Comparing TID Simulations Using 3D Raytracing and Mirror Reflection

X. Huang[1], B.W. Reinisch[1], G.S. Sales[1], V.V. Paznukhov[2], and I.A. Galkin[3]

[1] Lowell Digisonde International, LLC,
175 Cabot Street, Suite 200
Lowell, MA 01854, USA

[2] Boston College, Institute for Scientific Research,
Kenny Cottle Hall 207A, 140 Commonweath Ave,
Newton, MA 02467, USA

[3]University of Massachusetts Lowell, Space Science Laboratory,
600 Suffolk Street, 3rd Floor,
Lowell, MA 01854, USA

ABSTRACT

Measurements of Doppler frequencies and angles of arrival (AoA) of ionospherically reflected HF waves are a means of detecting the occurrence of traveling ionospheric disturbances (TIDs), using the time variations of these measurements. Simulations are made using the Huang and Reinisch [2006] ray tracing technique and the IRI electron density model in an effort to reproduce measured (or simulated) signatures. The TID is represented by a wavelike perturbation of the 3D electron density with an amplitude that varies sinusoidally with time and travels horizontally in the ionosphere in a given direction. By judiciously selecting the TID parameters the raytracing simulation can reproduce observed Doppler frequencies and AoA. Raytracing in a 3D realistic ionosphere is, however, excessively time consuming considering the involved homing procedures. To simplify the procedure we simulated the results for a mirror reflection model [Paznukhov et al., 2012]. The height and tilt of the undisturbed reflection surface are adjusted to agree with assumed or measured AoAs. This undisturbed reflection surface is then deformed into a wavelike moving surface. The rays reflected from the corrugated surface vary with time, and the Doppler frequencies and AoAs are determined. The simulation results from the ray tracing through the IRI-model ionosphere and the mirror model are compared to assess the applicability of the mirror model.

1. INTRODUCTION

It is important to assess the effects of travelling ionospheric disturbances (TIDs) on HF propagation in the ionosphere. The ionogram data from the DPS4D Digisonde at Millstone Hill in Figure 1 illustrate the signature of the ever-present TIDs. In this example the Digisonde measures the vertical electron density profile up to hmF2 every 5 minutes, and the contours of equal plasma frequency f_N^2, where $f_N^2 \sim N$, are plotted as function of time. The amplitude of these contours varies from 0 to several tens of kilometers. The effects of TIDs were also observed with the Millstone Hill Digisonde (42.60N, 288.50E) by measuring the angles-of-arrival (AOA) and Doppler frequencies of the HF skywaves received from the CHU transmitter in Ottawa (45.30N, 284.39E). Using the “FAS” (Frequency & Angle-of-arrival) technique [Paznukhov et al., 2012], the TID parameters (A, Ω, Λ, Ψ, see below) were determined, and these parameters where then applied in simulation studies using the Huang and Reinisch [2006] raytracing technique and the IRI electron density model in an effort to reproduce the measured or simulated TID signatures.

The IRI model [Bilitza et al., 2014] describes the average state of the ionosphere at any time and any location. For the simulations we have used the IRI Real Time Model "IRTAM" [Galkin et al., 2012]. This model is updated every 15 min by assimilating in real time the electron density profile data from the Global Ionosphere Radio Observatory "GIRO" [Reinisch and Galkin, 2011]. Some 50 GIRO stations send data to the Lowell GIRO Data Center (LGDC) in real time, where they are assimilated on the fly. We assume that during the passage of a TID the electron density $N(\lambda,\varphi,h,t)$ at height *h*, time t, and location (λ,φ) can be represented by

$$N(\lambda,\varphi,h,t) = N_{IRTAM}(\lambda,\varphi,h,t)\left[1 + A\cos(\Omega t \; - \mathrm{K}D + \Psi_0)\right]$$

The phase distance *D* depends on the azimuth of the direction of the TID propagation. The angular frequency Ω of the TID wave is related to its period *T*, and the wave number K to the wavelength Λ:

$$\Omega = 2\pi/T\,, \quad \mathrm{K} = 2\pi/\Lambda\,.$$

To simplify the discussion only the primary component of the TID spectrum is considered here, and the propagation of the TID wave in the vertical direction is ignored.

