Attenuation of gravity waves and kinetic viscosity in the ionosphere

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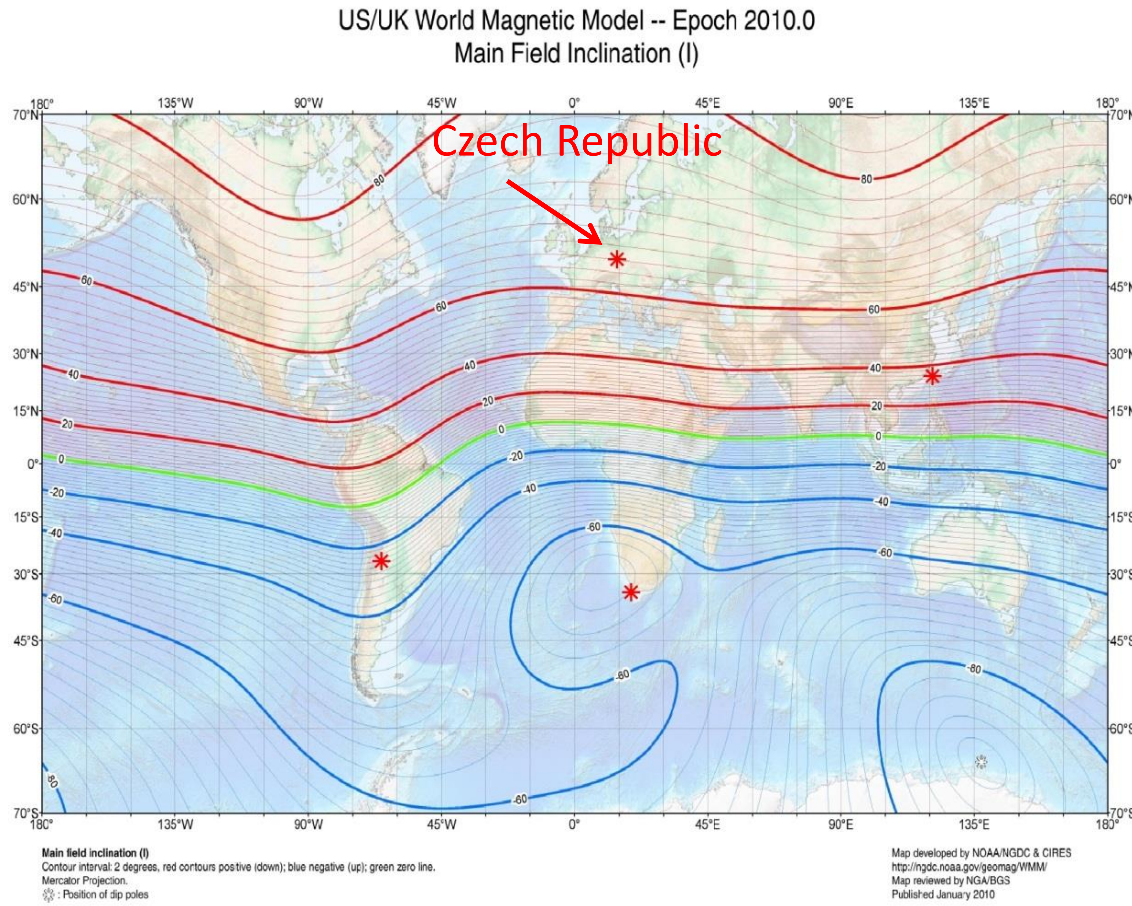
3D analysis
by Doppler sounding

Statistical results obtained for
1-year periods during
sol. max. and sol. min.

