A 3D ray-tracing software for OTH radar simulations

P. Coïsson, G. Occhipinti, P. Lognonné
Institut de Physique du Globe de Paris

J.-P. Molinie
Office National d'Etudes et de Recherche Aerospatiales

coisson@ipgp.fr
http://ipgp.fr

Introduction

Over-the-horizon (OTH) radar are powerful instruments to observe objects flying on the Earth surface, but also to study the ionospheric dynamics and the propagating phenomena that occur in the ionosphere. We are developing numerical simulation tools to explore the OTH radar capability in the ionospheric sounding.

We present here a 3D electromagnetic wave ray-tracing software (TDR) based on the geometrical optics linear theory. Ray propagation through a 3D heterogeneous ionosphere above an ellipsoidal Earth (WGS-84) is solved using fourth-order Runge-Kutta method for the solution of the eikonal equation. Modeling is specifically developed for mono-static over-the-horizon radar.

Two 3D empirical ionospheric models are alternatively used in the calculation of the local refraction index along the ray-path: International Reference Ionosphere (IRI) and NeQuick. Both are global median models that provide the electron density at any point of the Earth ionosphere. They present different features, especially in the representation of the bottomside ionosphere, from 90 to 300 km, the region scanned by OTH radars.

Here we explore the sensitivity of ray propagation to the theoretical seasonal/geographical/solar activity variations typical of the ionosphere dynamic. We present preliminary results of comparison between synthetics and data supplied by the OTH-radar Nostradamus managed by ONERA.

OTH radar

Over-The-Horizon radars operate in HF radio band (from 3 to 30 MHz). This frequency range covers the range of frequency that can be reflected by the Earth ionosphere. OTH radars form signals with elevation and azimuth capability to cover areas up to few thousands km from the emitter.

Nostradamus radar

Nostradamus is a monostatic OTH radar located in France, developed and managed by ONERA. It is composed by 288 bi-cone antenna elements distributed over three arms in a star deign. This structure performs an azimuthal coverage of 360°.

Figure 1: Nostradamus Antenna Array (photo Stéphane Muratet) (right) and cartoon of radar operation (left).

Even though the primary use of OTH radars is the detection of aircrafts and ships, their operational range of frequency is ideal for the observation of the bottomside ionosphere from the ground (oblique sounding).

HF propagation and ray-tracing in the ionosphere

The index of refraction in a cold plasma is expressed by:

$$n = \sqrt{1 - \frac{N_e e^2}{4\pi^2 m_e \varepsilon_0 f^2}}$$

being f the wave frequency, N_e the electron density, e and m_e electron charge and mass, ε_0 the vacuum permittivity.

Imposing the conditions of isotropic and non-dispersive medium, we use the eikonal equation for rays calculation:

$$(\nabla S)^2 = n^2$$

It can be represented by a system of three equations:

$$\frac{d}{dr}\left(n\frac{dx}{dr}\right) = \frac{\partial n}{\partial x}$$

$$\frac{d}{dr}\left(n\frac{dy}{dr}\right) = \frac{\partial n}{\partial y}$$

$$\frac{d}{dr}\left(n\frac{dz}{dr}\right) = \frac{\partial n}{\partial z}$$

we solve this system numerically using a Runge-Kutta recursive method [Occhipinti, 2006].

Ionospheric Ray-tracing

The TDR software

We are developing a 3D electromagnetic wave ray-tracing program based on the geometric optic linear theory and including a heterogeneous ionosphere above an ellipsoidal Earth (WGS-84). It is used along with a 3D model of electron density in the ionospheric plasma in order to calculate the index of refraction at any point of the propagation path. Two options for the ionosphere have been included in the program to check rays response to different ionospheric representation: IRI 2007 [Bilitza, 2008] and NeQuick 2 [Nava et al., 2008]. They present different characteristics that have to be tested to understand the ability of the ray-tracing program to predict the propagation behavior of radar signals.

- **IRI 2007**: it includes all ionospheric bottomside layers (D, E, F1, F2), but can have electron density spatial discontinuities when F1 layer appears. The default foF2 model is based on URSI coefficients.
- **NeQuick**: it is spatially continuous, with continuous spatial first derivatives, but does not include D layer and E layer height is fixed. It uses ITU-R coefficients for foF2.