Assuming the TID parameters are known, raytracing can in principle calculate the Doppler frequencies, and the arrival azimuth and elevation angles, however, it seems not feasible to use the raytracing technique to derive the TID parameters, especially in real time, because raytracing with homing for a realistic 3D ionosphere is too time consuming.

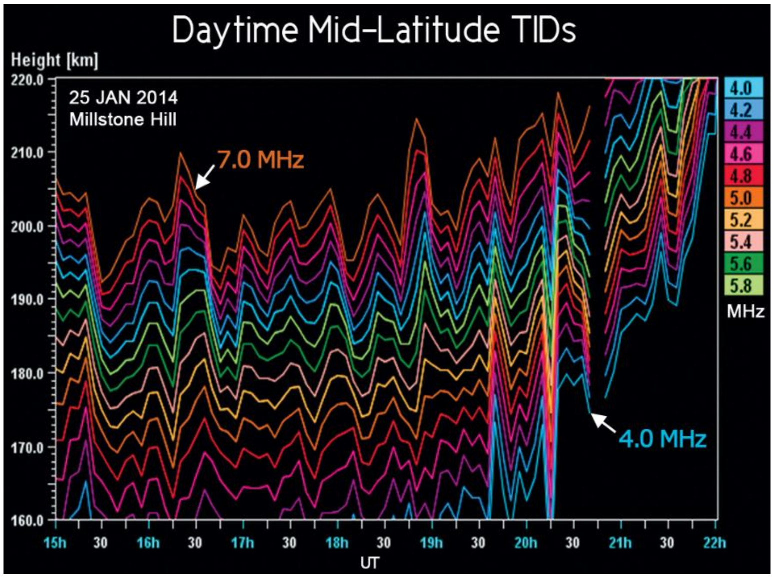

Figure 1. Electron density contours derived from the sequence of vertical electron density profiles measured by the Digisonde at Millstone Hill

It is therefore desirable to describe the TID phenomena by a simple mirror model [e.g., Galushko et al., 2003]. In the mirror model, the ionosphere is replaced by a corrugated moving mirror. This paper describes the construction of the mirror model, and compares the Doppler frequencies and arrival angles obtained by raytracing via reflection on a moving corrugated mirror and propagation through IRTAM. The link Ottawa – Millstone Hill is assumed for these simulations.

2. CONSTRUCTION OF THE MIRROR

Both planar and spherical mirror models were constructed for the simulations. The ground distance from Ottawa to Millstone Hill is only 445 km, and for this short link the planar mirror gives almost identical results as the spherical mirror. This paper therefore only describes the spherical mirror, which would also be applicable to longer links. For a given time and location, the height and the tilt of the undisturbed (no TID) spherical mirror (left panel in Figure 2) is selected in such a way that the raytracing for the mirror reflection produces the same angles of arrival (azimuth and zenith) as the average angles obtained by raytracing through the IRTAM ionosphere.

The corrugated spherical mirror during the passage of a TID can then be represented by

$$\sqrt{(x-x_o)^2+(y-y_0)^2+(z-z_0)^2} = r_{m0}\left[1+A_m\cos(\Omega_m t-K_m D_m+\psi_{0m})\right]$$

Here A_m is the amplitude of the corrugation, and $A_m = 0$ describes the undisturbed mirror, (x_0, y_0, z_0) are the coordinates of the center of the spherical mirror, and the radius $r_{mo} = O_mP_0$, as shown in the left panel of Figure 2. Tracing the ray from T to R for the mirror reflection simply requires Snell's law and a homing procedure, and is very fast compared to the raytracing through the ionosphere.