Discussion on the attenuation
and viscosity

Summary



Continuous Doppler sounding of the ionosphere

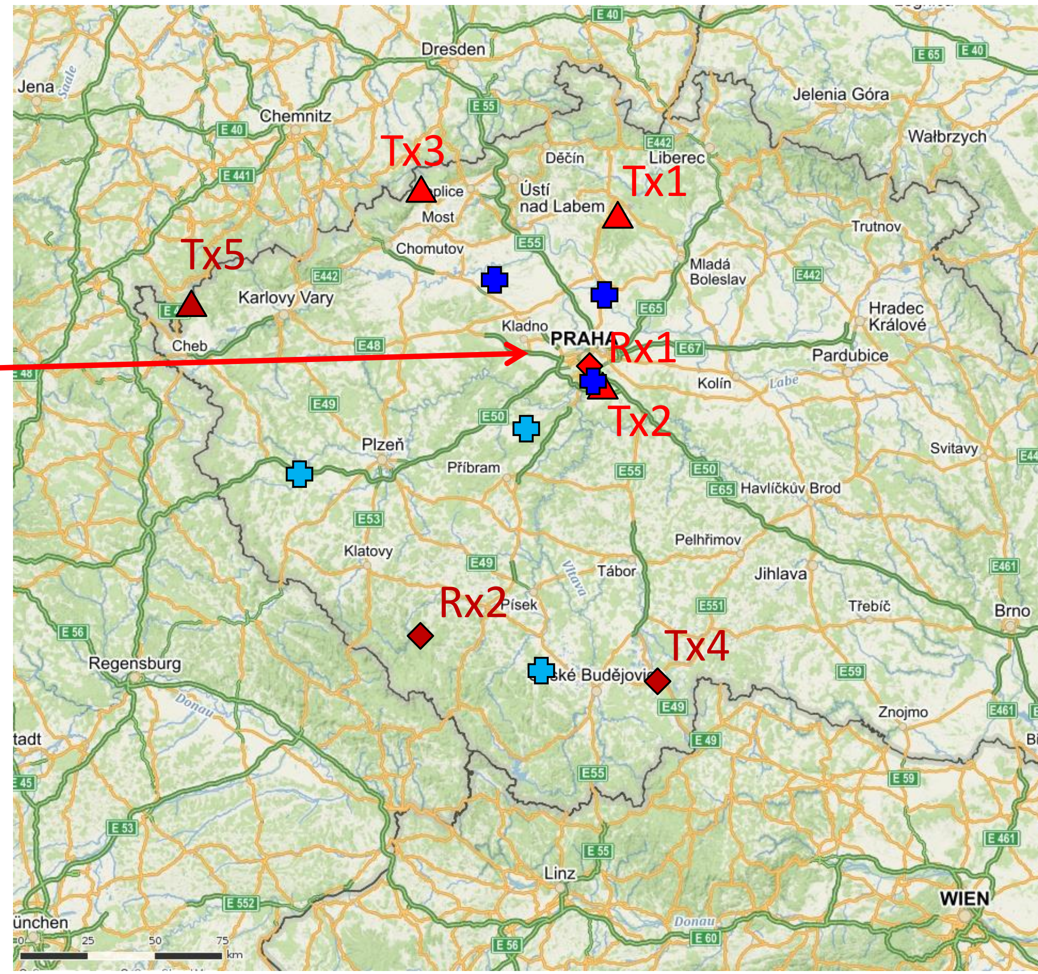
Multi-frequency (different reflection heights) and **multi-point** continuous Doppler sounding is performed in the Czech Republic. Plasma motion (changes) are evaluated from the Doppler shift of the received signals.

Locations of Doppler transmitters in the Czech Republic
(at each location, frequency of 3.59, 4.65 and 7.04 MHz is transmitted)

