Elevation angles and attenuation of gravity waves in the ionosphere

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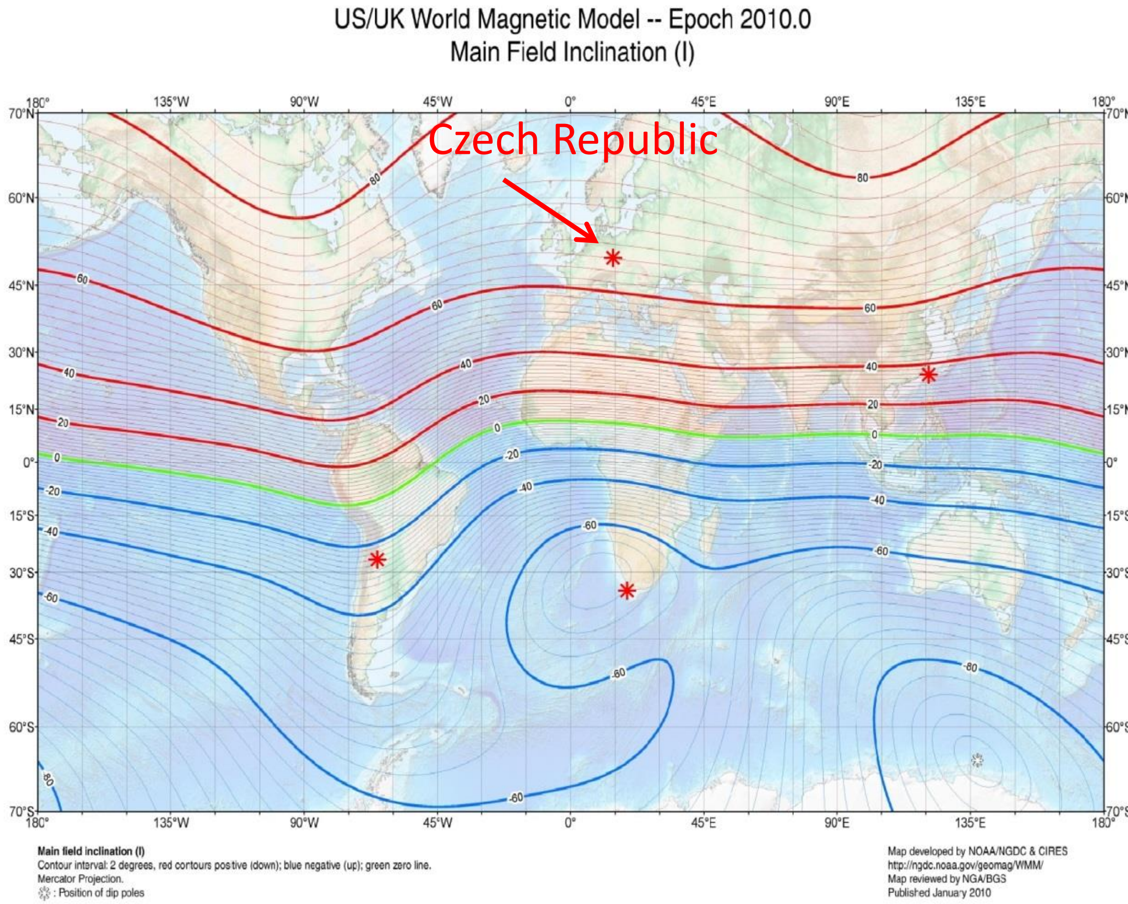
Introduction, Doppler sounding

