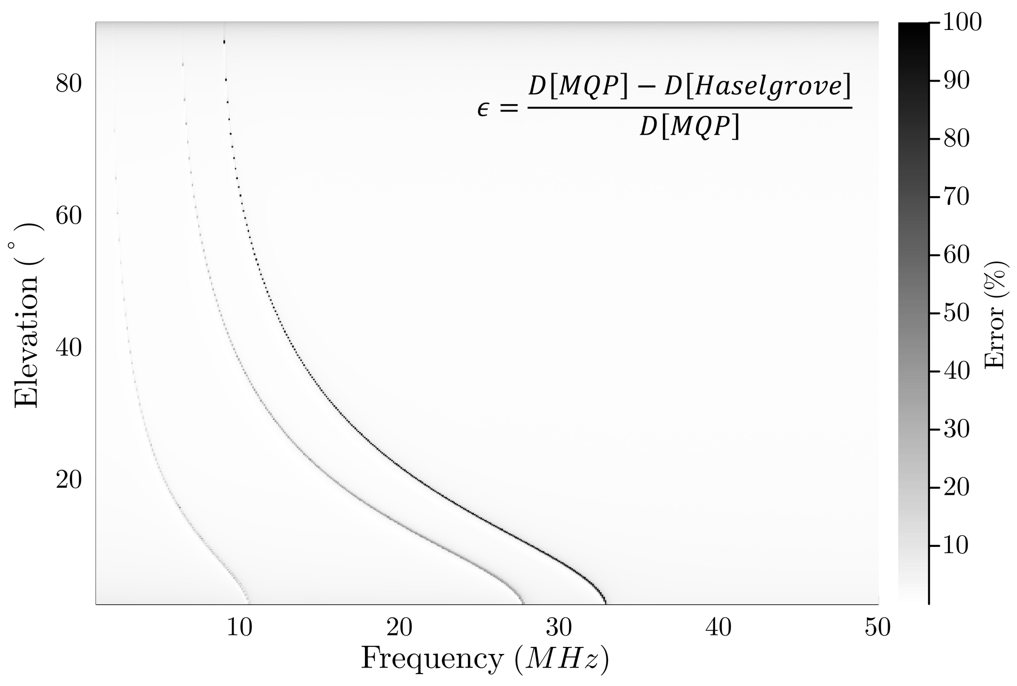


Figure 3: Error heatmap between the two methods.

They can also be used with long-term prediction models (IRI, NeQuick, ...)

The MQP method can be used by fitting a set of parabolas to the electron density profile

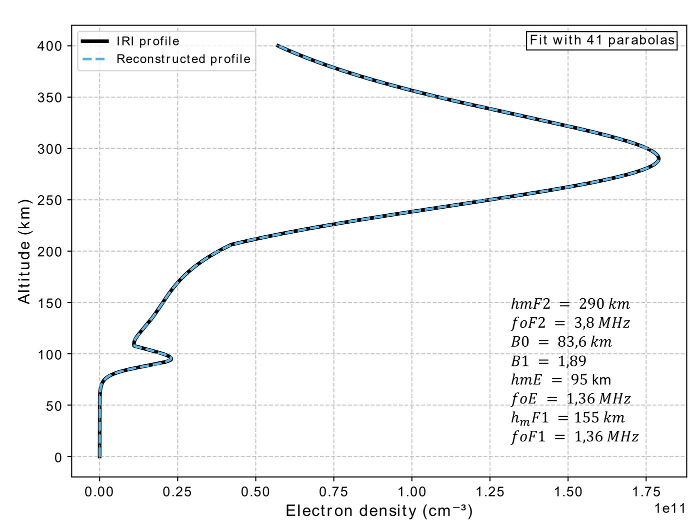


Figure 4: Profile generated by fitting MQP equations on an IRI profile.

