Effects of artificial *D*-region disturbances on the transionospheric propagation of VLF waves

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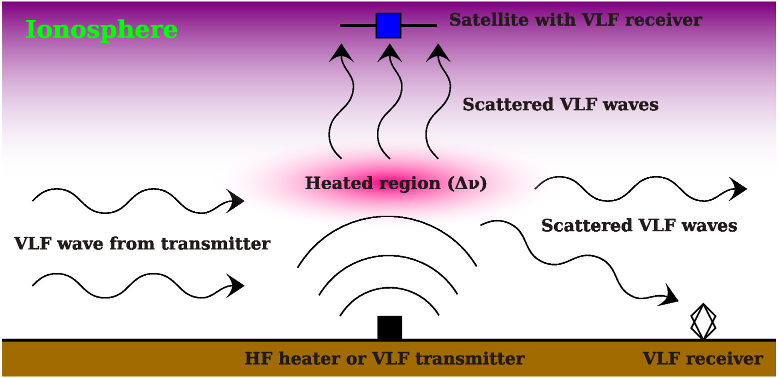
Outline

VLF scattering by *D*-region disturbances

Artificial *D*-region disturbances are caused by **HF heaters** or **VLF transmitters**. The ground VLF perturbations were calculated previously (using Earth-ionosphere waveguide mode theory both WKB and Born approximations):

- for HF heaters: *Barr et al* [1985]; *Demirkol* [Ph. D thesis, 1999]
- for VLF transmitters: *Inan et al* [1992]; *Rodriguez* [Ph. D thesis, 1994]

We use Stanford Full-Wave Method (SFWM), with Born approximation (but no WKB approximation).



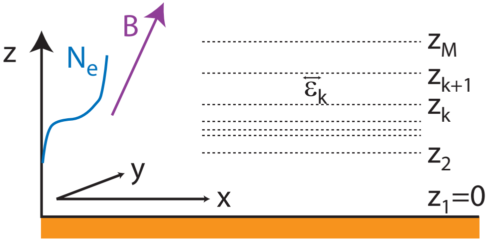
Outline

Capabilities:

- Arbitrary plane stratified medium, e.g., a horizontally-stratified magnetized plasma with an arbitrary direction of geomagnetic field (such as ionosphere)
- Arbitrary configuration of harmonically varying currents
- Provides full wave 3D solution of both whistler waves launched into ionosphere and VLF waves launched into Earth-ionosphere waveguide
- Stable against the “swamping” instability by evanescent waves
- Efficient use of the computer resources, easily parallelized

Applications:

- Trans-ionospheric propagation
- Earth-ionosphere waveguide propagation
- Scattering on *D*-region disturbances

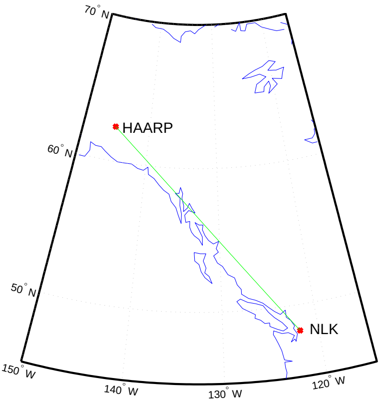


We work in Fourier (horizontal wave vector $\mathbf{k}_\perp$) domain:

1. For each $\mathbf{k}_\perp = const$ (Snell's law) $\Longrightarrow$ find k_z, E and H in each layer for each of 4 plane wave modes (2 up, 2 down)
2. Use continuity of $\mathbf{E}_\perp$ and $\mathbf{H}_\perp$ between layers to find reflection coefficients $\mathrm{R}^{u,d}$ and mode amplitudes $\mathbf{u}$, $\mathbf{d}$
   - Recursion order $\mathrm{R}^u_{k+1} \rightarrow \mathrm{R}^u_k$ and $\mathbf{u}_k \rightarrow \mathbf{u}_{k+1}$ provides stability against "swamping" of solution by evanescent waves
   - Represent source currents as boundary conditions on $\mathbf{E}_\perp$ and $\mathbf{H}_\perp$ between layers
3. Inverse Fourier transform from $\mathbf{k}_\perp$ to $\mathbf{r}_\perp$