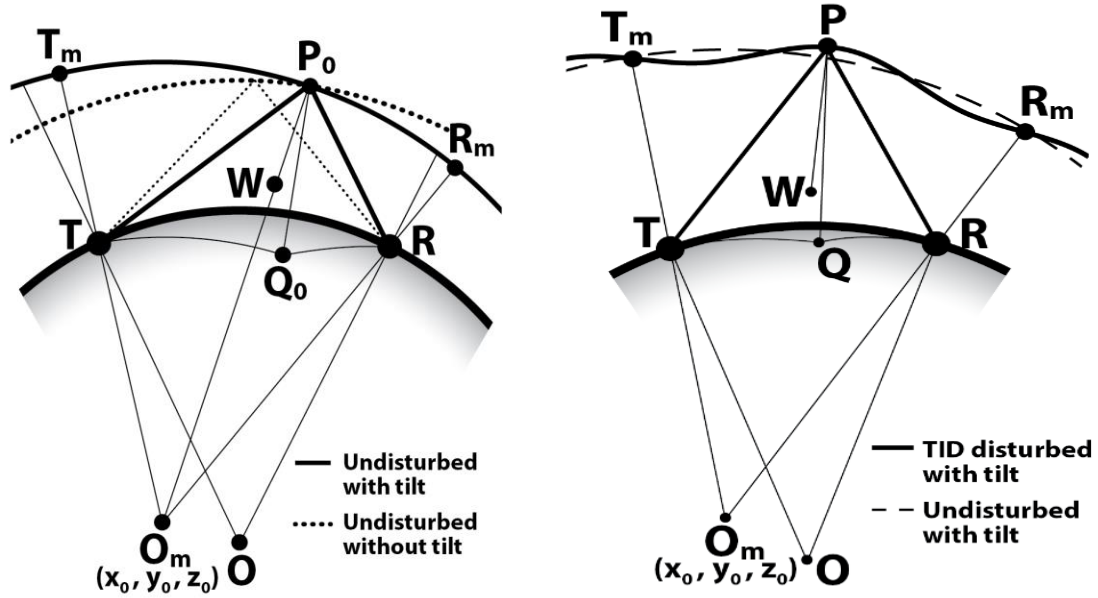

Figure 2. Construction of the spherical mirror model. O is the center of the Earth, O_m is the center of the mirror sphere, P_0W or PW is the surface normal.

3. COMPARISONS OF THE SIMULATION RESULTS

Simulations were performed for a one hour daytime period on 16 January 2015, 1900-2000 UT (15-16 LT) covering the time of two TID cycles assuming a TID wave period of 30 min. The simulations were done for the Ottawa – Millstone Hill link for a frequency of 7.85 MHz. Table 1 lists the nominal TID parameters.

Table 1. Nominal TID wave parameters

Model	IRTAM Raytracing	Mirror Model Reflection
TID Amplitude	$A = 0.05$	$A_m = 0.00015$
TID Period	$T = 30$ min	$T = 30$ min
TID Wavelength	$\Lambda = 250$ km	$\Lambda = 250$ km
Initial Phase	$\Psi_0 = 0$	$\Psi_0 = 0$
Direction of TID Wave	170° from north	170° from north

The selected parameters are representative for small- to medium-scale TIDs. Note that the TID amplitude for raytracing is referring to the electron density variation, while the TID amplitude in the mirror simulation is defined as a height variation. To investigate the effect of each individual parameter the simulations were repeated by changing just one of the 5 parameters and keeping the nominal values of the other parameters unchanged. Figure 3a, for example, shows how the Doppler frequency, azimuth angle, and zenith angle vary when the amplitude A is set to 0.02, 0.04, 0.06, 0.08 and 0.10 for the IRTAM raytracing simulation (top row). The bottom row shows the corresponding mirror simulations when A_m is set to 0.00005, 0.00010, 0.00020, 0.00025 and 0.00030. Figures 3b through 3e show the responses for changing period, wavelength, TID propagation direction, and initial phase, respectively.