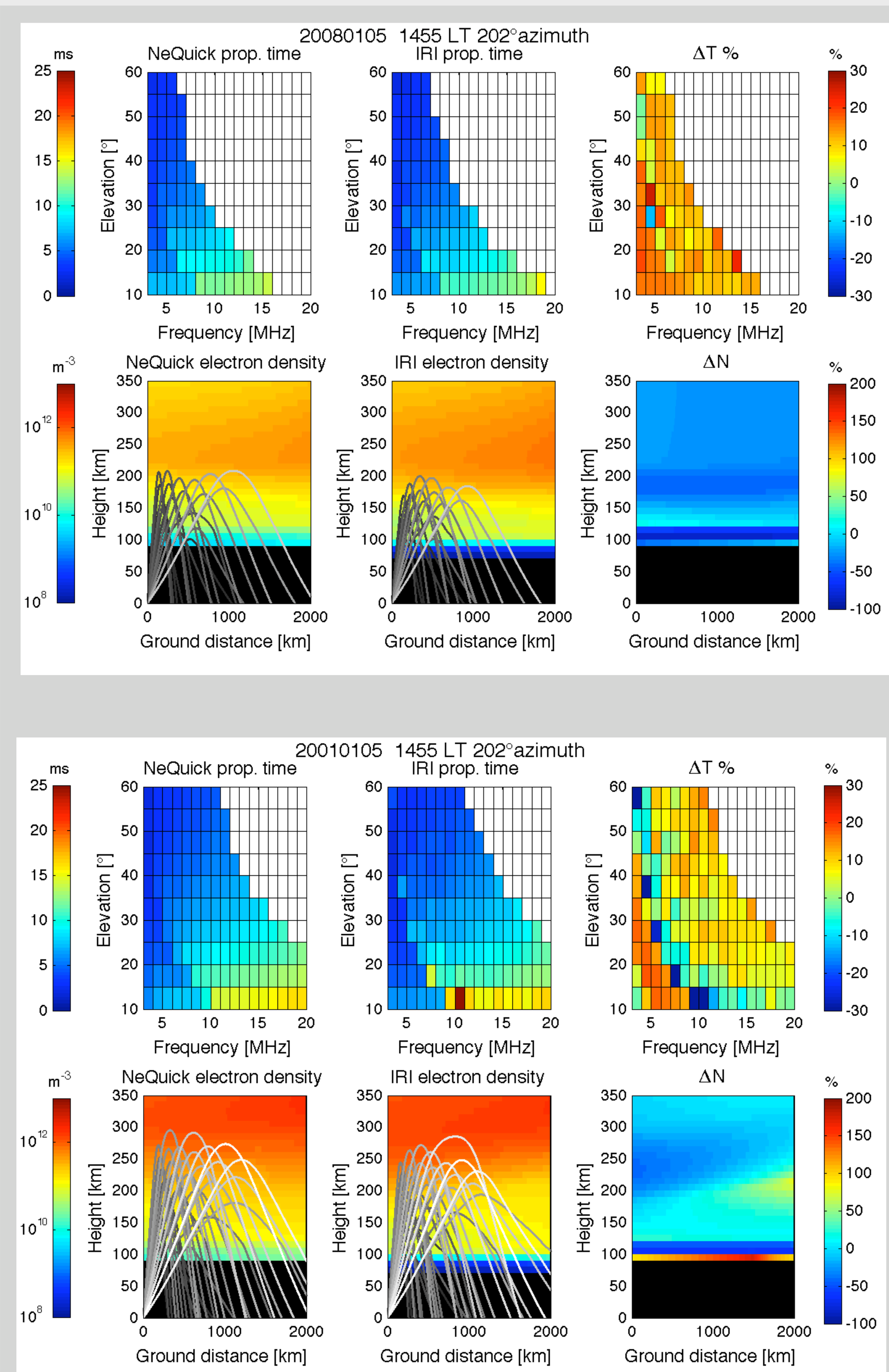

Figure 2: Comparison between TDR rays using NeQuick or IRI ionospheres for low (top panel) and high (bottom panel) solar activity, day-time.