Example of measurements

Analysis of 3D propagation
and attenuation

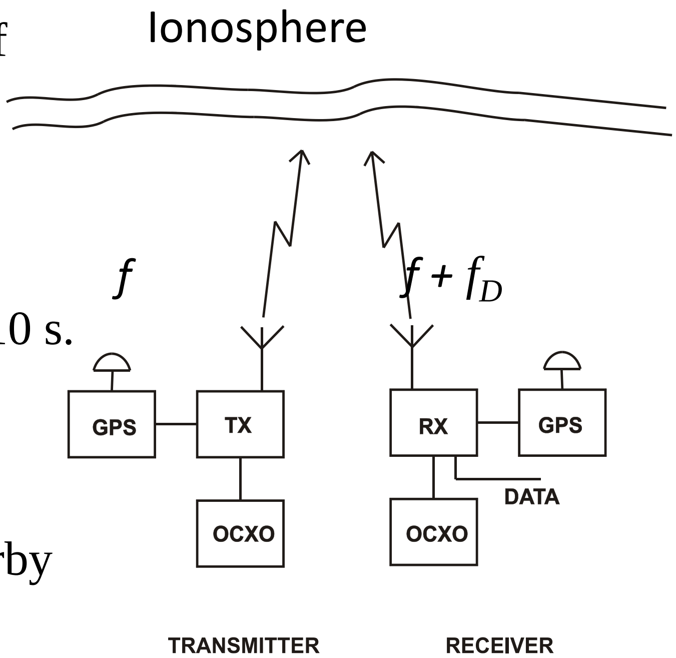
Statistical results obtained for
1-year periods during
sol. max. and sol. min.

Summary



Continuous Doppler sounding

Continuous, highly stable sine wave of frequency f is transmitted. [That is different from the ionosonde, pulses of short (coded) waveforms are transmitted.]



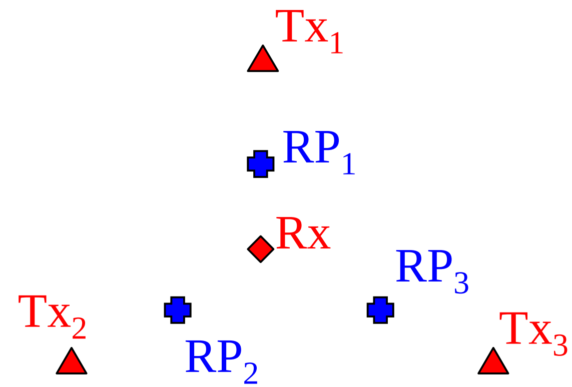
Doppler shift f_D of the reflected wave is measured.

To study variability on short time-scales, time resolution ~10 s. [Ionosondes typically sample at 5 to 15 minutes rate.]

Reflection is from a specific height, $f=f_p$, which changes during the day. Reflection height can be obtained from nearby ionosondes.

Movements of the ionosphere (reflecting level) and also increase/decrease of electron density cause f_D.

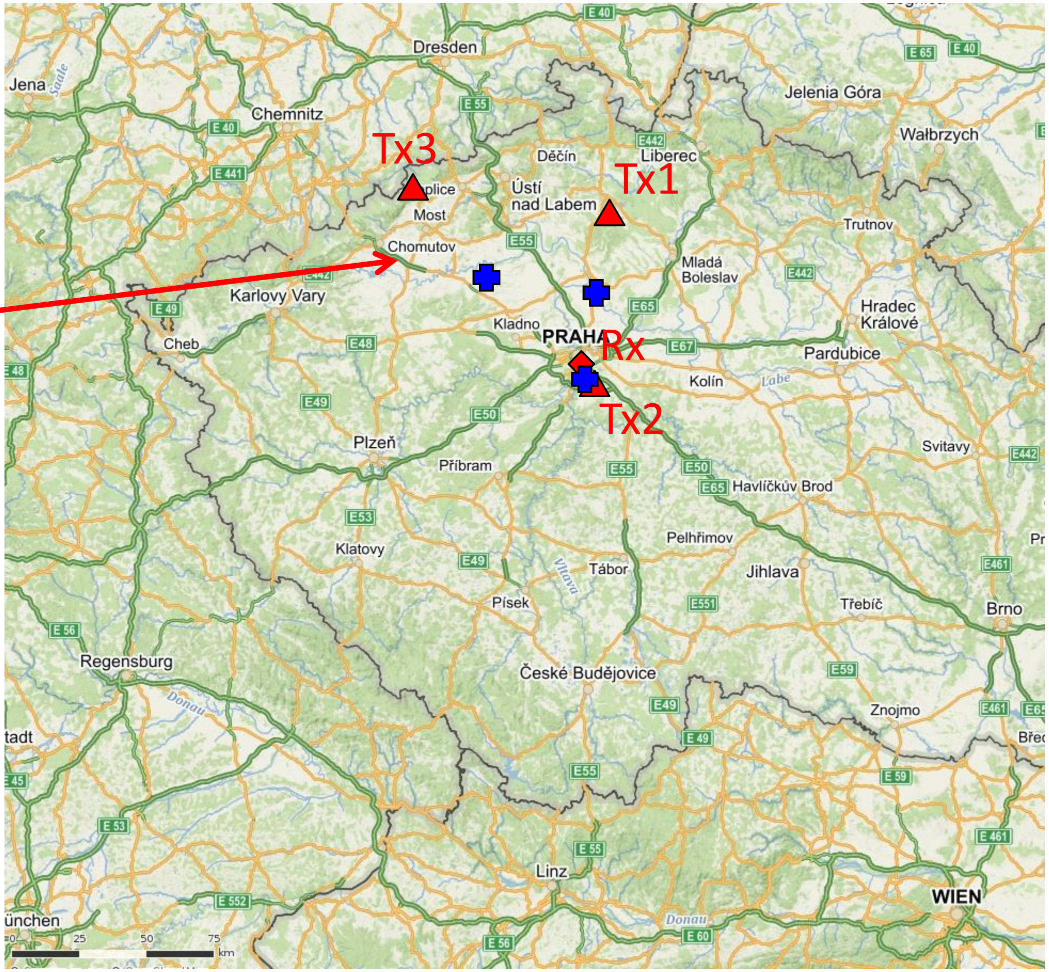
Multi-point sounding
- scale about 100 km
- minimum 3 reflection points (to study horizontal propagation