Outline

NLK/HAARP



NLK VLF transmitter:

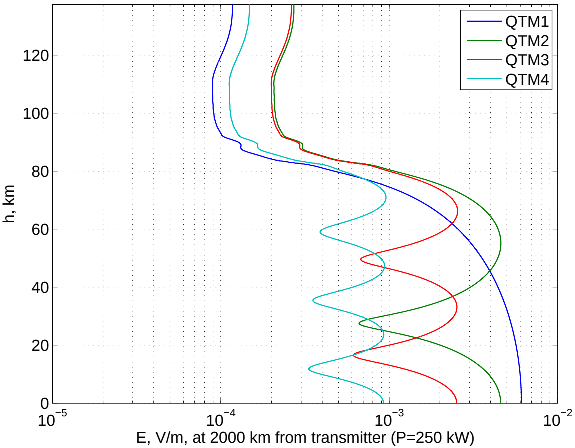
- Modelled as a ground-based vertical dipole
- $f = 24.8$ kHz
- $P = 250$ kW

HAARP HF heater:

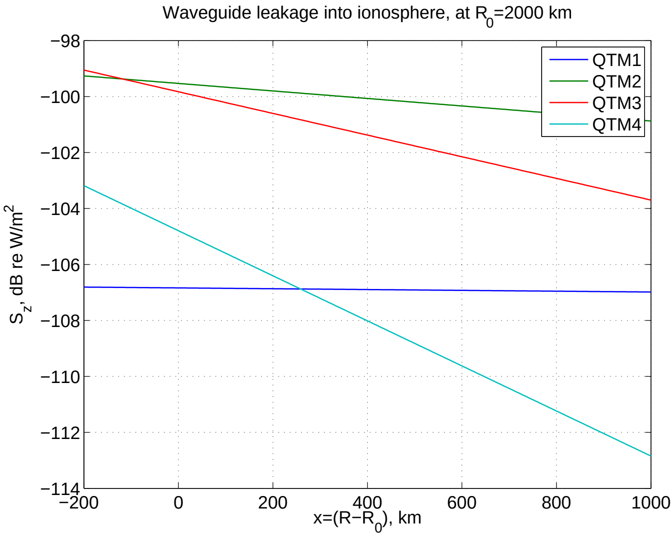
- $f_{\mathrm{HF}} = 5$ MHz
- $\mathrm{ERP} = 1$ GW
- Beam width ~23 km *[Payne et al, 2007]*, we assume Gaussian horizontal shape
- ΔT_e and $\Delta \nu_e$ are found using kinetic equations

Strongest modes at $R_0 = 2000$ km (disturbance)

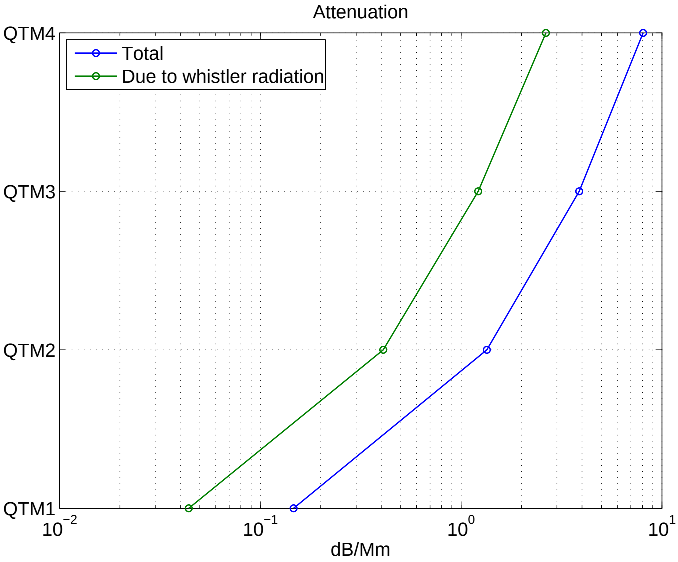
- Modes are calculated using SFWM using night-time ionosphere
- Attenuation is due to both absorption and radiation into ionosphere



