Ionospheric HF Doppler indication of GNSS positioning accuracy degradations

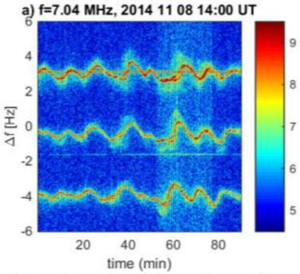
Institute of Atmospheric Physics CAS, Czech R.

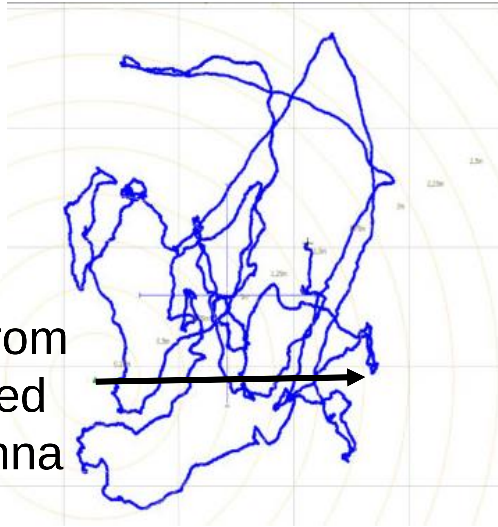
Urbář J., Rejfek L., Chum J., Truhlík V.

- SBAS-aided SPP for UAV (drone-like) application (without differential corrections) related to ionospheric disturbances @mid-latitudes.

- GNSS receivers use splitter to single common antenna (Septentrio AsteRx, Mosaic-X5,PolaRxS; two uBlox ZF9)

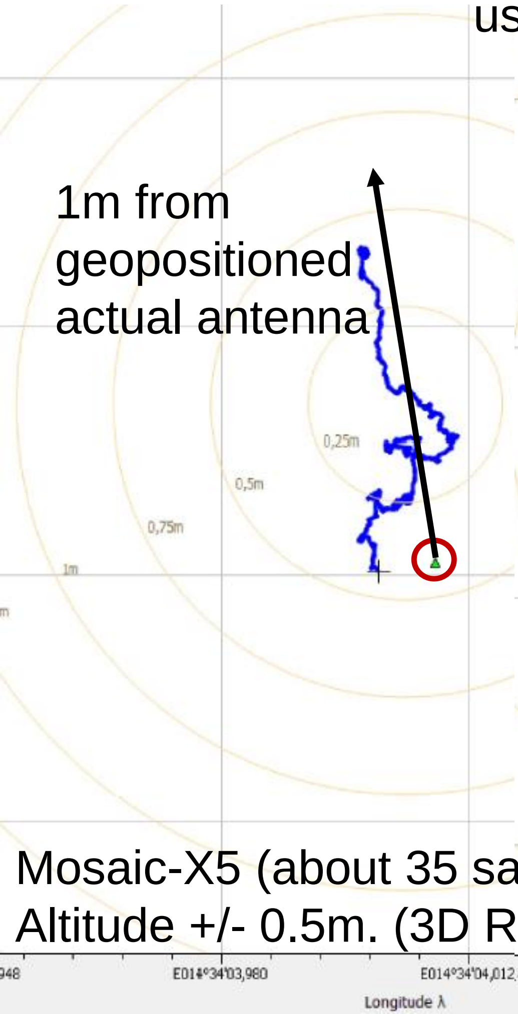
- NN-provided actual degradation evaluator (not V/HPL)





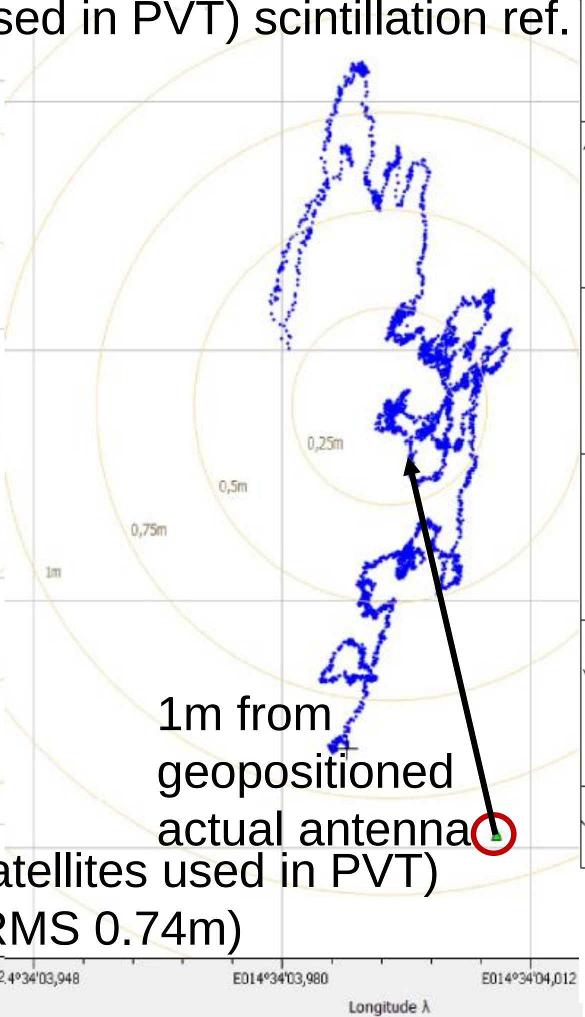
- Motivation: MSTID waves in the ionosphere (~100km) influence the positioning accuracy (current 5°x5° grid used by SBAS not capable to provide corrections for such MSTID waves of ~1° wavelength)