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)



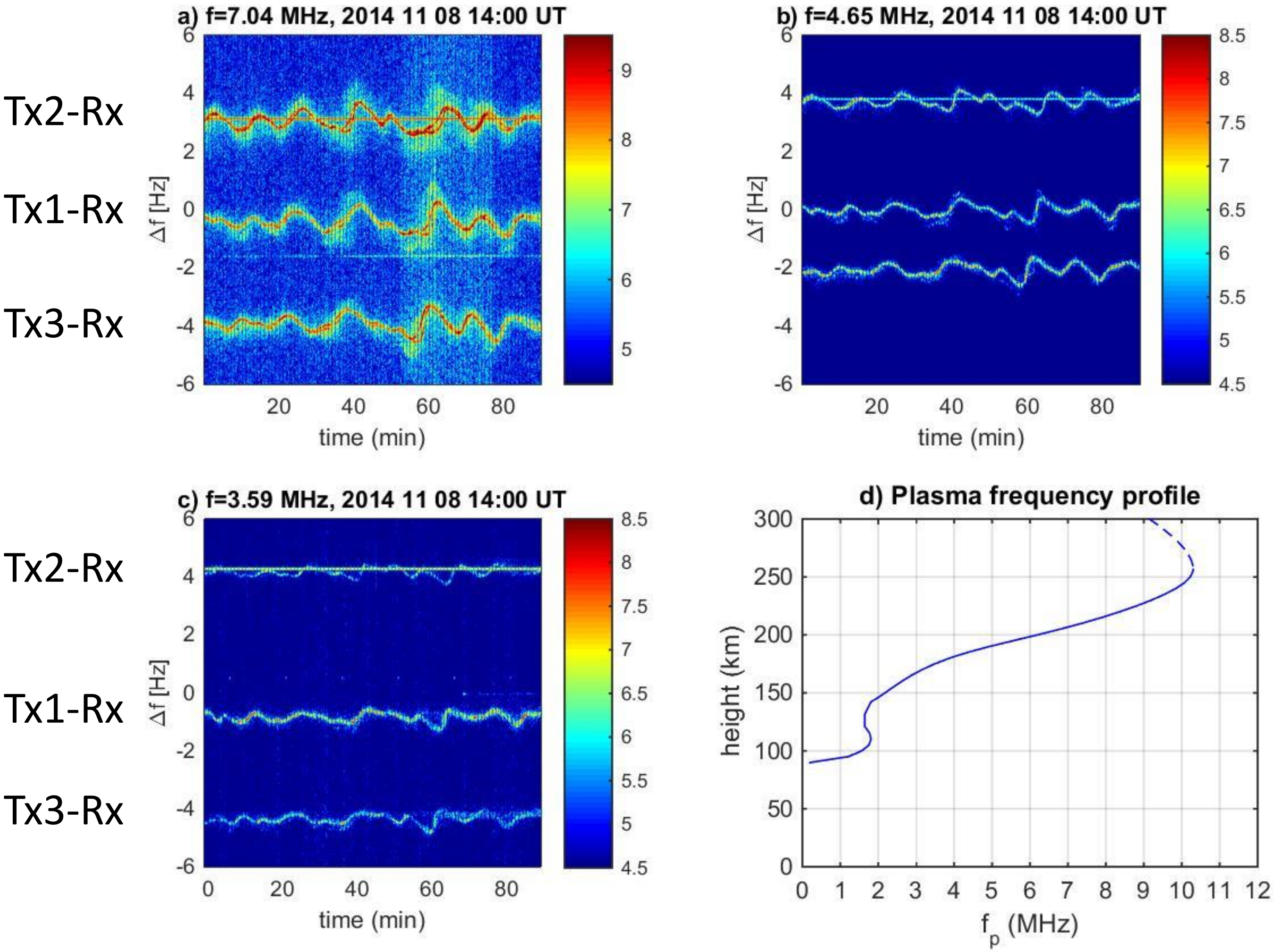
Receiver Rx is at our Institute in Prague