Receiver Rx1 is at the Institute in Prague

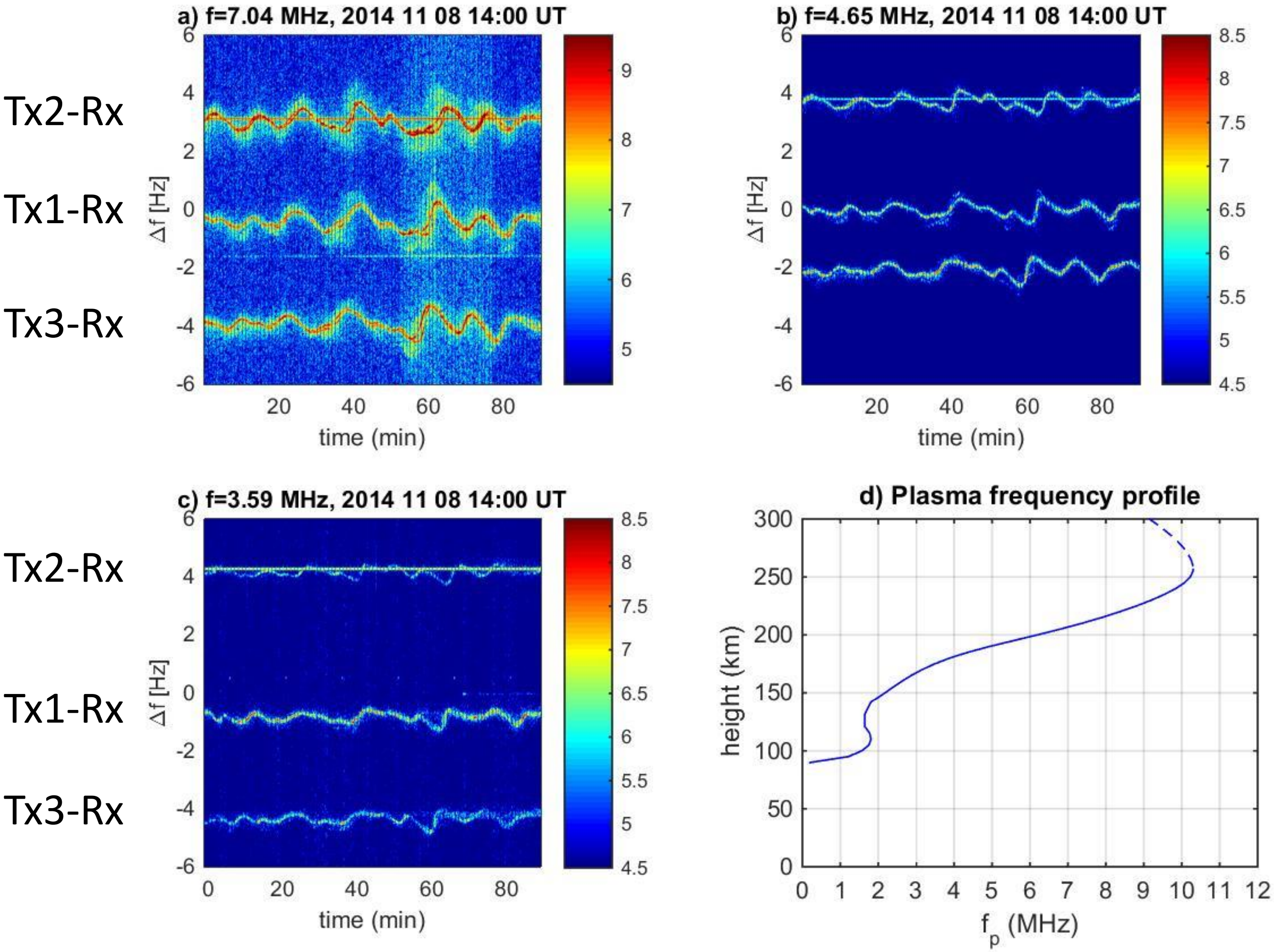
Digital ionosonde is close to Tx2 and makes it possible to estimate reflection heights of the Doppler sounding signals.

*Additional transmitters **Tx4, Tx5** and receiver **Rx2** installed in the southwest in autumn 2019;*
not used in this study.



Example of Doppler shift spectrograms

Doppler shifts measured at 3 different frequencies on 8 November 2014 from 14:00 to 15:30 UT



Time (phase) shifts between fluctuations recorded for different Txi-Rx pairs are used to calculate propagation velocities (in 3D if signals are at more frequencies).

Measured plasma frequency f_p profile (true heights) is used to determine reflection heights h_R.

f **(MHz)**	$\mathbf{h_{RO}}$/ $\mathbf{h_{RX}}$ (km)
3.59	176/165
4.65	187/181
7.04	207/201

First, maxima of spectral intensities for each transmitter are evaluated to obtain Doppler shifts as single-valued functions of time.

Notes to the results that follow in the next slides

Only two different frequencies are used for the statistical study to enhance the probability that signals at different frequencies are correlated.

The **Doppler receiver does not distinguish ordinary L-O and extraordinary R-X modes**, therefore results are computed separately for both modes.

Periods: solar maximum, July 2014 – June 2015, *f*=7.04 and 4.65 MHz
solar minimum, September 2018 – August 2019, *f*=4.65 and 3.59 MHz
(Chum et al., 2021, Earth Planets Space ***73,*** *60)*

Attenuation *A* is also studied by comparing kinetic energies of GW observed at different altitudes using the observed Doppler shifts. Mass densities ρ are obtained from NRLMSISE-00 model at reflection heights for specific frequencies and mode of propagation.