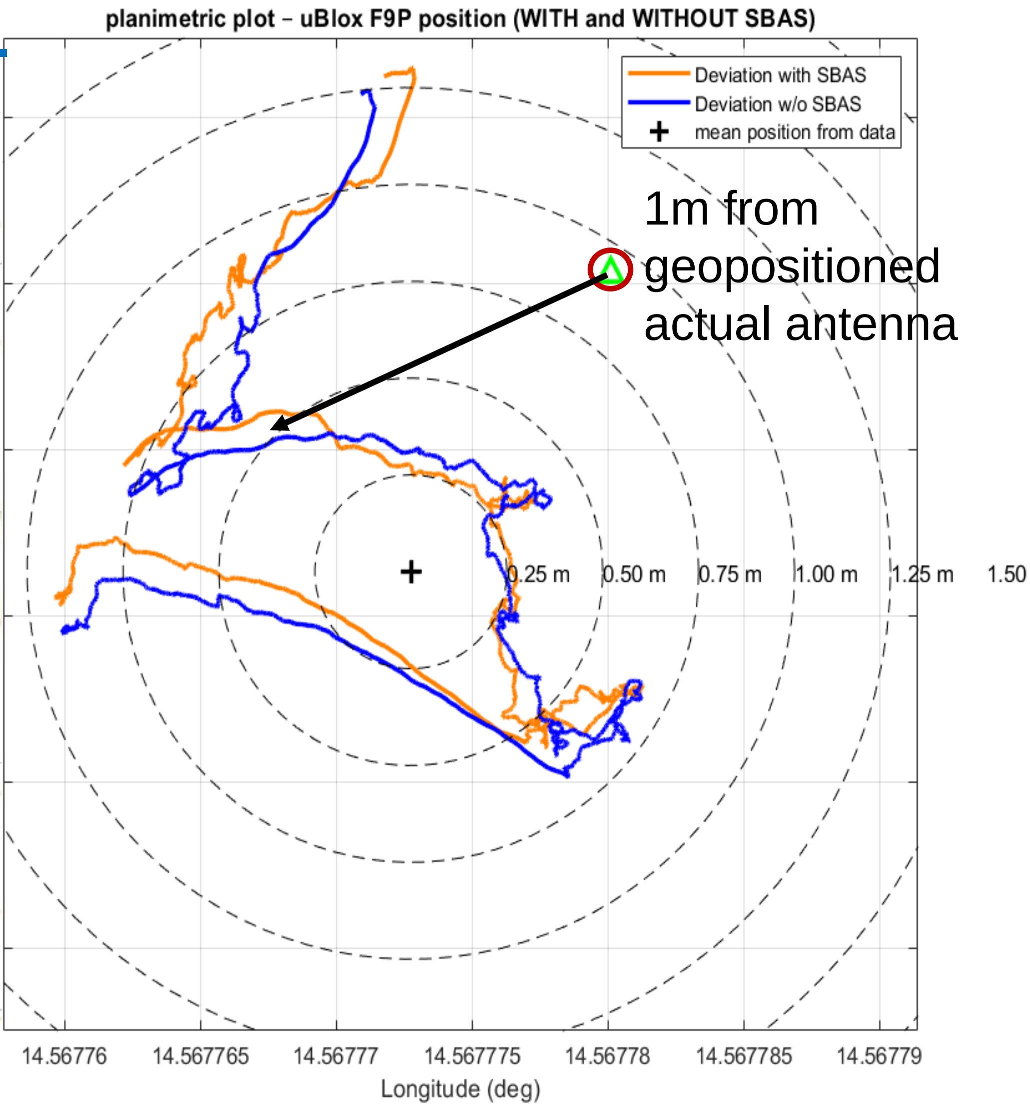
Position deviations of GNSS rec.



Mosaic-X5 (about 35 satellites used in PVT)
Altitude +/- 0.5m. (3D RMS 0.74m)

PolaRxS (about 24 satellites used in PVT) scintillation ref.





Testing of GNSS positioning deviations influencing factors

<u>Input parameters:</u>

GNSS: 3D position/altitude deviation+(&dTEC/S4), TEC

HF Doppler sounder (dF, SpreadF 3/7MHz night/day…);

Ionosonde parameters (foF2, hmF2, NmF2, B0/1);

TechTIDE Ionospheric indices (MSTID, AATR, HTI, HFI)

IRI (IRTAM): Ne@350km,Ne@450km,Ne@550km

~~Tropospheric total humidity~~

Geomagnetic indices (SYM/H, SYM/D,… local dH)

WWLLN nr. of lightning strokes in specific distances

EMIC (ULF) wave intensities

<u>Outputs:</u>

Improved accuracy estimator. (As H/VPL(m) is only max.)

Ionospheric disturbance indices - TIDs

HF Doppler - 3/7MHz RMSE Root mean squared (21-min floating) night/day power of CDSS-Doppler shift night/day offset, MSTID wave phase-related (new development, Chum+ 2018).

HFI - Identification of travelling ionospheric disturbances applying interferometry analysis to classical ionogram data from an ionosonde network, (Altadill+ 2017)

HTI - height-time-reflection intensity (HTI) methodology is similar to the technique producing range-time intensity (RTI) radar displays within a given time interval. (Haldoupis et al., 2006)

MSTIDix activity indicator (in LI [m]): Medium Scale Traveling Disturbances Affecting GPS Measurements: Spatial and Temporal Analysis (Hernández-Pajares+ 2006).

Along Track TEC Rate (AATR) index, related to degradation in the performance of SBAS, LSTID (Sanz+ 2014, Juan+ 2018).