Echo time calculation using TDR

We calculated maps of echo time using TDR and the two model options for the frequency range 3-20 MHz and elevation from 10° to 60°.

Figure 2 shows examples of TDR calculation for low (top panel) and high (bottom panel) solar activity, day-time.

The discontinuity in the maps of echo time indicate the change of reflecting layer from E to F.

Comparison with OTH data

Validation of TDR using radar data

We compared TDR simulation results with low solar activity experimental data, during the period 2006-2008, when available hourly Nostradamus observations at 8 different azimuths.

Results shown in Figure 2 and 3 indicate that during day-time for very low solar activity the trends of echo time with elevation are respected and echo time error are below 50% for frequencies up to 9 MHz at all azimuths. In the north sector for higher frequencies errors can be bigger than 150%.

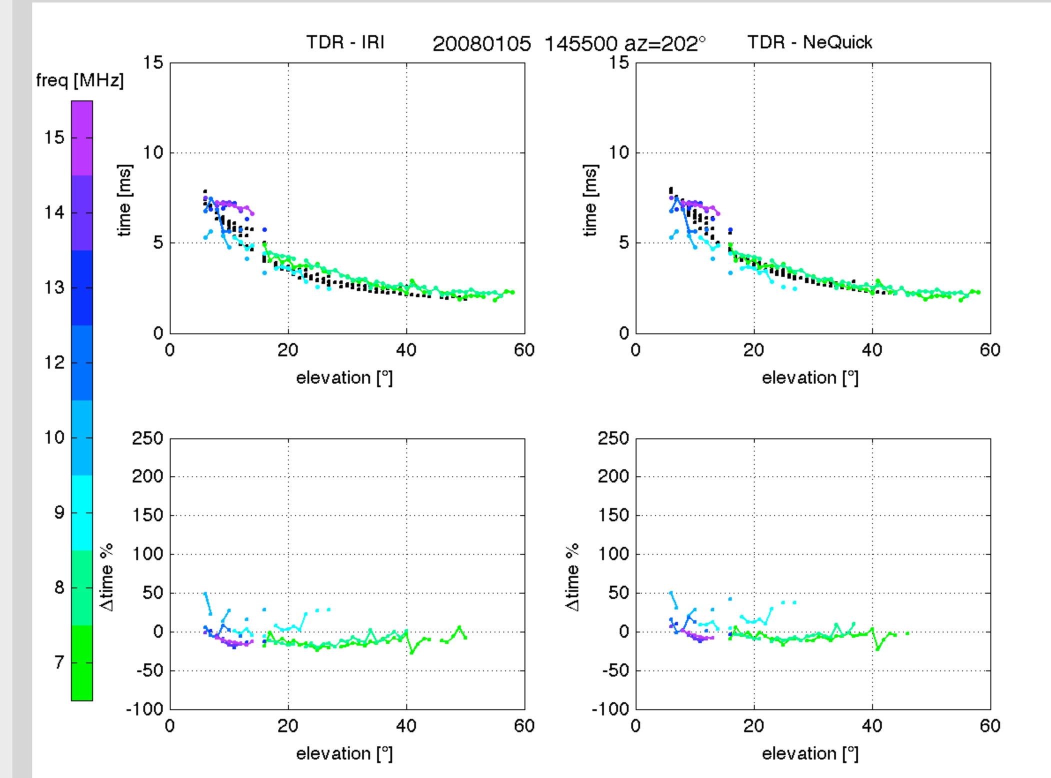

Figure 2: Comparison between Nostradamus echoes (colored lines) and TDR using IRI (left, black) and NeQuick (right, black) ionosphere. Winter, South sector, day-time.