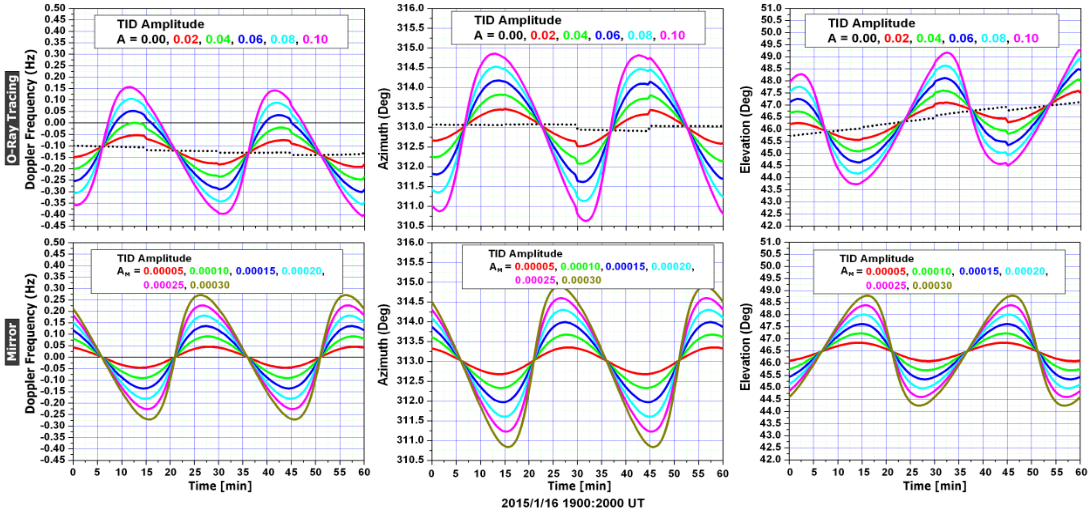

Figure. 3a Simulation results testing the effect of the TID amplitude

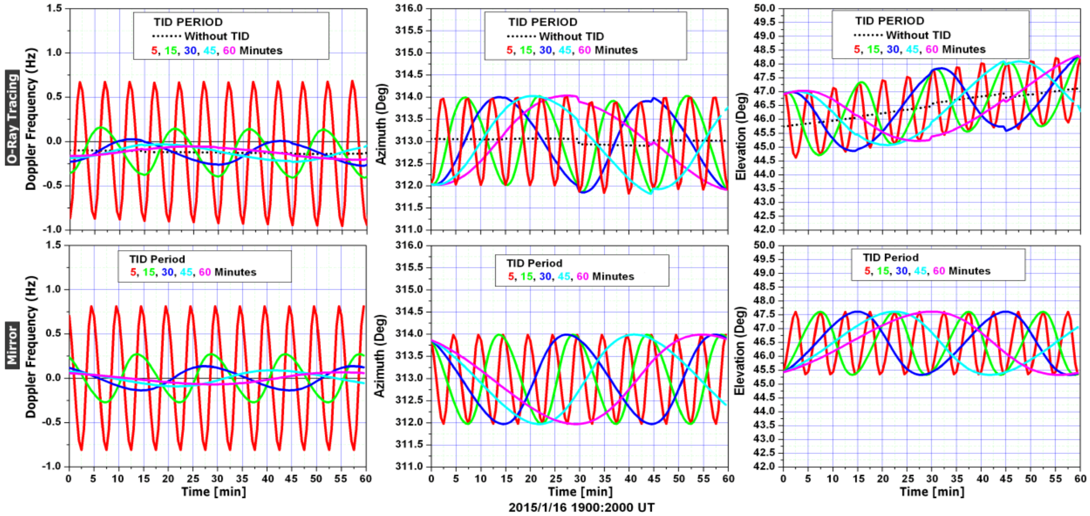

Figure 3b. Simulation results testing the effect of the TID period