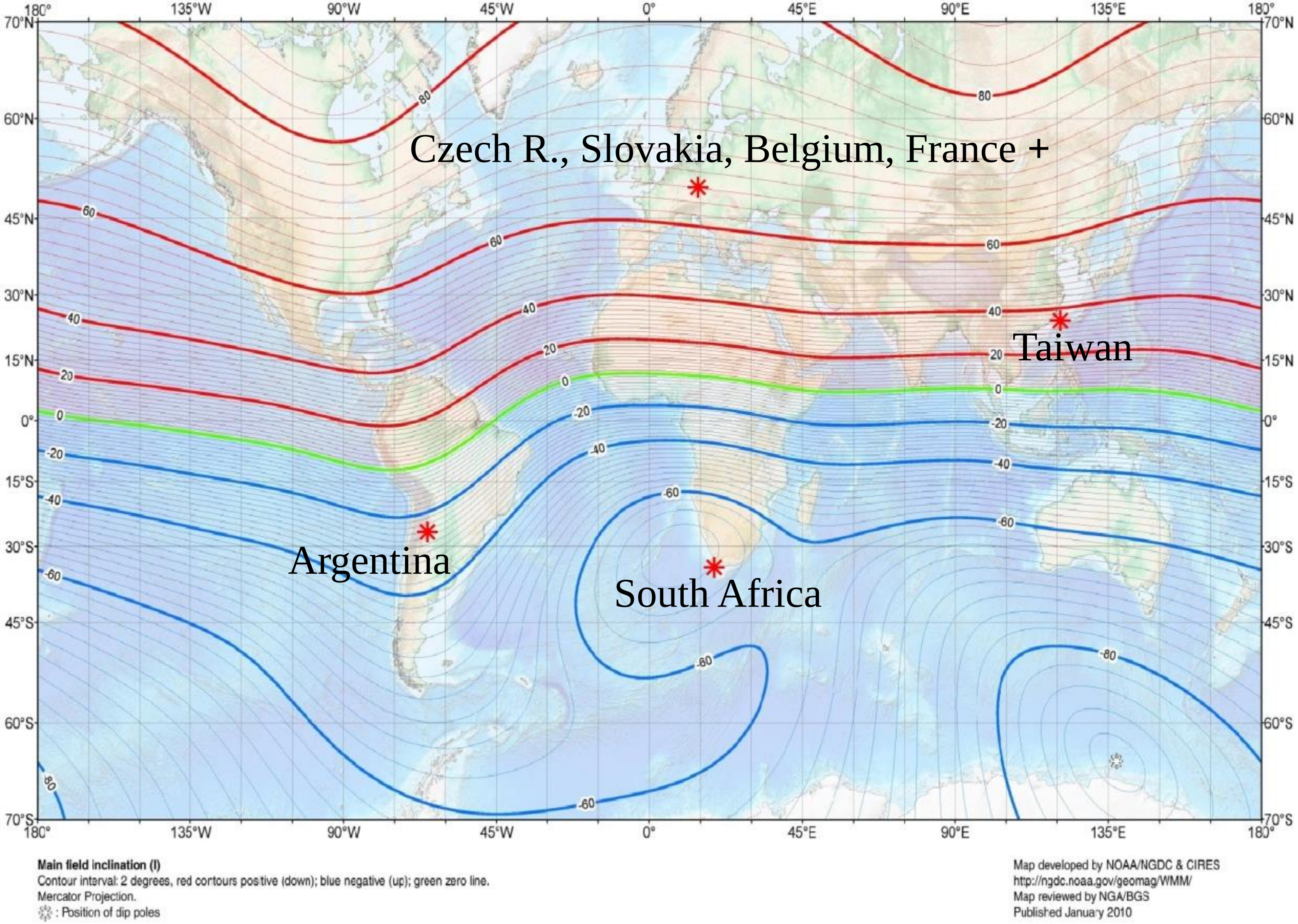
Sanz, J., J.M. Juan and G. González-Casado+ Novel Ionospheric Activity Indicator Specifically Tailored for GNSS Users. Proc. 27th International Technical Meeting of The ION GNSS+ 2014, Florida, September 8-12, 2014.

Juan JM, Sanz J, Rovira-Garcia A, González-Casado G, Ibáñez D, Perez RO AATR an ionospheric activity indicator specifically based on GNSS measurements. J. Space Weather Space Clim. 8: A14, 2018

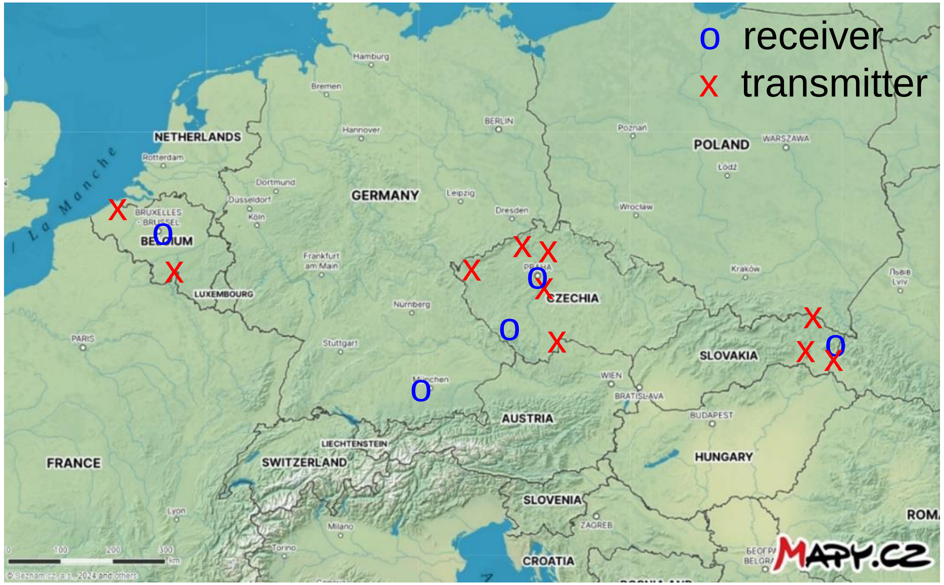
Chum, J., Urbář, J., Laštovička, J., Cabrera, M.A., Liu, J.Y., Bonomi, F., Fagre, M., Fišer, J., and Mošna, Z., "Continuous Doppler sounding of the ionosphere during solar flares", Earth, Planets and Space, 2018, ***70****, 198,*

Hernández-Pajares, M., J. Miguel Juan Zornoza, Jaume Sanz, "Medium Scale Traveling Disturbances Affecting GPS Measurements: Spatial and Temporal Analysis", JGR, Vol.111, A07-S11, 2006, (doi:10.1029/2005JA011471).