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 shown as 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.

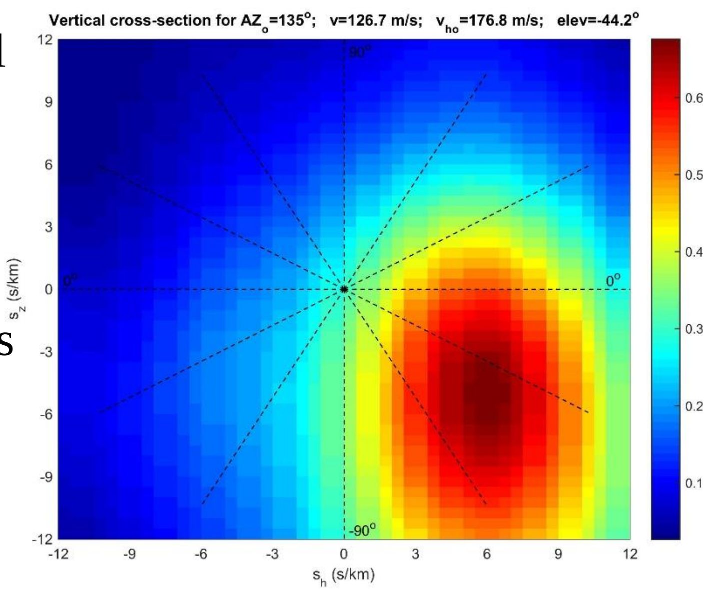
f **(MHz)**	$\mathbf{h_{RO}}$/ $\mathbf{h_{RX}}$ (km)
3.59	176/165
4.65	187/181
7.04	207/201

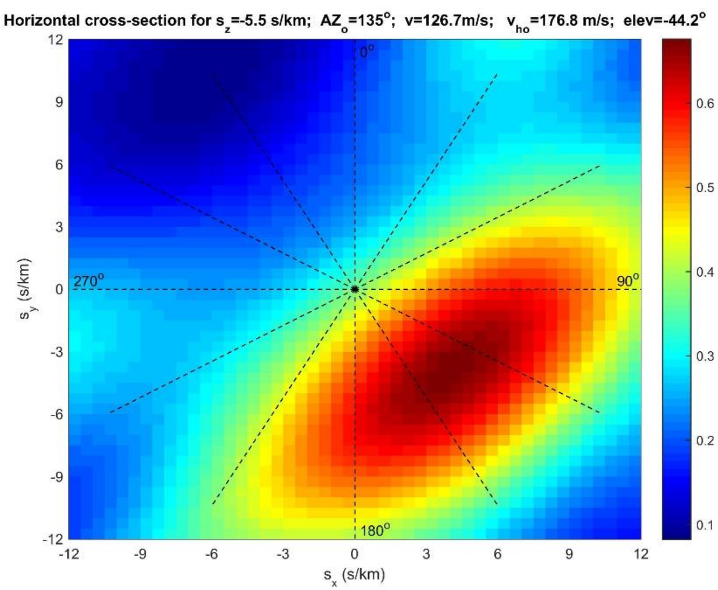
First, maxima of spectral intensities for each transmitter are evaluated to obtain Doppler shifts as single-valued functions of time.