Waveguide radiation leaking into ionosphere

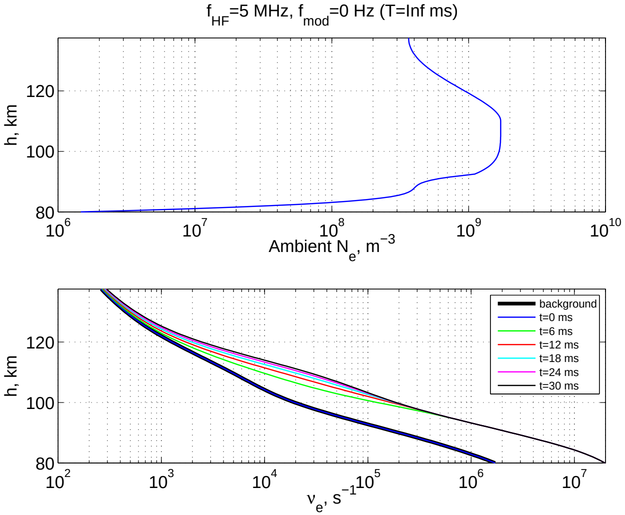


Role of whistler radiation in the total attenuation



Change in ν_e due to heating

Steady heating; the heater is turned on at $t = 0$



We must solve the wave equation:

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 \hat{\varepsilon} \mathbf{E} = 0 \qquad (k_0 = \omega/c)$$

where $\mathbf{E} = \mathbf{E}_0 + \mathbf{E}_s$, $\hat{\varepsilon} = \hat{\varepsilon}_0 + \Delta\hat{\varepsilon}$,

- $\mathbf{E}_0$ — incoming wave (e.g., a waveguide mode in stratified $\hat{\varepsilon}_0$);
- $\mathbf{E}_s$ — scattered wave;
- $\Delta\hat{\varepsilon}$ — inhomogeneous change in the dielectric permittivity tensor.

In a stratified waveguide $\nabla \times (\nabla \times \mathbf{E}_0) - k_0^2 \hat{\varepsilon}_0 \mathbf{E}_0 = 0 \quad \Longrightarrow$

$$\nabla \times (\nabla \times \mathbf{E}_s) - k_0^2 \hat{\varepsilon}_0 \mathbf{E}_s = k_0^2 \Delta\hat{\varepsilon} (\mathbf{E}_0 + \mathbf{E}_s)$$

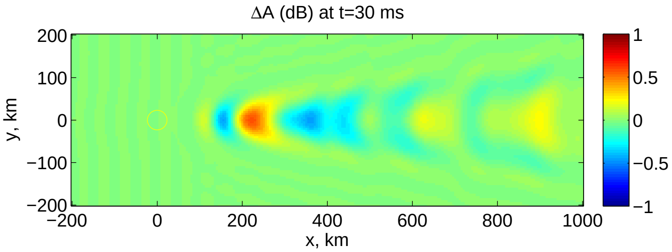
- Born approximation: neglect $\mathbf{E}_s$ compared to $\mathbf{E}_0$ inside the scattering region (rhs).
- rhs gives the source currents for scattered waves:

$$\nabla \times (\nabla \times \mathbf{E}_s) - k_0^2 \hat{\varepsilon}_0 \mathbf{E}_s \approx k_0^2 \Delta\hat{\varepsilon} \mathbf{E}_0 = i k_0 Z_0 \Delta \mathbf{J}$$

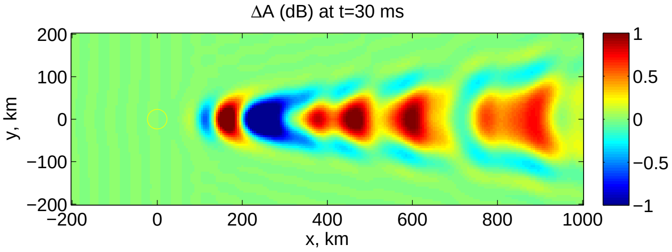
where Z_0 is the impedance of free space.