Locations of IAP’s multipoint HF Doppler sounding systems



Continuous Doppler sounding in Europe



Country	Site num. in Figure 1	Component	Frequency (MHz)	Latitude	Longitude
Czech Republic	1	Rx1	3.59, 4.65, 7.04	50.04°N	14.48°E
Czech Republic	2	Rx2	3.59, 4.65, 7.04	49.13°N	13.58°E
Germany	3	Rx3	4.65	48.09°N	11.28°E
Czech Republic	4	Tx1	3.59, 4.65, 7.04	50.528°N	14.567°E
Czech Republic	5	Tx2	3.59, 4.65, 7.04	49.991°N	14.538°E
Czech Republic	6	Tx3	3.59, 4.65, 7.04	50.648°N	13.656°E
Czech Republic	7	Tx4	3.59, 4.65	48.988°N	14.777°E
Czech Republic	8	Tx5	3.59, 4.65	50.236°N	12.373°E
Slovakia	9	Rx	3.59	48.93°N	22.27°E
Slovakia	10	Tx1	3.59	48.706°N	21.261°E
Slovakia	11	Tx2	3.59	48.625°N	22.205°E;
Slovakia	12	Tx3	3.59	49.399°N	21.483°E
Belgium	13	Rx	4.59	50.80°N	4.36°E
Belgium	14	Tx1	4.59	51.19°N	3.06°E
Belgium	-	Tx2	4.59	TBD	TBD
Belgium	15	Tx3	4.59	50.099°N	4.591°E

Multi-point and multi-frequency (Czechia) sounding
→ propagation of MSTIDs

Time resolution ~10 s, Transmitted power: 1 W

Continuous HF Doppler sounding concept

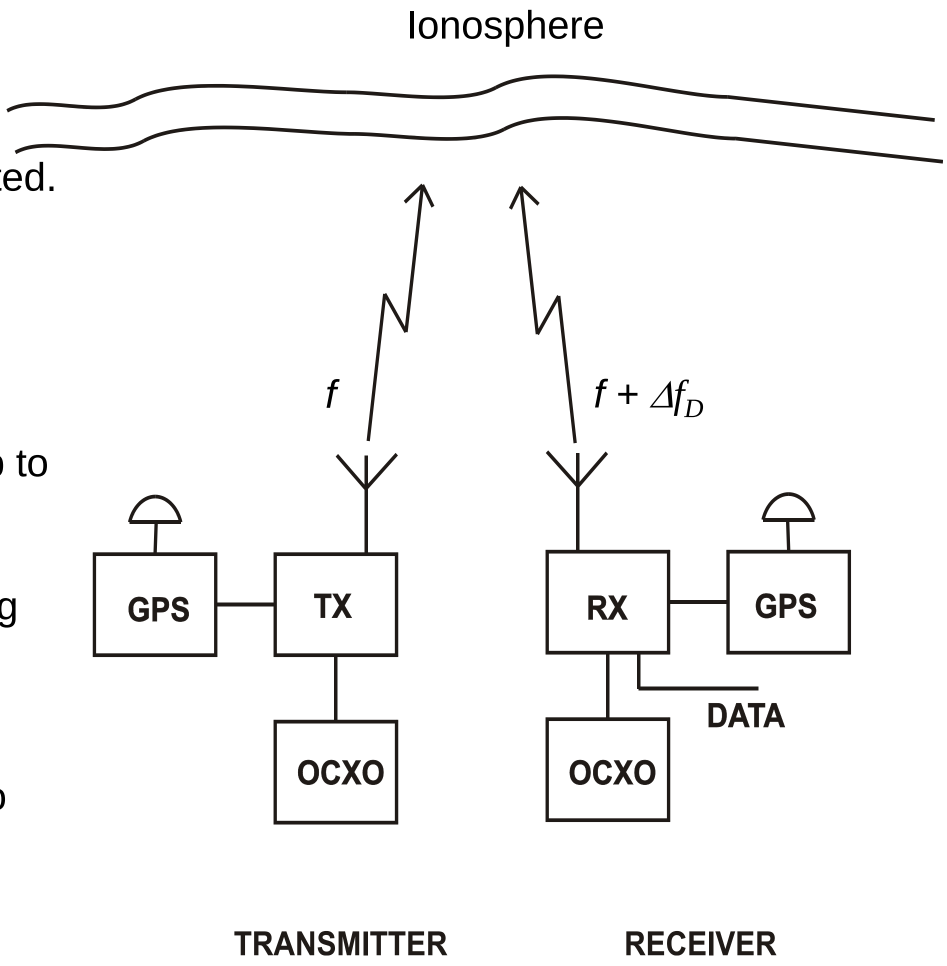
Continuous, highly stable sine wave of frequency *f* is transmitted. (That is different from the ionosonde - pulses of short (coded) waveforms are transmitted.)

Doppler shift Δf_D of the reflected wave is measured.

Makes it possible to study variability on shorter time-scales up to ~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 (of the reflecting layer) and also increase/decrease of electron density cause Doppler shift Δf_D.



Doppler shift in detail

$$\Delta f_D = -2\cdot\frac{f}{c}\frac{d}{dt}\left(\int_0^{z_R} n\cdot dr\right) = -2\cdot\frac{f}{c}\int_0^{z_R}\frac{\partial n}{\partial N}\cdot\frac{\partial N}{\partial t}\cdot dr$$

Time change of the phase path of sounding radio wave

Δf_D .. Doppler shift; *n* .. refractive index; *N* .. electron density, *f* .. sounding frequency, *c* .. speed of light, z_R .. reflection height (radial distance).

Largest contribution to the Doppler shift is in the region of reflection, where *n*->0, (*f* ->*fp*)