Calculating propagation velocities

* The **velocity (slowness) vector** is determined **from the phase (time) delays** between signals on different sounding paths (transmitter-receiver pairs) by **three different methods:** best beam slowness search, least square fitting based on weighted and unweighted cross-correlations of the signals. (*Chum and Podolská, GRL, 2018GL079695* or the next slide)
* The **uncertainties** are estimated from the variance of the results obtained by three different methods. If the results differ significantly, they are discarded as unreliable.
*** Slowness** (the inverse of phase velocity) is used in calculations. The algebra is simpler using slowness than velocity as scalar products of slowness and spatial coordinates are in formulas.

Example of vertical cross-section (left) and horizontal cross-section (right) of normalized energies for various slowness components (method 1)





Methods to calculate propagation velocities

1. Slowness search
(summing shifted signals to reference point)

$$C(s_x, s_y, s_z) = \sum_{t_i} \left[\sum_{n=1}^{M} \frac{f_{Dn}(t_i + s_x \Delta x_n + s_y \Delta y_n + s_z \Delta z_n)}{\sigma_{fDn} M} \right]^2,$$

Slowness components s_x, s_y, s_z for which the best normalized signal - maximum of $C(s_x, s_y, s_z)$ is obtained are searched .Δx_n, Δy_n and Δz_n are the coordinates of the individual reflection points with respect to their center, σ_{fDn} are the RMS values of the Doppler shifts calculated over the time interval of the analysis (90 min).

2. Least Squares fitting

$$J = \sum_{i=1}^{N} (\Delta\tau_i - \Delta\xi_i \cdot s_x - \Delta\psi_i \cdot s_y - \Delta\zeta_i \cdot s_z)^2,$$

Solution are slowness components s_x, s_y, s_z for which the residuum J is minimum. $\Delta\tau_i$ are time delays between Doppler shift time series found from cross-correlation functions (times at which the corresponding cross-correlation functions have maximum are considered), and $\Delta\xi_i$, $\Delta\psi_i$, and $\Delta\zeta_i$ are corresponding mutual distances of reflection points along x, y, and z axes, respectively. $N=M(M-1)/2 = 15$ different combinations exist for $M=6$ reflection points.

3. Weighted Least Squares fitting

$$J_w = \sum_{i=1}^{N} \frac{(\Delta\tau_i - \Delta\xi_i \cdot s_x - \Delta\psi_i \cdot s_y - \Delta\zeta_i \cdot s_z)^2}{w_i^2},$$

The same as 2. However, the equations (time delays) are considered with different weights that correspond to maxima of cross-correlation functions.

(*Chum and Podolská, GRL, 2018GL079695*)

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)*

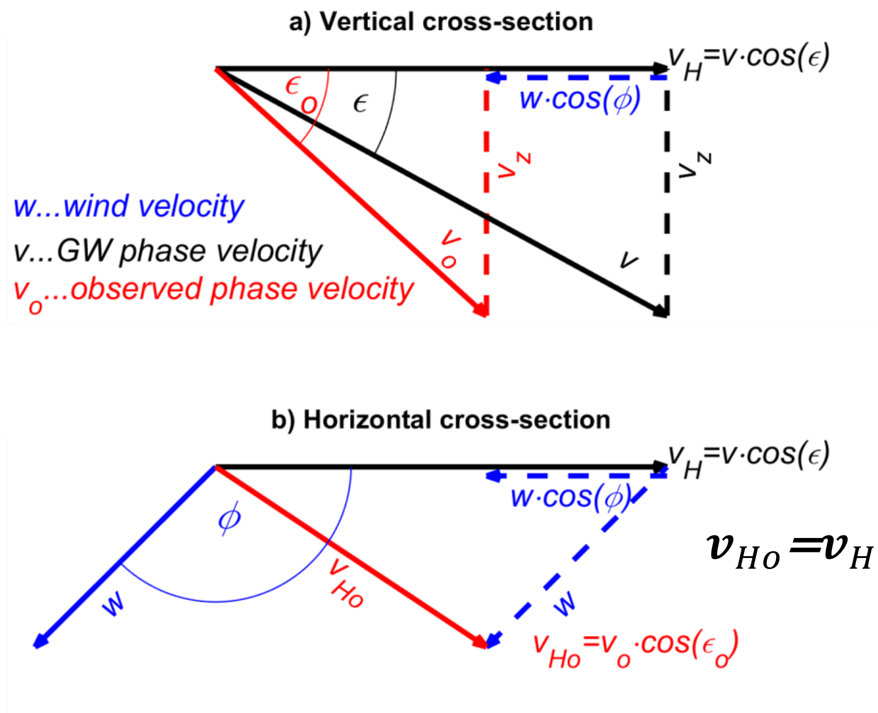
Attenuation *A* is also studied by comparing kinetic energies of GW observed at different altitudes using the observed Doppler shifts. Mass densities ρ are obtained from NRLMSISE-00 model at reflection heights for specific frequencies and mode of propagation.

