Comment on "Simulation study of the interaction between large-amplitude HF radio waves and the ionosphere" by B. Eliasson and B. Thidé

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[1] The following comments apply to the paper "Simulation study of the interaction between large-amplitude HF radio waves and the ionosphere" by *Eliasson and Thidé* [2007]. The main comment is that in their discussion of simulation results, while referring to linear mode conversion and nonlinear effects, they do not take into account the allowance for spatial dispersion. The use of a warm-plasma dispersion relation would be more justified for their problem. The allowance for spatial dispersion due to the thermal motion of the electrons results in a thermal correction to the refractive index function that has to be considered.

[2] The first remark is about their Figure 6d. In this figure, the authors have plotted the frequency f as a function of the wave number k using the Appleton-Hartree dispersion relation [*Stix*, 1982]. In their Figure 6d, the second branch of the extraordinary X mode, which in the ionospheric context is referred to as the Z mode, is below the reflection points of the ordinary O mode and the first branch of the extraordinary X mode. For the propagation of the HF radio wave/pulse through an inhomogeneous magnetized plasma, this will not likely happen. In their simulations, the reflection of the R-X mode occurs at $z \sim 270.5$ km that is below the reflection point of the L-O mode ($z \sim 277$ km). However, in their Figure 6d, the reflection of the L-O mode occurs below the reflection of the R-X mode. The authors use the electron plasma frequency $\omega_{\mathrm{pe}} = 5$ MHz as a constant. When plotting the refractive index function $n_{\mathrm{O,X}} = \frac{kc}{\omega}$ or k_z, one should use the electron plasma frequency $\omega_{\mathrm{pe}}^2(z) = \frac{4\pi N(z)e^2}{m_e}$ as a function of z, where $N(z)$ is the given density profile. In this case, k_z as a function of z for their density profile would look like the one shown in Figure 1b of this comment. In Figure 1b, the label X_1 is for the first branch of the extraordinary mode and X_2 is for the second branch or so-called Z mode. One can see that dispersion curves they have plotted are for the top side of the ionosphere. However, for normal incidence, the wave will not propagate to the top side of the ionosphere.

[3] The next comment is for their discussion of linear mode conversion and generation of the electrostatic waves associated with this process. This process takes place near the reflection point of the O mode at the resonance region which is omitted in their discussion. In Figure 1c of this comment, one can see the fragment (from 250 km to 300 km) of the k_z function, shown above, as a function of frequency $f(z) = \sqrt{N(z)e^2/(\pi m_e)}$. Here, the reflection points of the X_1, O, and Z modes are shown with labels $V = 1 - Y$, $V = 1$, and $V = 1 + Y$, respectively. $V = \omega_{\mathrm{pe}}^2/\omega^2$ and $Y = \omega_e/\omega$ is the ratio of the gyrofrequency to the propagation frequency. For oblique propagation, the O mode can be transformed near the layer $V = 1$ into the Z mode. The reflected Z mode propagates towards a plasma resonance region V_∞ where it is converted into an electrostatic mode (or absorbed, according to the cold plasma theory) as shown in simulations for linear mode conversion in inhomogeneous magnetized plasmas during ionospheric modification by HF radio waves by *Gondarenko et al.* [2003]. Here, the resonance layer $V_\infty = (1 - U)/(1 - U\cos^2\alpha)$, $U = Y^2$, and α is an angle between the magnetic field and the z axis. For normal incidence, the O wave can be transformed into a wave of extraordinary polarization when the distance between the ordinary mode reflection layer ($V = 1$) and the resonance layer (V_∞), $\Delta_{R,\infty} = (U\sin^2\alpha)/(1 - U\cos^2\alpha)$ is less than about two wavelengths of the heater wave [*Gondarenko et al.*, 2003]. In this case, $\Delta_{R,\infty} \sim 100$ m. For the finite values α, the polarization depends on V. For $V = 1$, the O wave is always linearly polarized. The polarization index of the O mode $|K_{\mathrm{O}}| = |\frac{E_{xO}}{E_{yO}}| \to \infty$, i.e. $E_{yO} = 0$, and the vector $\vec{E}$ is linearly polarized in the xy plane. The O wave is also linearly polarized in the xz plane that follows from equation (7) [*Gondarenko et al.*, 2003] (with an approximation to 1D) for the field E_z, the component E_z is in phase with E_x,

$$E_z = \frac{VU\sin\alpha\cos\alpha}{[U - (1 - V) - UV\cos^2\alpha]}E_x - \mathrm{i}\frac{\sin\alpha\sqrt{U}V}{[U - (1 - V) - UV\cos^2\alpha]}E_y. \qquad (1)$$