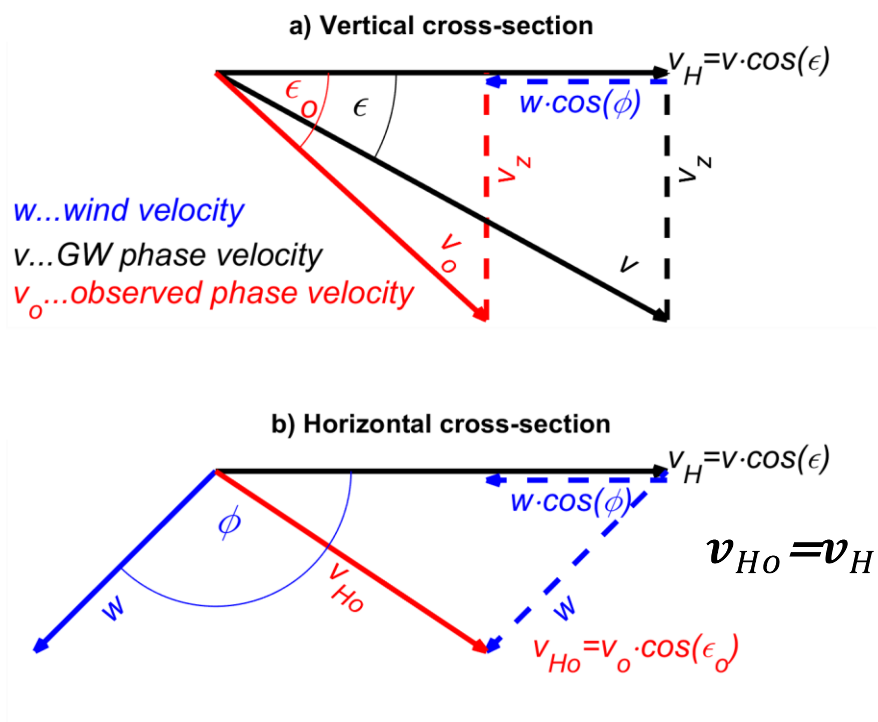
$$A = \frac{\rho v^2}{\rho_{z0} v_{z0}^2} \approx \frac{\rho f_D^2 \; f_{z0}^2}{\rho_{z0} \, f_{Dz0}^2 \, f^2},$$

(Chum and Podolská, GRL, 2018GL079695)

Wind rest frame (intrinsic) characteristics of GWs are obtained by subtracting neutral wind velocities from the observed GW velocities. HWM-14 model is used.

Wind rest frame velocities *v*, observed velocities v_o

Observed velocities, including azimuths and elevations angles differ from those in the wind – rest frame.



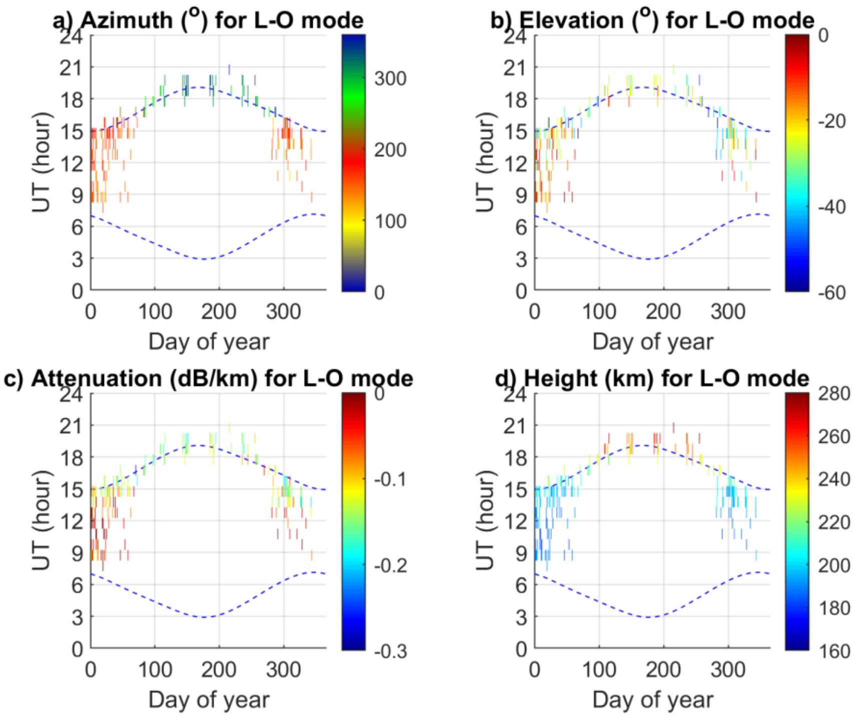
$$\boldsymbol{v}_{Ho} = \boldsymbol{v}_H + \boldsymbol{w}$$