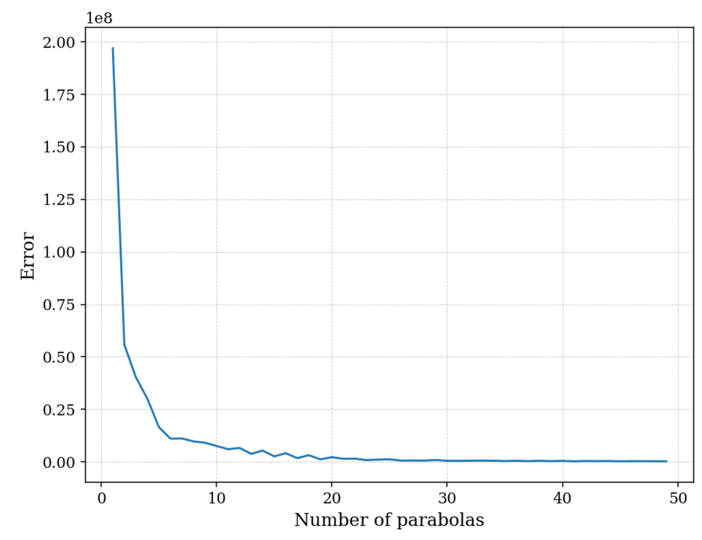


Figure 5: RMS error vs number of parabolas

PREDICTING THE MAXIMUM USABLE FREQUENCY: HOW RELIABLE ARE OUR SIMULATION MODELS ?

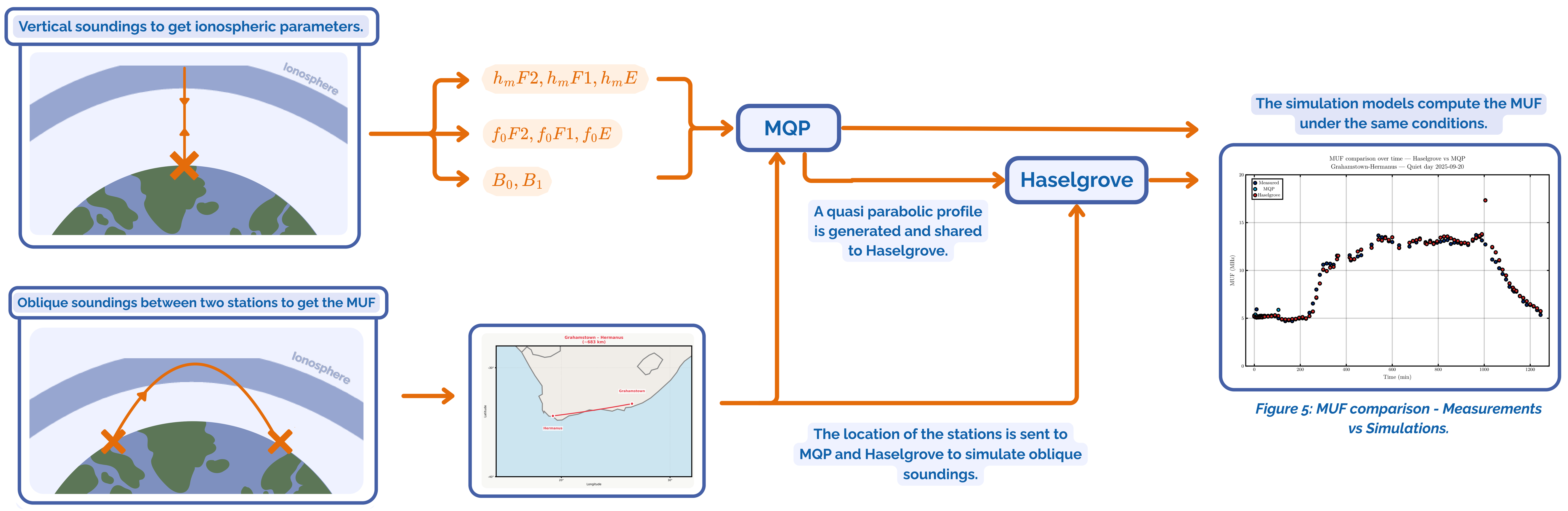


Figure 5: MUF comparison - Measurements vs Simulations.

Perspectives :

- Further comparison with oblique measurements
- Study of the Earth's magnetic field impact
- Integration of attenuation
- Integrating ionospheric variations along the propagation path

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