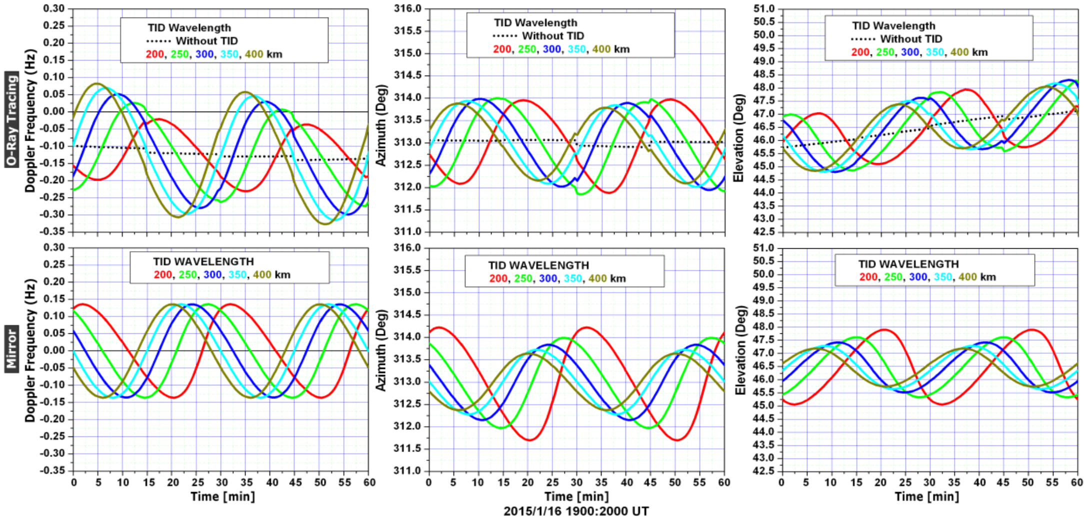

Figure 3c. Simulation results testing the effect of the TID wavelength

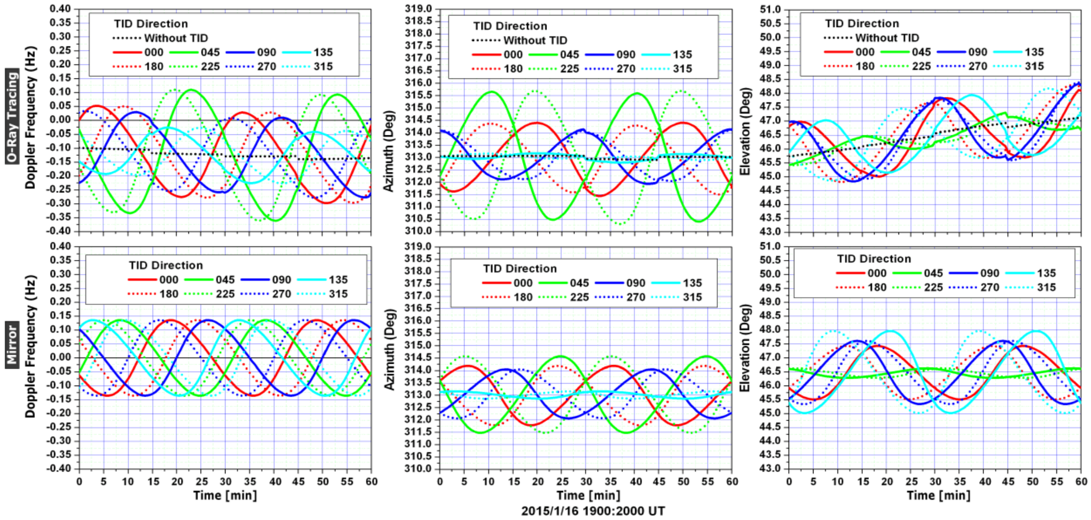

Figure 3d. Simulation results testing the effect of the direction of the TID wave