$$\omega_o = \omega + \boldsymbol{k} \cdot \boldsymbol{w} = \omega + k \cdot w \cdot \cos(\epsilon) \cdot \cos(\phi) = \omega \cdot (1 + w/v \cdot \cos(\epsilon) \cdot \cos(\phi)),$$

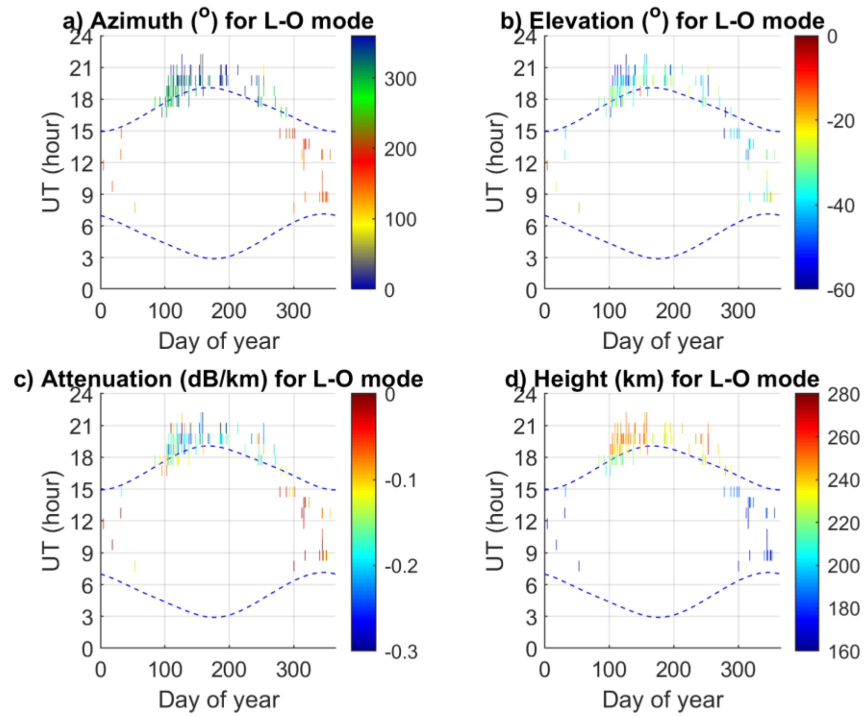
$$r = \frac{\omega_o - \omega}{\omega} = \frac{w}{v} \cdot \cos(\epsilon) \cdot \cos(\phi) \,,$$ **Relative Doppler shift**