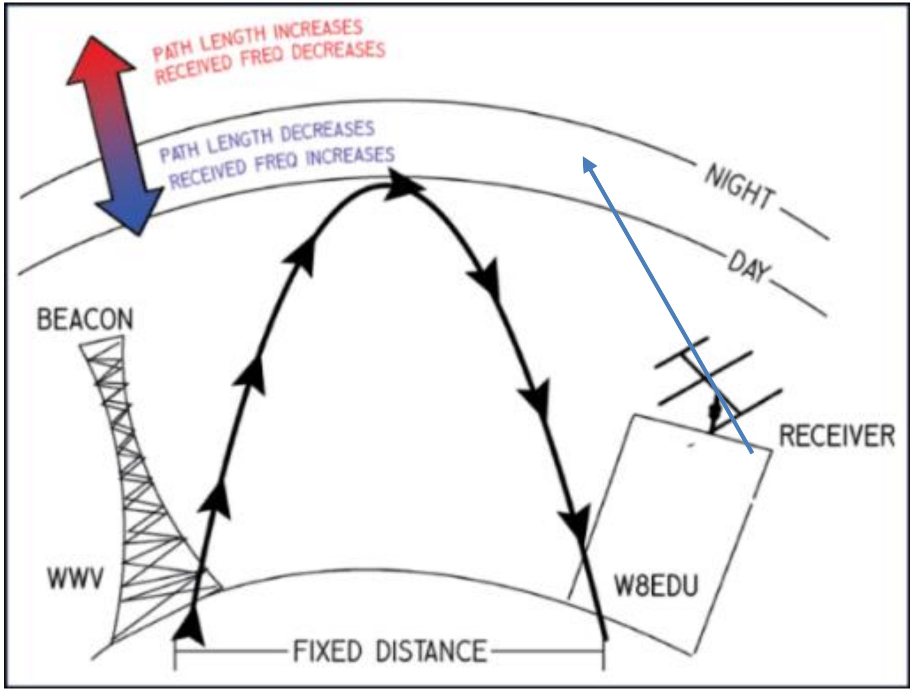
Terms contributing to electron density changes and hence Doppler shift

$$\frac{\partial N}{\partial t} = -\nabla\cdot(N u_P) + P - L = -\nabla N\cdot u_P - N(\nabla\cdot u_P) + P - L,$$

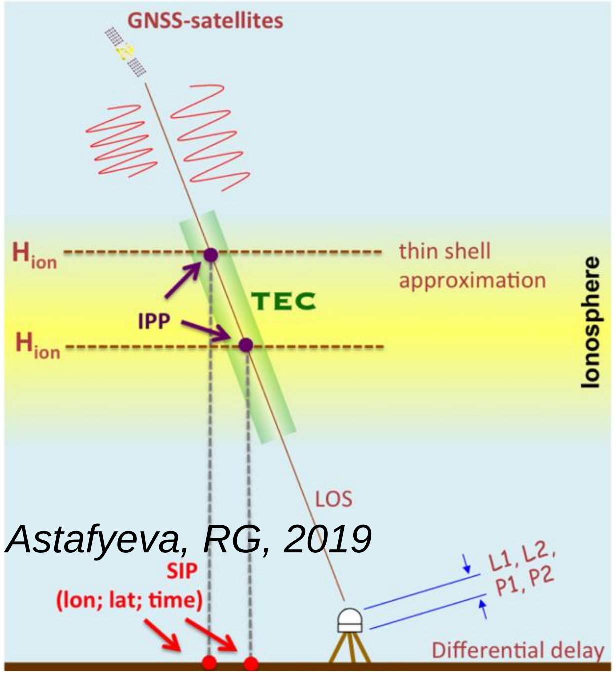
Equation of continuity

Advection	Compression	Production	Losses
Movement of reflecting level (GWs, ***E***x***B***)	Infrasound	Photo-ionisation	Recombination, Electron attachment

Continuous Doppler sounding versus TEC (dTEC) measurements



Information on wave amplitude and phase at a specific reflection point (height from ionograms)
Doppler shift → Vertical oscillation velocities of plasma/air due to the waves
multi-point and multi-frequency sounding → propagation velocities from time delays between different sounding paths
Limited spatial coverage, but high time resolution.