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

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.

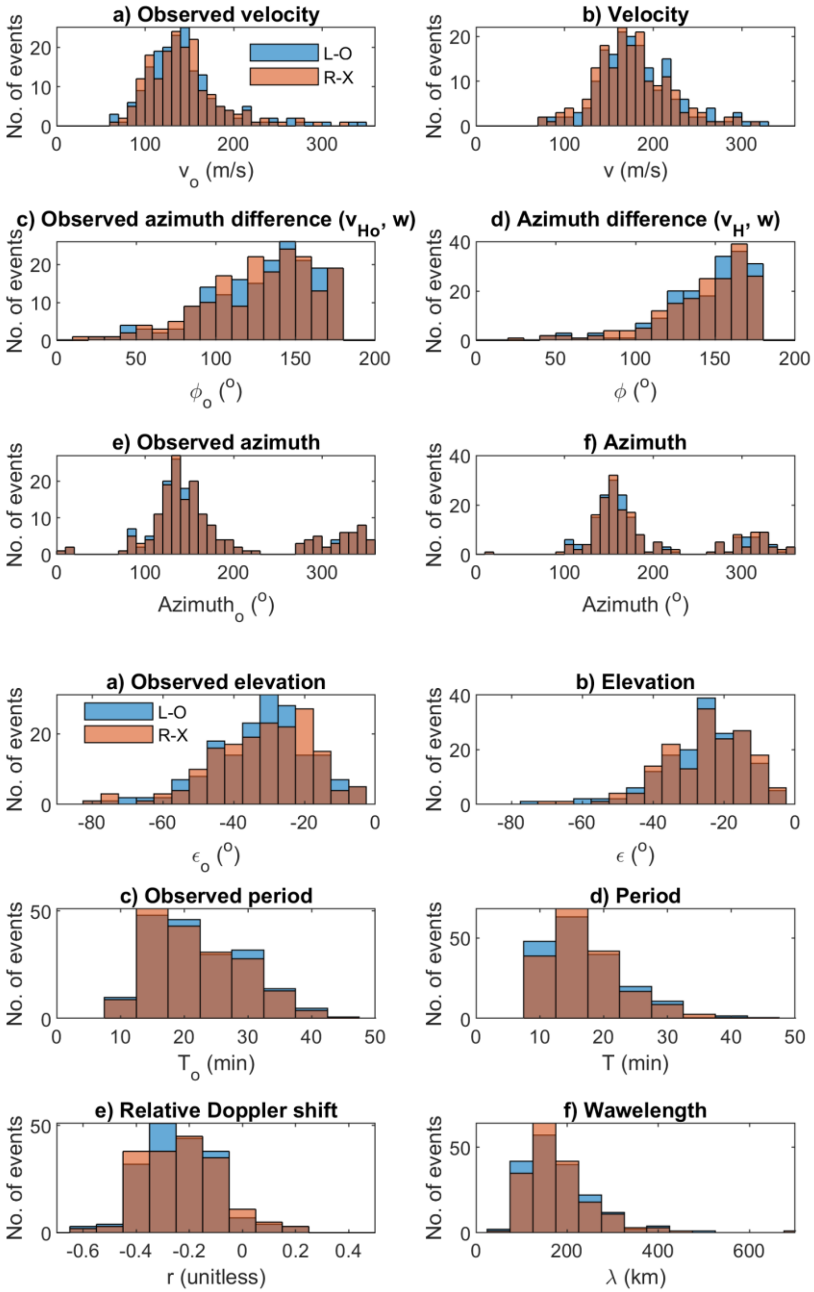


$$\boldsymbol{v}_{Ho} = \boldsymbol{v}_H + \boldsymbol{w}$$