[4] In their Figure 3b, one can see that the O wave changes polarization in the xy plane from elliptical to linear near the O wave reflection point. For $V = 1$, the polarization index of the X-mode $|K_{\mathrm{X}}| = 0$, i.e. $E_x = 0$. The polarization also behaves in a singular manner at the regions $V \to V_\infty$. One can see from equation (1) that at the resonance region

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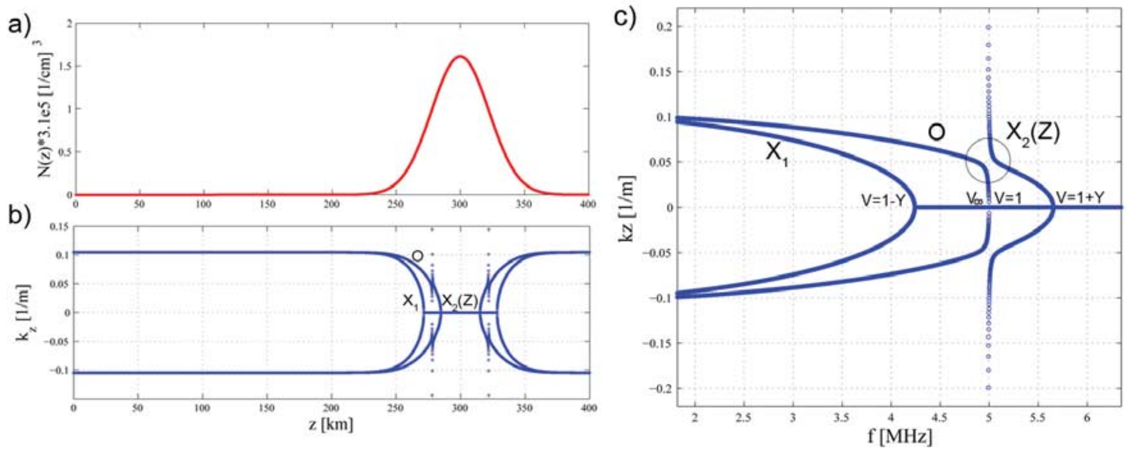

Figure 1. (a) The normalized density profile and (b) the refractive index function n (k_z) as a function of altitude z for the cold-plasma approximation model with the propagation frequency $\omega = 2\pi \cdot 5$ MHz, $\omega_e = 2\pi \cdot 1.4$ MHz, and $\alpha = 13°$; and (c) n (k_z) as a function of frequency f (for the bottom side of the ionosphere $z \in [250-300]$ km).

$|E_z| \to \infty$ for finite E_x and E_y in the absence of absorption. The waves are linearly polarized in the direction of the wave vector $\vec{k}$, i.e. they are longitudinal. The mode conversion due to the presence of small-scale irregularities has been shown in the simulations for the nonlinear evolution of thermal self-focusing instability in ionospheric modifications at high latitudes [*Gondarenko et al.*, 2006].

[5] Although electrostatic waves are not described in a cold plasma model, the inclusion of the absorption (the effective electron collision frequency ν_{eff}) into the model can resolve the singularity that occurs when the wave approaches the plasma resonance so that absorption can be interpreted as conversion into electrostatic waves for the cold plasma approximation model. In their model, neglecting collisions, the singularity can be resolved when the effect of the thermal motion on the propagation of high-frequency waves is taken into account by including the pressure term in the momentum equation. This would be appropriate because for the problem considered the change in the electron density is due to the non-zero divergence of the electric field, and that should also be accounted for in the momentum equation.