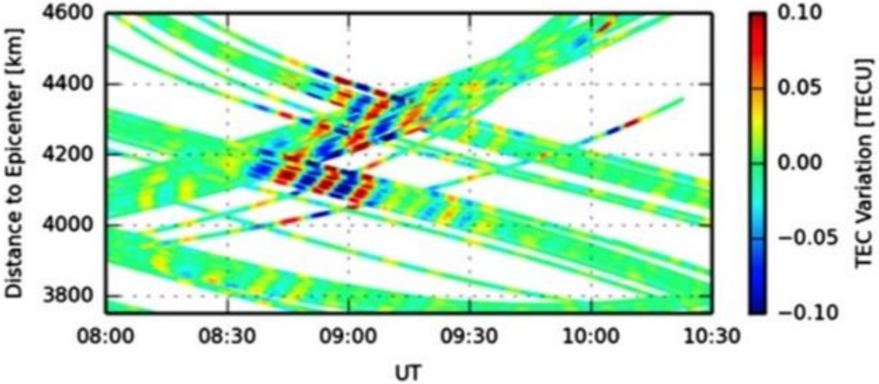


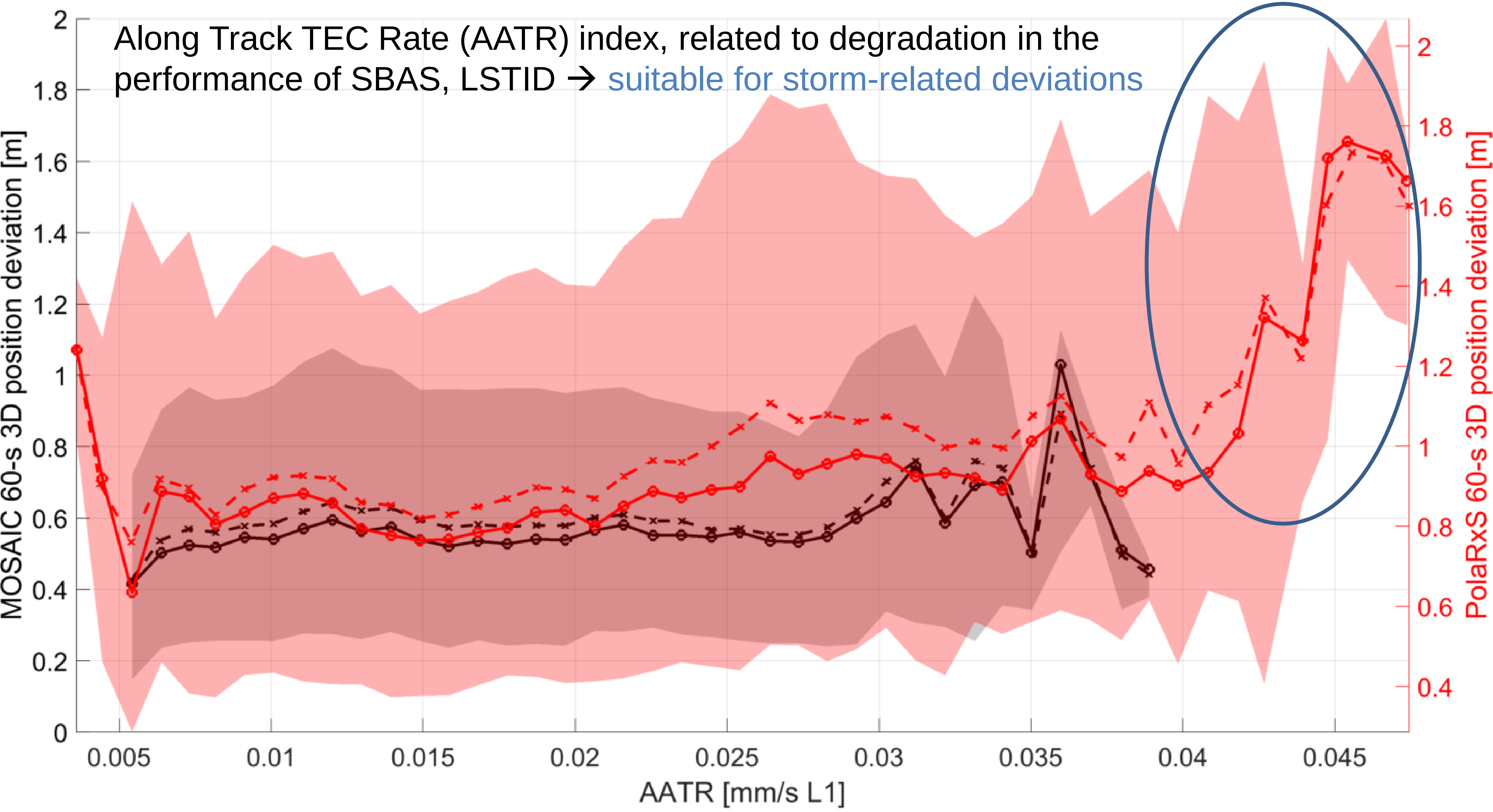
Astafyeva, RG, 2019

Integral values of TEC along LOS

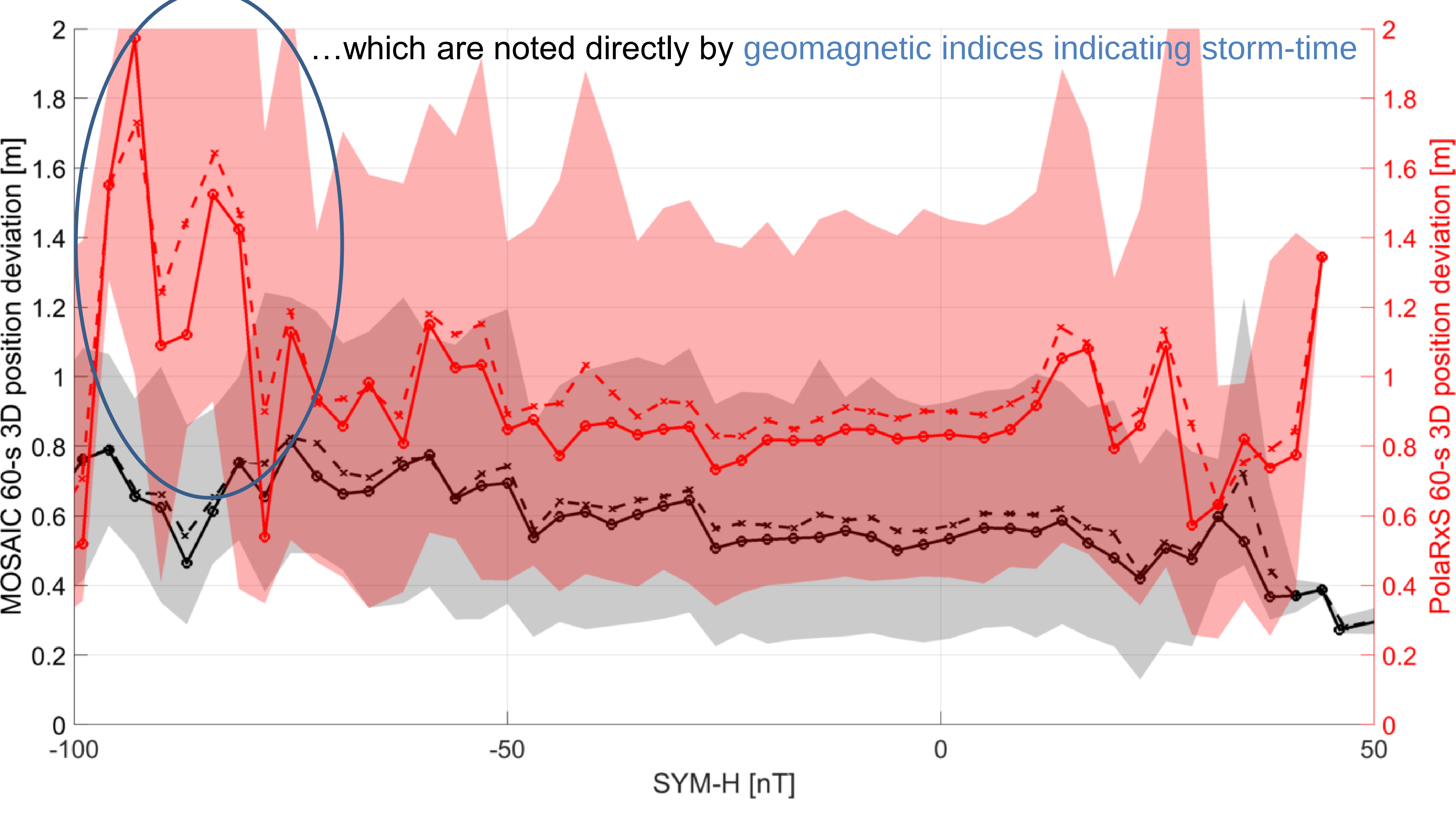
TEC (dTEC) maps for IPPs (good spatial coverage)