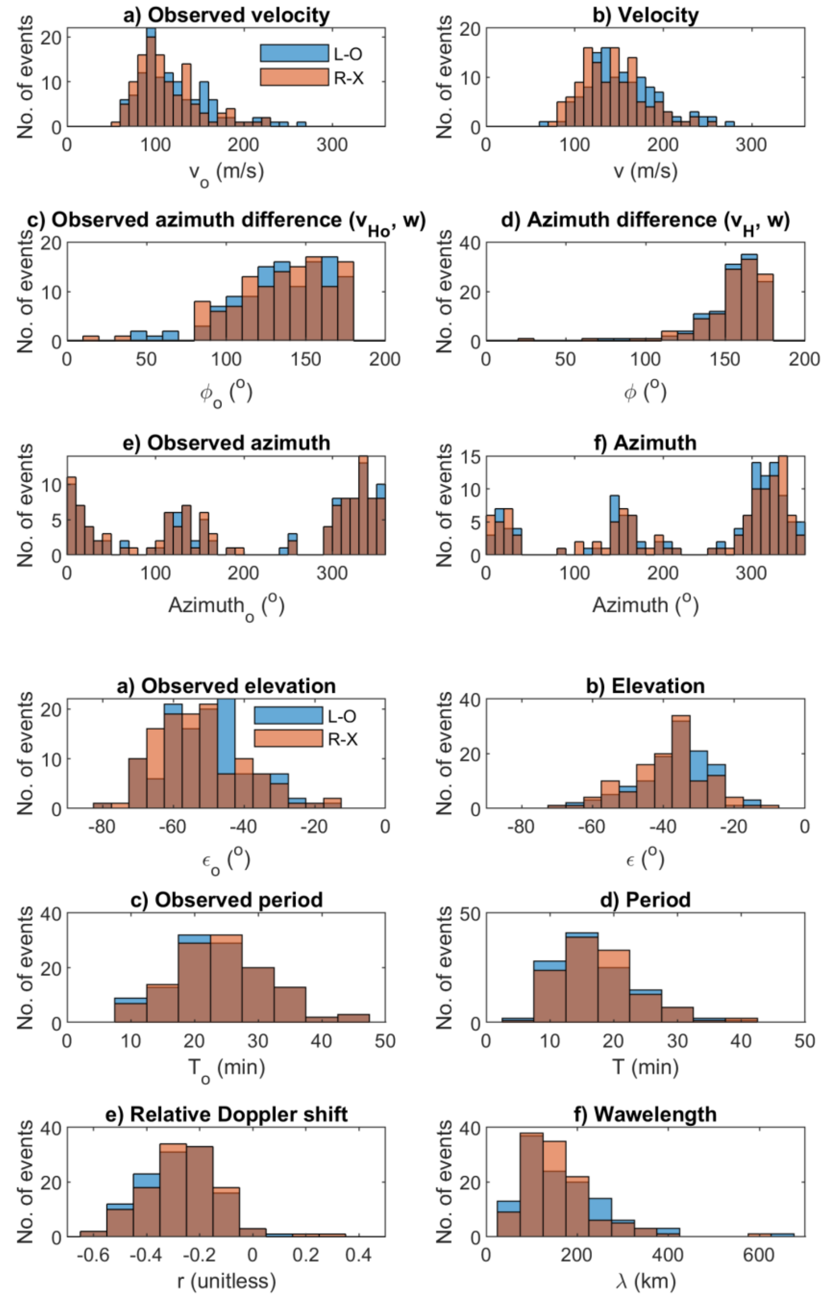
$$\omega_o = \omega + \boldsymbol{k} \cdot \boldsymbol{w} = \omega + k \cdot w \cdot \cos(\epsilon) \cdot \cos(\phi) = \omega \cdot (1 + w/v \cdot \cos(\epsilon) \cdot \cos(\phi)),$$