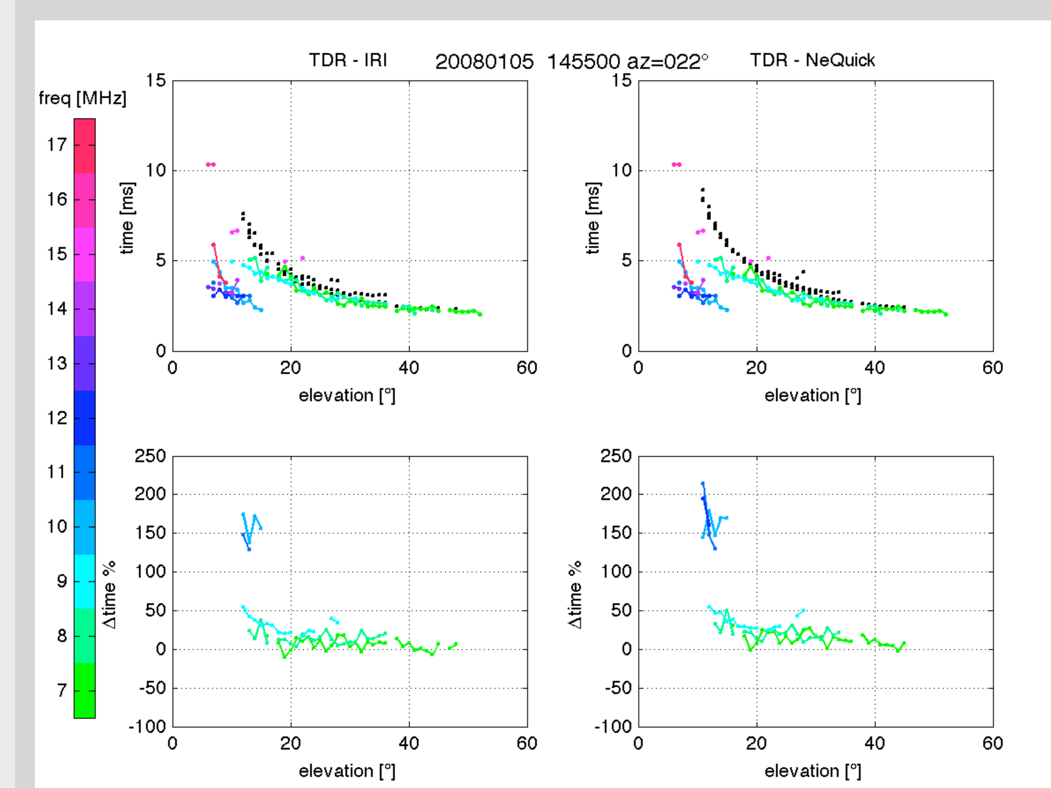

Figure 3: Comparison between Nostradamus echoes (colored lines) and TDR using IRI (left, black) and NeQuick (right, black) ionosphere. Winter, North sector, day-time.

References

[Bilitza and Reinisch, 2008] Adv. Space. Res. 42, 599-609, 2008.
[Nava et al., 2008] JASTP, 70, 1856-1862, 2008.
[Occhipinti, 2006] Thesis, IPGP, 2006.

Ionospheric variability

During night-time (Figure 4 and 5) for extremely low solar activity only few radar echoes are recorded, that are not reproduced by TDR, but for moderate solar activity reflected rays are computed and the error are slightly bigger than during day-time and are below 50%.

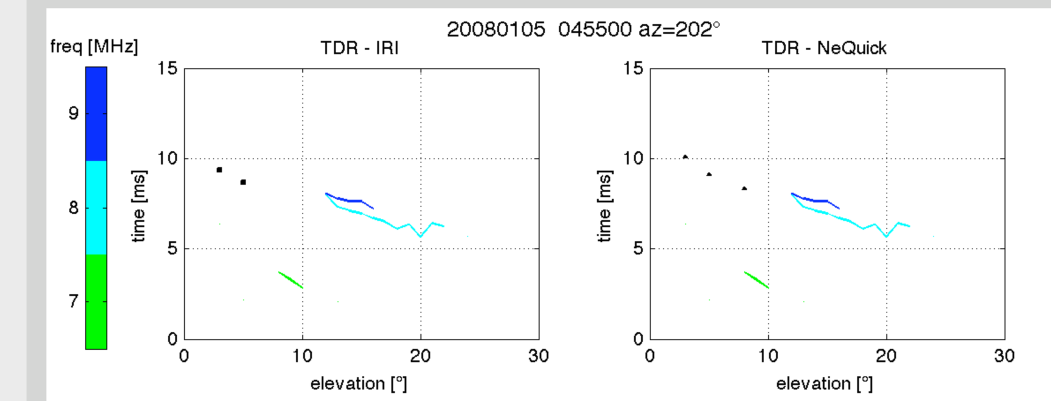

Figure 4: Comparison between Nostradamus echoes (colored lines) and TDR using IRI (left) and NeQuick (right) ionosphere. Winter, South sector, night-time.