- VLF wave propagates from left to right ($x = R - R_0$)
- scattering region is indicated by a circle at $x = 0$, $y = 0$

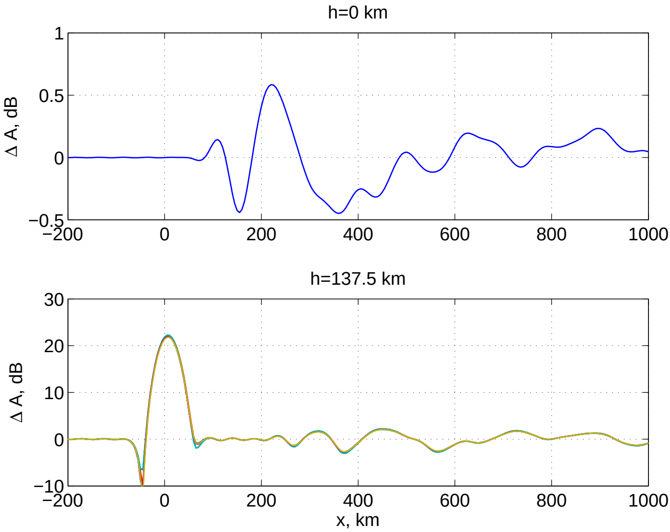
QTM1 mode



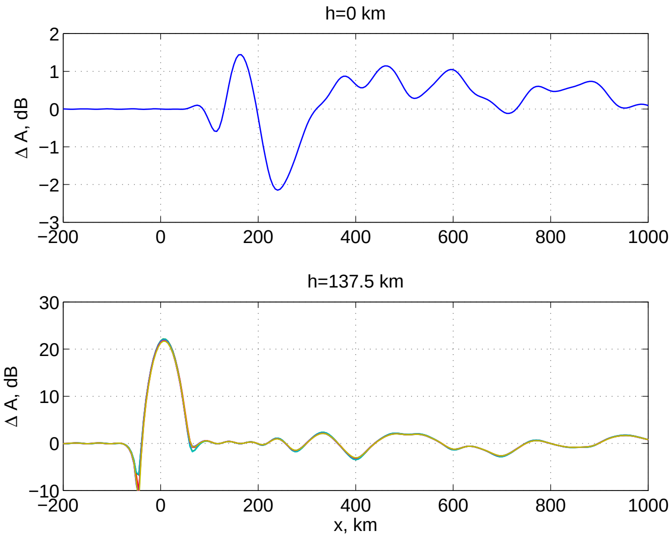
QTM2 mode



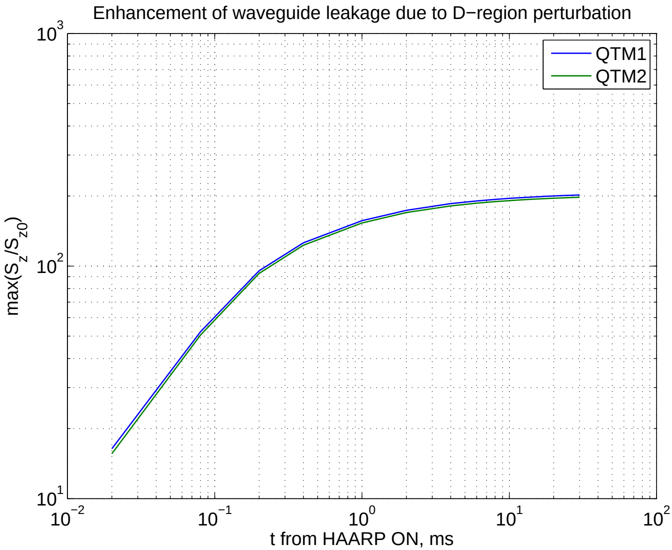
ΔA on the ground and in space: **QTM1 mode**