(Chum et al., 2021, Earth Planets Space ***73,*** *60)*

Sol. max. 2014/7 – 2015/6,



Sol. min. 2018/9 – 2019/8

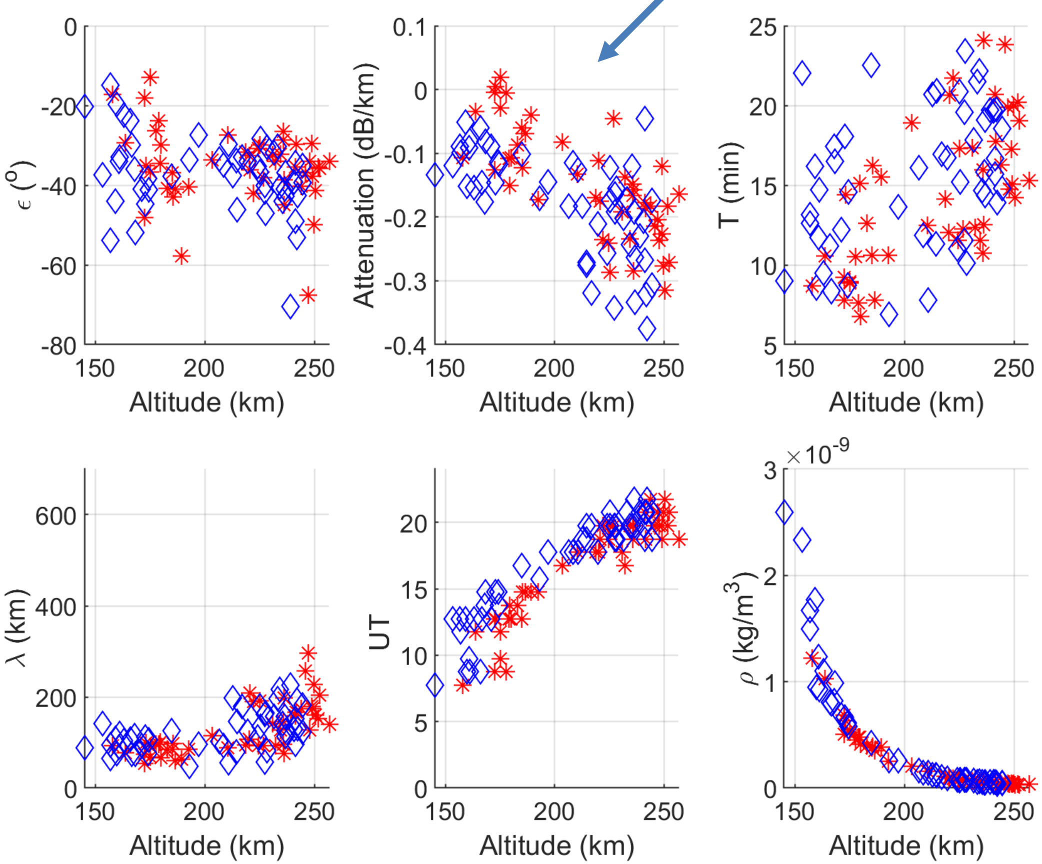


Selected parameters that exhibit dependence on the daytime and day of year.

Only sparse data coverage for 3D analysis because not all frequencies might be available (low *foF2*, sporadic E, low cross-correlation of signals etc.). Different for 2D analysis!

Attenuation and other GW characteristics on height

2018/9 – 2019/8



Attenuation increases with height

Consistent with energy dissipation due to the increase in kinematic viscosity (Vadas and Fritts, 2005)

Vadas and Crowly (2017) suggested that above ~220 km kinematic viscosity $\nu = \mu/\rho$,increases less rapidly (dynamic viscosity μ) is not approximately constant but decreases due to low collision frequency.

Can be verified from Doppler measurements?

Estimating viscosity

$$A = e^{-2\int_{r0}^{r} Im\{k\}dr} \approx e^{-2\int_{r0}^{r} Im\{k_z\}dz}$$

$$k_z \approx \frac{-ln(A)}{2(z_0 - z_1)}$$

Waves explicitly decay in space (altitude)
Wave number (its vertical component) is complex in dispersion relation