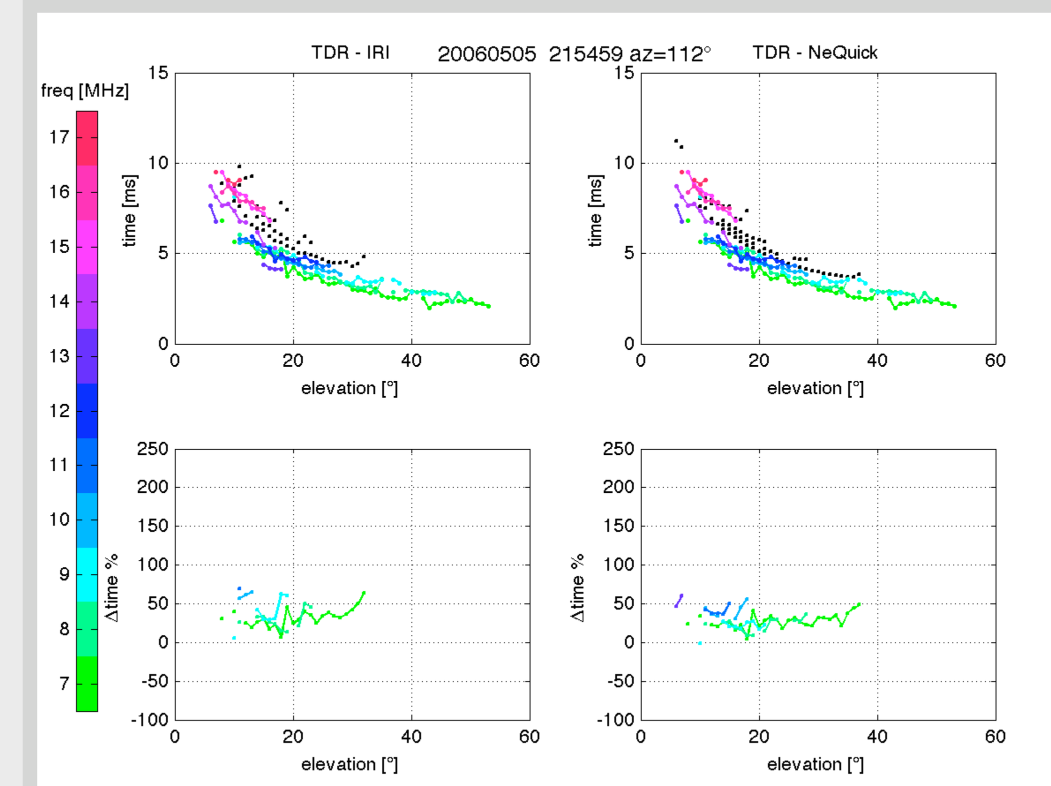

Figure 5: Comparison between Nostradamus echoes (colored lines) and TDR using IRI (left, black squares) and NeQuick (right, black squares) ionosphere. Spring, East sector, night-time.

Experimental data can be used to tune the ionosphere models; the validation of TDR software is a primary step in the use of ray-tracing as forward model in the tomography of the ionosphere performed by OTH radar.

Conclusions and Perspective

TDR software includes now the latest versions of IRI and NeQuick models.

The first comparisons with Nostradamus data acquired during low solar activity show that the travel times are in agreement preferentially during day-time for frequencies up to 14 MHz.

During night time for moderate solar activity TDR results are satisfactory up to 20 MHz but for extremely low solar activity the ionosphere calculated by the models is not able to reproduce Nostradamus echoes at 7-9 MHz, therefore fine tuning of ionospheric parameters will be necessary.

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