ΔA on the ground and in space: **QTM2 mode**



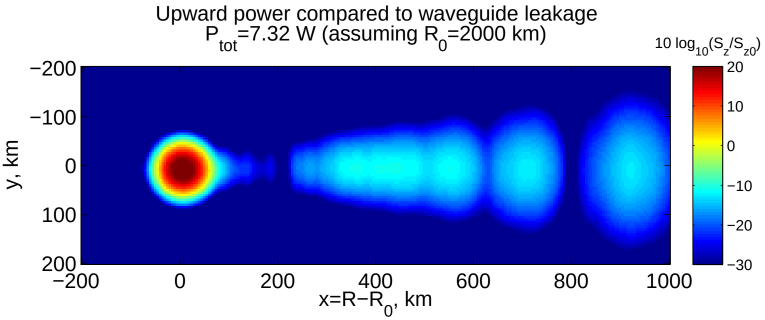
The flux scattered by the heated region upward significantly exceeds the waveguide leakage



Whistler flux scattered into space ($h = 137.5$ km)

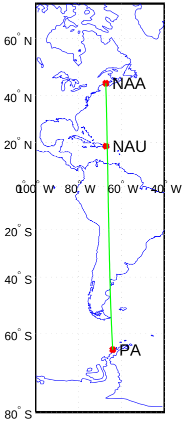
- intense "column"
- weaker "tail" in the shadow of the scatterer

Results are shown for **QTM1** mode (other modes are similar)



Outline

NAA/NAU (chosen after *Inan et al* [1992])



NAA VLF transmitter:

- $f = 24$ kHz
- $P = 1000$ kW

NAU VLF transmitter as a heater:

- $f = 40.75$ kHz
- $P = 100$ kW
- ΔT_e and $\Delta\nu_e$ are found using SFWM and a model presented on the next slide

PA is the VLF receiver at Palmer station, Antarctica

VLF heating model

T_e is obtained from the temperature balance due to E-field heating and cooling due to collisions:

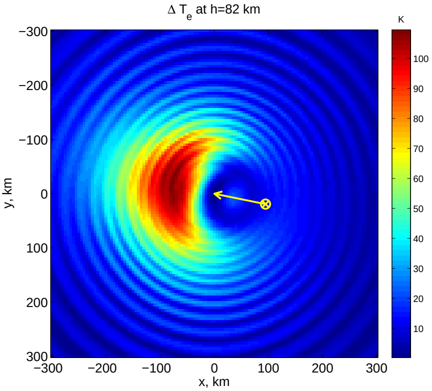
$$T_e = T_0 + \frac{2U}{3\delta\nu_e N_e k_B}$$

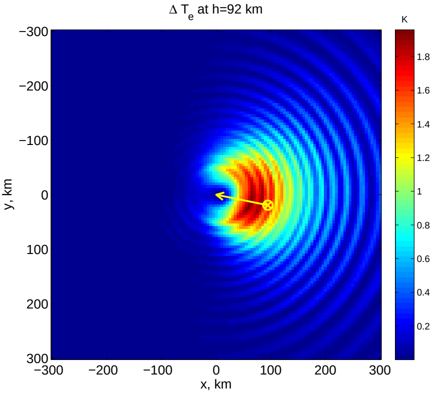
where

- $\delta\nu_e$ is the energy loss rate, with $\delta \approx 1.3 \times 10^{-3}$ being the fraction of electron energy lost in a collision with a molecule [*Inan et al*, 1992]. Note that ν_e is the *momentum* loss rate;
- $U = \frac{1}{2}\mathfrak{Re}(\mathbf{J}^* \cdot \mathbf{E})$ is the absorbed VLF wave power;
- $\mathbf{J} = \hat{\sigma}\mathbf{E}$, with anisotropic $\hat{\sigma}$
- **E** is calculated in the vicinity of the transmitter using the (linear) SFWM model.
- $\nu_e = (T_e/T_0)\nu_{e0}$ is the heated collision frequency, ν_{e0} is the background collision frequency [*Inan et al*, 1992].