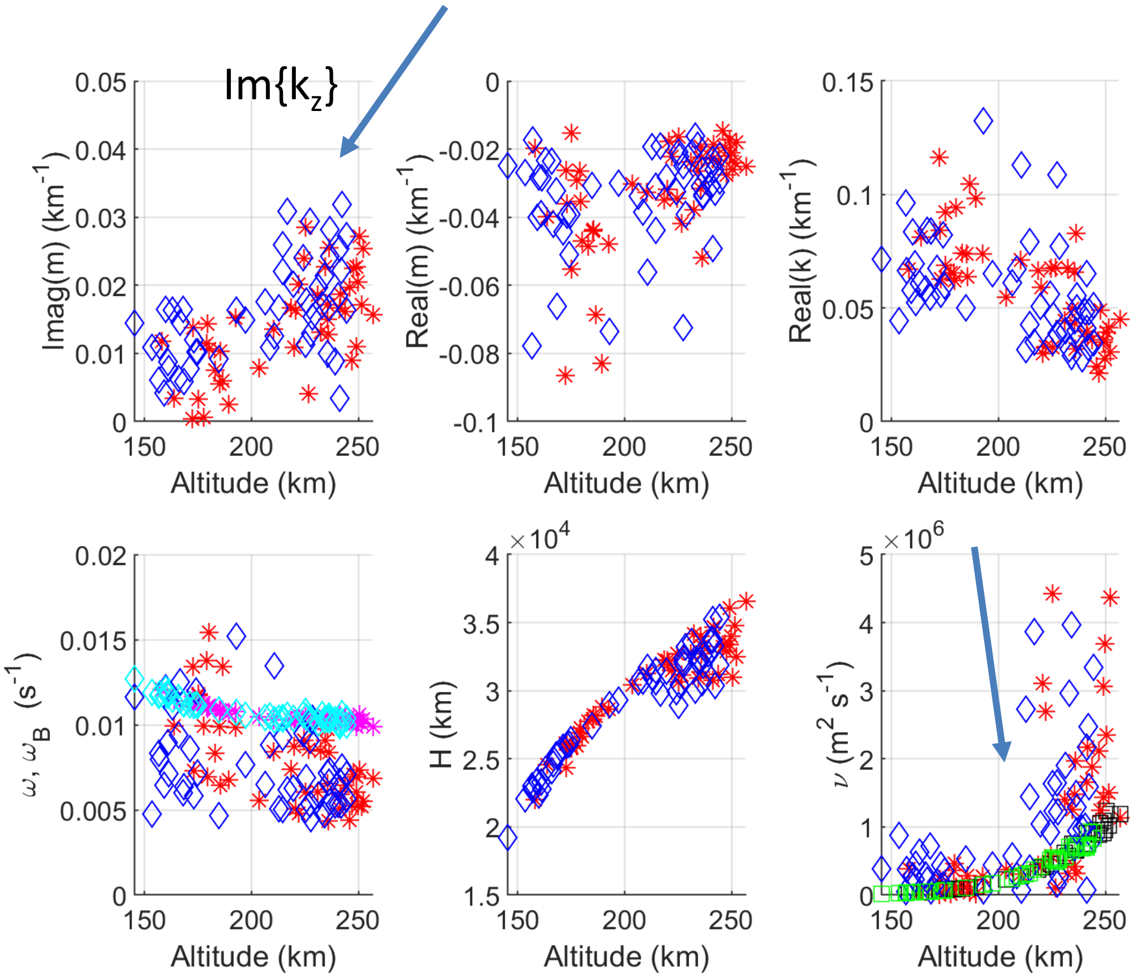
$$A = e^{-2\int_{t0}^{t} Im\{\omega\}dt}$$

Waves explicitly decay in time – frequency is complex
Requires comparison with ray tracing simulation

Complex dispersion relation for GWs (Vadas and Fritts, 2005).
Simplified case for *Pr*=1….much simple algebra (Pr≈0.7 for air)

$$\left[\omega - i\nu(-k_h^2 - k_z^2 + \frac{1}{4H^2} + i\frac{k_z}{H})\right]^2 = \frac{k_h^2 N^2}{k_h^2 + k_z^2 + \frac{1}{4H^2}}$$

Preliminary results assuming explicit decay with altitude



Problem – relatively large uncertainties of measurements and model values of temperature and density (buoyancy in dispersion relation).
Measurements not always perfectly match dispersion relation.

“Measured” values of ν seem to be larger at h>220 km than those obtained from model (μ≈const).

? Low number of collision might also hinder wave propagation not only reduce viscosity.
? Is Prandtl number *Pr* the same
? Nonlinear effects

Summary

Propagation of medium–scale GWs in the ionosphere at heights from ~150 to 250 km was analyzed in 3D on the basis of time (phase) delays between different observation points using multipoint and multifrequency continuous Doppler sounding.

Typical observed values were:
absolute phase velocity: ~ 100-220 m/s
Elevation of phase vector: ~ -50^{o}-10^{o}.
Period: ~ 10-30 min
Attenuation with height: ~ 0.05-0.3 dB/km

-Attenuation was lower at lower altitudes, consistent with GW damping due to viscosity and thermal conductivity.

-Large uncertainties in viscosity values, future studies and analysis needed

Thank you for your attention