Apparent horizontal velocities from time evolution (time-distance plots)

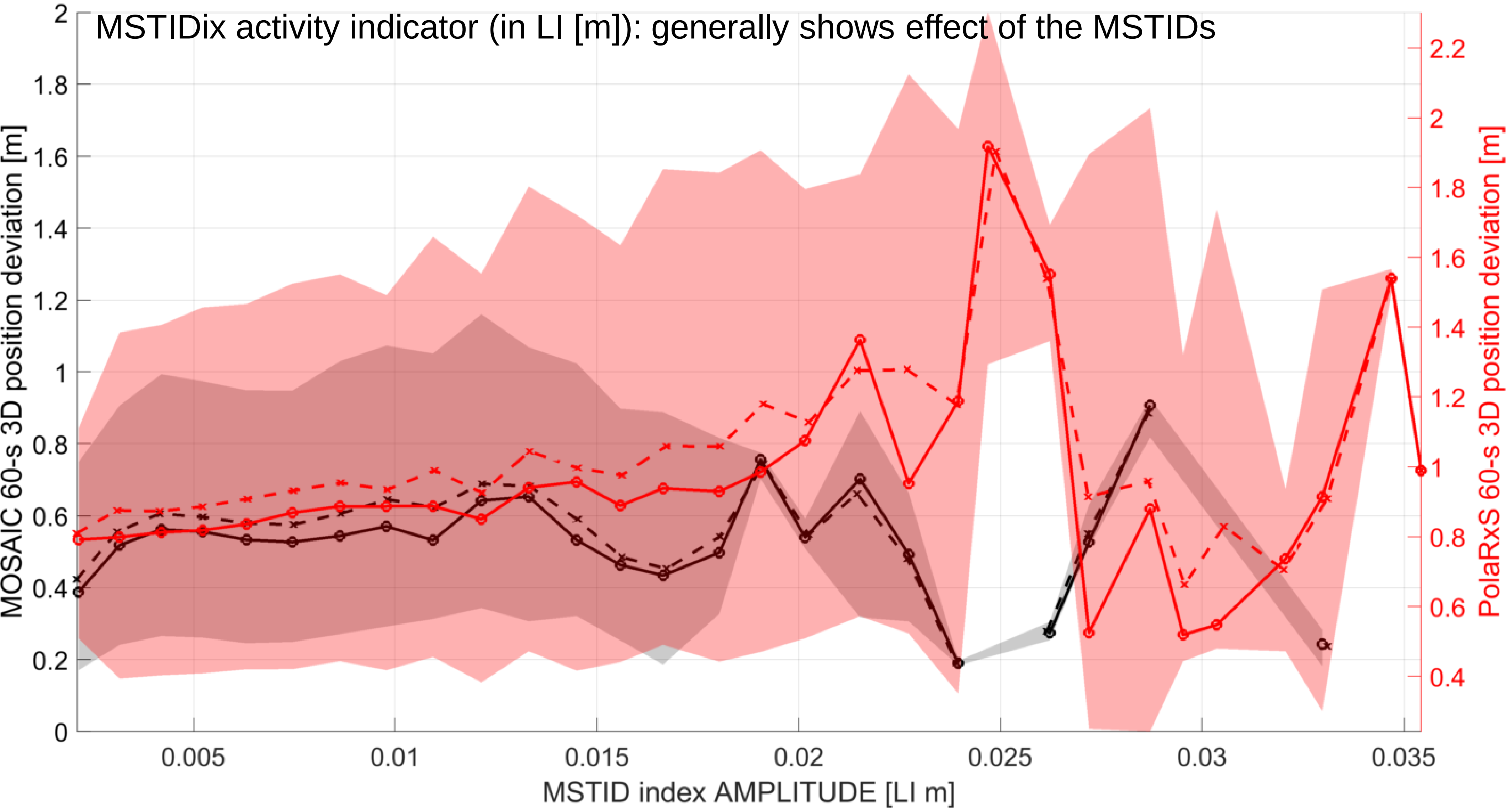




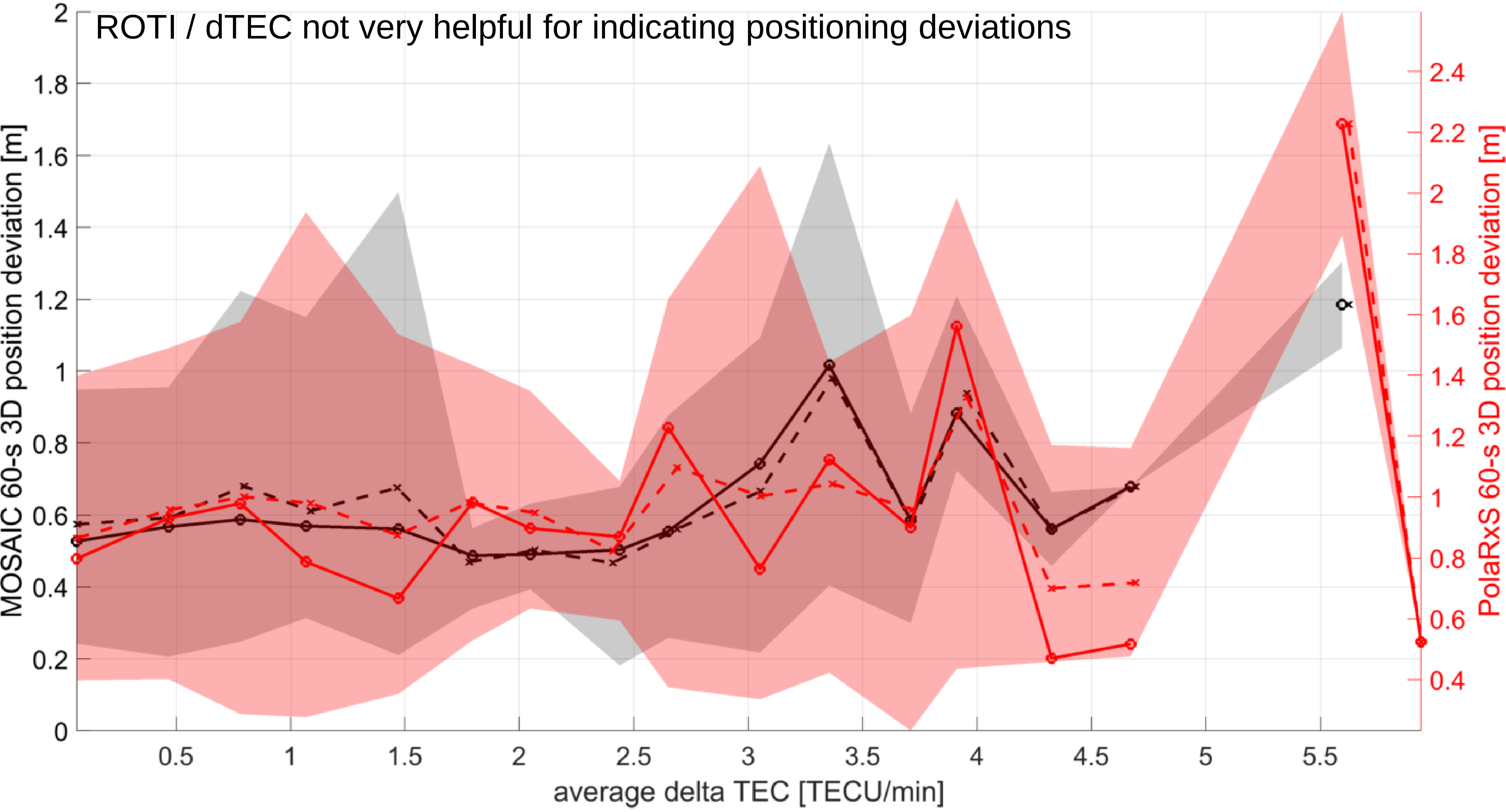
Along Track TEC Rate (AATR) index, related to degradation in the performance of SBAS, LSTID → suitable for storm-related deviations
MOSAIC 60-s 3D position deviation [m]
PolaRxS 60-s 3D position deviation [m]
AATR [mm/s L1]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045