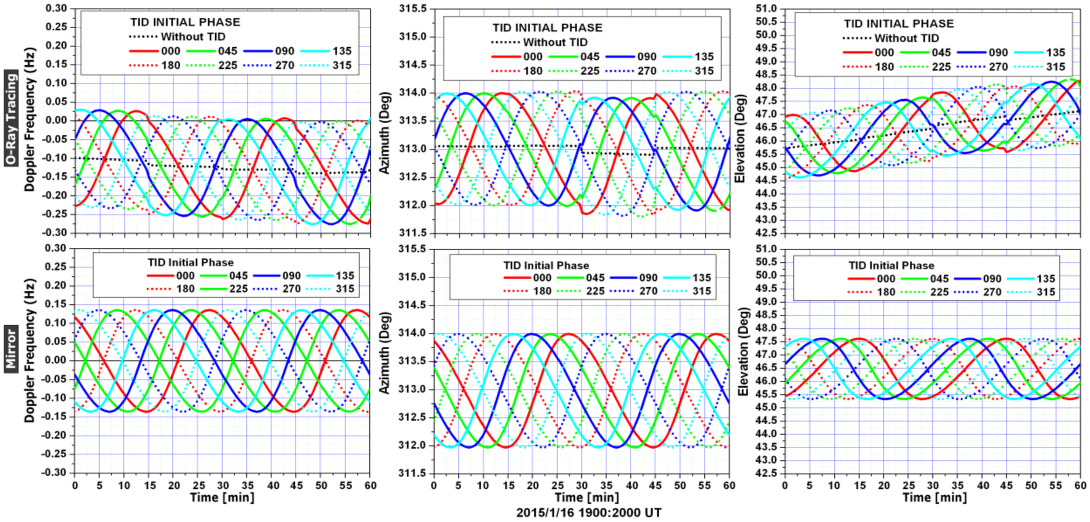

Figure 3e. Simulation results testing the effect of the TID initial phase

The upper panels in Figure 3 are the results of raytracing simulations through IRTAM, and the lower shows the results for the mirror reflections. In all five figures, the variations of all curves from the raytracing and mirror simulations are 180° out of phase. This was expected since the TID modulates the electron density in the IRTAM model, while the mirror model modulates the reflection height. When the reflection occurs near the node (maximum density) of the TID wave, the reflection height is small, and it is large when it occurs at the antinode. The ray trajectory is controlled by the index of reflection, n, which varies –to first order- as

$$n^2 = 1 - \frac{k}{f^2} N, \qquad dn = -\frac{k}{2nf^2} dN$$

The minus sign is the cause for the 180° phase shift. But disregarding this phase shift, the simulation results are similar. Note that model for the IRTAM raytracing simulations is updated every 15 min, while for the mirror simulations the mirror height and tilt are kept constant using the average IRTAM values for the 1 hour period. Examination of the elevation plots reveals that the F layer height is rising during the 1 hour period.

As is well known, the propagation of radio waves in the ionosphere is very complicated, and one can therefore not expect that the mirror model can exactly reproduce the IRTAM raytracing results. However, by applying appropriate height and tilt information from ionosonde measurements, a suitable mirror model can be defined for which the TID parameters can be derived using Doppler frequency and AoA measurements. Our simulations have also revealed (not shown here) that the dependence of the Doppler frequency and AoA on the TID parameters is nonlinear, and this fact may cause some difficulties in the inversion. For example, when the TID period is getting smaller, the Doppler frequencies are increasing more than proportionally.

Only ordinary wave polarization O-rays have been discussed in this paper. Since the X-rays have slightly different trajectories, the appropriate average height and tilt for the X-ray mirror must be obtained from the IRTAM X-ray tracing results.

4. Summary

For a simple but reasonable TID model, simulations were performed using raytracing through IRTAM, and the results of the Doppler frequency and AoA simulation data were compared with mirror reflections simulations. Comparison of the simulation results found reasonable agreement of the two approaches as long as the layer height and tilt of the mirror is adjusted using ionosonde measurements. The simplicity of the mirror model provides a convenient way to derive the TID parameters from measured Doppler frequency and AoA data.

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