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

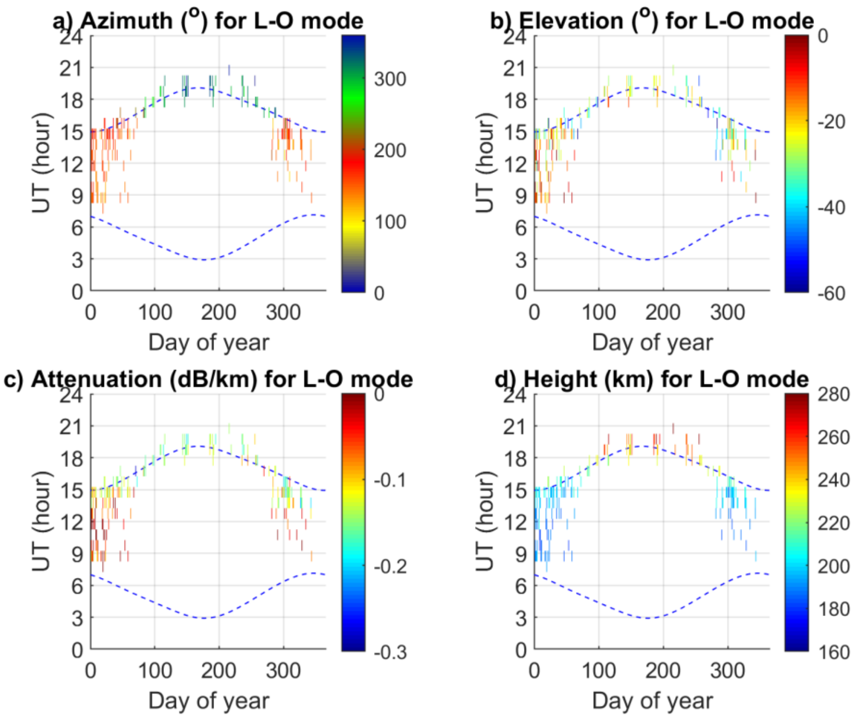
Sol. max. 2014/7 – 2015/6,



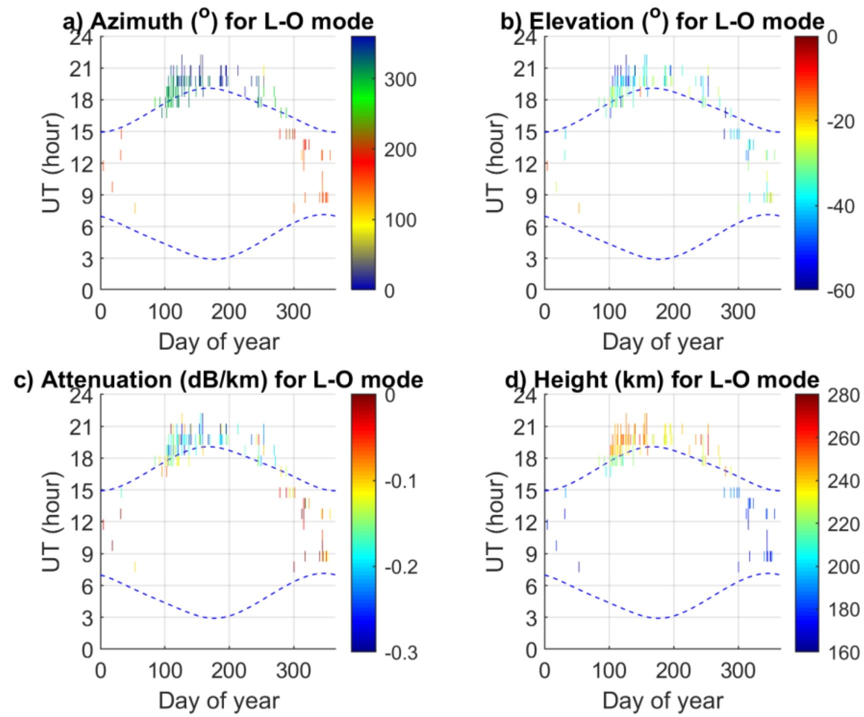
Sol. min. 2018/9 – 2019/8



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!

Summary

Propagation of medium–scale GWs in the ionosphere at heights around 200 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°-10°
Period: ~ 10-30 min
Attenuation with height: ~ 0.05-0.3 dB/km

-Azimuth of phase vector changed and exhibited dependence on season and daytime
-Attenuation was lower at lower altitudes, consistent with GW damping due to viscosity and thermal conductivity.

Sparse statistics. Simultaneous observation of well correlated signals at different frequencies was limited (*e.g.*, *foF2* was often lower than 7 MHz at night, Doppler shift is usually negligible around noon at 3.59 MHz that might reflect from E layer, …).

Reference: *Chum et al. (2021), Statistical investigation of gravity wave characteristics in the ionosphere. Earth Planets Space* ***73,*** *60, https://doi.org/10.1186/s40623-021-01379-3*

Thank you for listening/reading!