ΔT_e

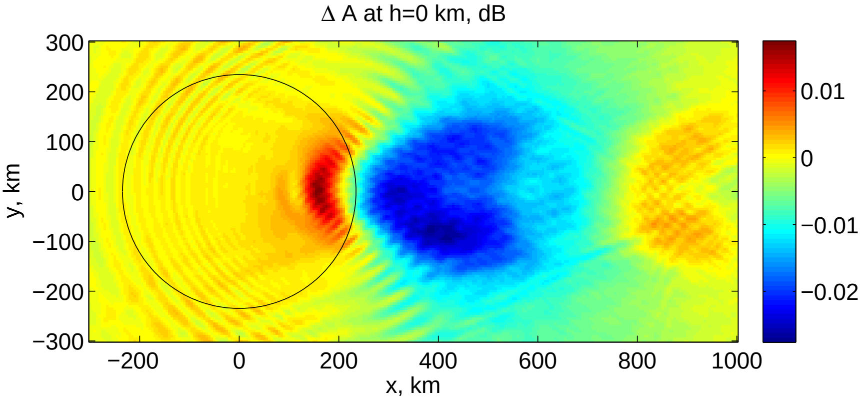
- VLF propagation is from left to right
- White arrow indicates (downward) **B**
- The "hole" in the middle is due to dipole radiation pattern
- At $h = 82$ km, more heating at $x < 0$ because the electrons are heated better when **E** $\|$ **B**
- At $h = 92$ km, more heating at $x > 0$ because whistlers propagate more favorably along **B**





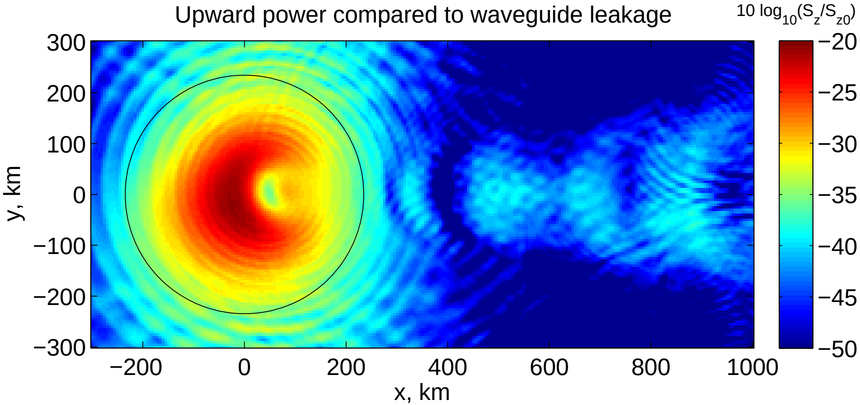
VLF perturbation on the ground

Experimental value: ±0.03–0.12 dB [*Inan et al*, 1992]



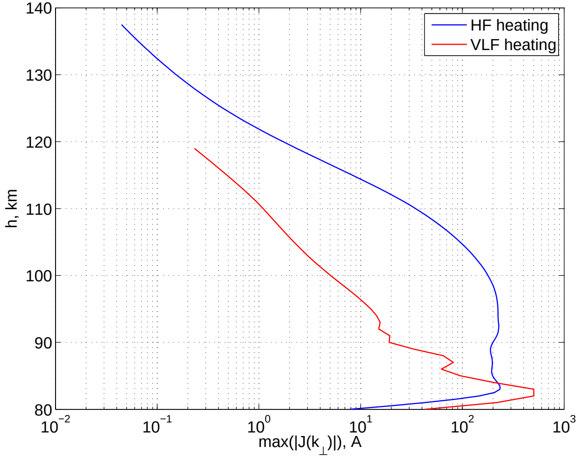
Scattered whistlers in ionosphere

Notice that the upward-scatter power flux is negligible compared to waveguide leakage.



Why such a difference in upward scattering?

The VLF heating occurred at lower altitudes, and therefore was more attenuated.



Outline

Summary:

- Stanford Full-Wave Method (SFWM) was applied to calculate Earth-ionosphere waveguide modes and their scattering on *D*-region disturbances
- The scattered waves are emitted both into the Earth-ionosphere waveguide and into the ionosphere
- Whistler waves scattered into the ionosphere form an intense “column” and a weaker “tail” in the shadow of the scatterer
- VLF enhancements inside the whistler “column” may significantly exceed the background leakage from the Earth-ionosphere waveguide
- *D*-region disturbances may contribute to the electromagnetic radiation environment in the ionosphere and magnetosphere

To do:

- Include VLF perturbations due to change in N_e (longer timescale, due to change in attachment coefficient)
- Kinetic model of VLF heating
- Experimental verification