[6] The Appleton-Hartree dispersion relation for the electromagnetic electrons modes, which the authors have

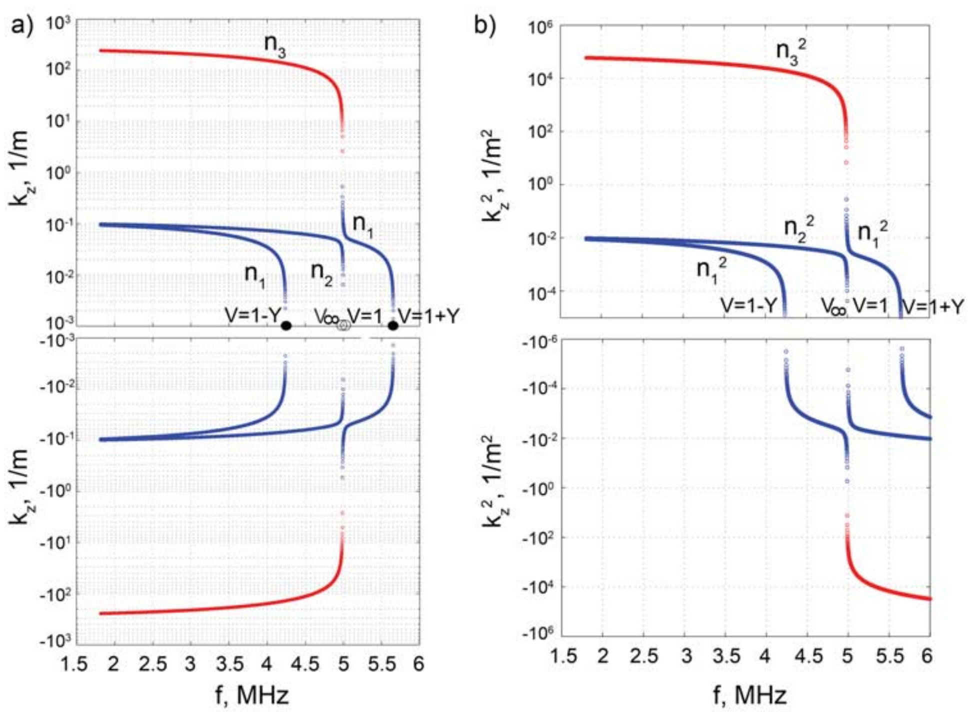

Figure 2. The refractive index function (a) n (k_z) and (b) n^2 (k_z^2) as a function of frequency f for the warm-plasma approximation model with the thermal correction $\beta_T = 4 \cdot 10^{-4}$.

used, is the solution of the bi-quadratic equation for a cold-plasma approximation model:

$$An^4 - Bn^2 + C = 0. \quad (2)$$

[7] The refractive index with the thermal correction results from the following dispersion equation for a warm-plasma approximation model

$$An^6 - Bn^4 + Cn^2 - D = 0. \quad (3)$$

[8] The allowance for the thermal motion (spatial dispersion) leads to the appearance of the third root for the squared refractive index n_3^2 near the plasma resonance region V_∞. The waves with $n = n_3$ are conventionally called plasma waves. The thermal motion gives a correction of the order $\beta_T^2 = \frac{\kappa T}{mc^2} \ll 1$. However, even slight spatial dispersion may result in new effects, for example the appearance of "new waves", i.e., the occurrence of plasma waves with non-zero group velocity [*Ginzburg*, 1970].

[9] In Figure 2a of this comment, one can see the refractive index (k_z) in log scale as a function of frequency with $\beta_T = 4 \cdot 10^{-4}$. The root n_3 (red line) is very large everywhere except near the resonance point. The maximal value of n_3 is about 250 m^{-1} (2.5 cm wavelength). The occurrence of the third solution is due to the disappearance of the discontinuity of the function n_1. This solution does not form an independent branch of the refractive index function. In Figure 2b of this comment, the function n^2 (k_z^2) is shown. For the negative values of n^2, the corresponding waves are strongly damped with $e^{-\omega|n|z/c}$ ($e^{-|k_z|z}$) [*Ginzburg*, 1970]. The plasma waves are damped even when collisions are neglected. The collisionless absorption is weak if $\beta_T n_3 \cos\alpha \ll 1$ [*Ginzburg*, 1970]. The authors may like to decrease their spatial grid size to resolve smaller scales for waves which may occur in their problem.

[10] We hope that these comments would be useful and taken into account in future publications.

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