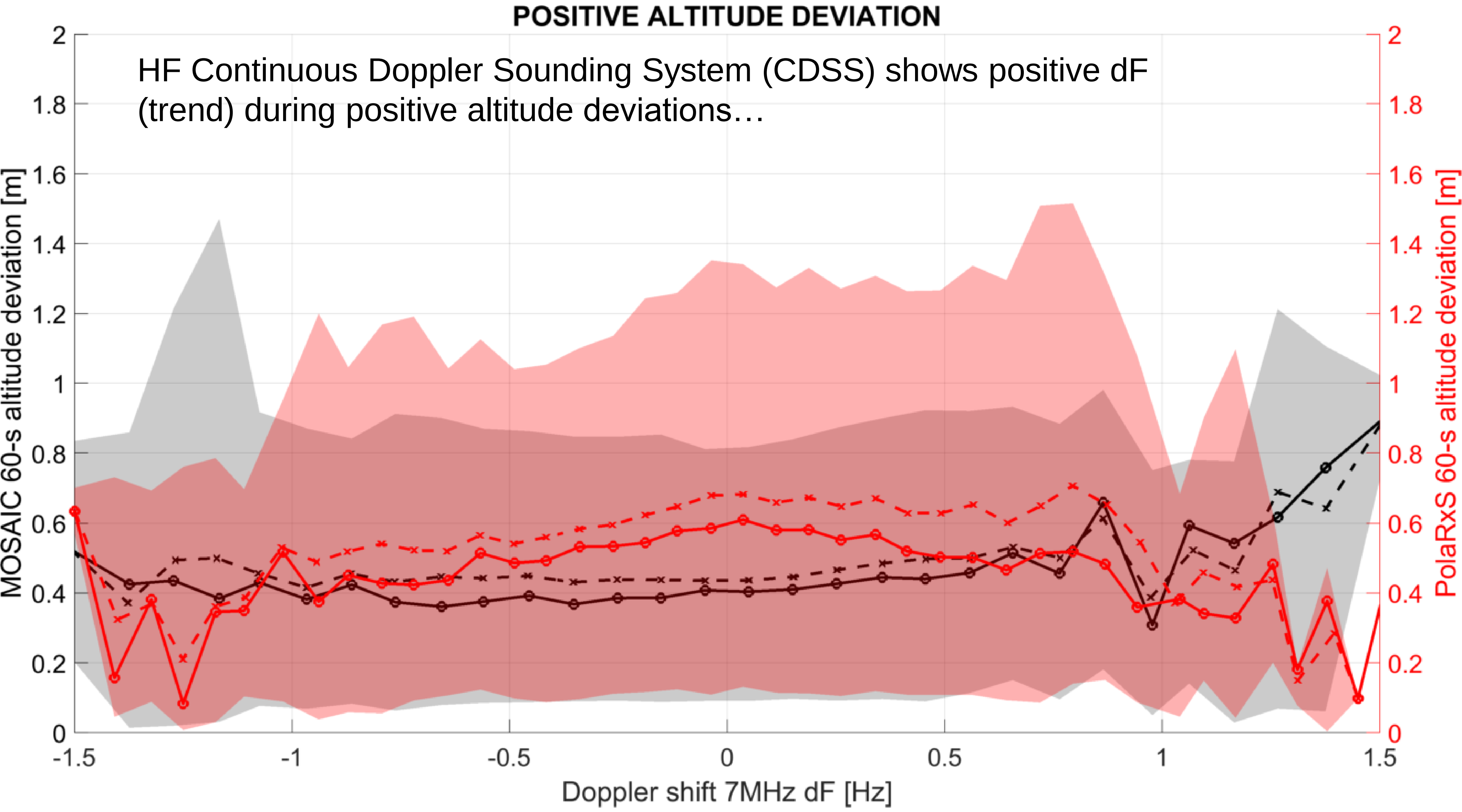


…which are noted directly by geomagnetic indices indicating storm-time
MOSAIC 60-s 3D position deviation [m]
PolaRxS 60-s 3D position deviation [m]
SYM-H [nT]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
-100
-50
0
50

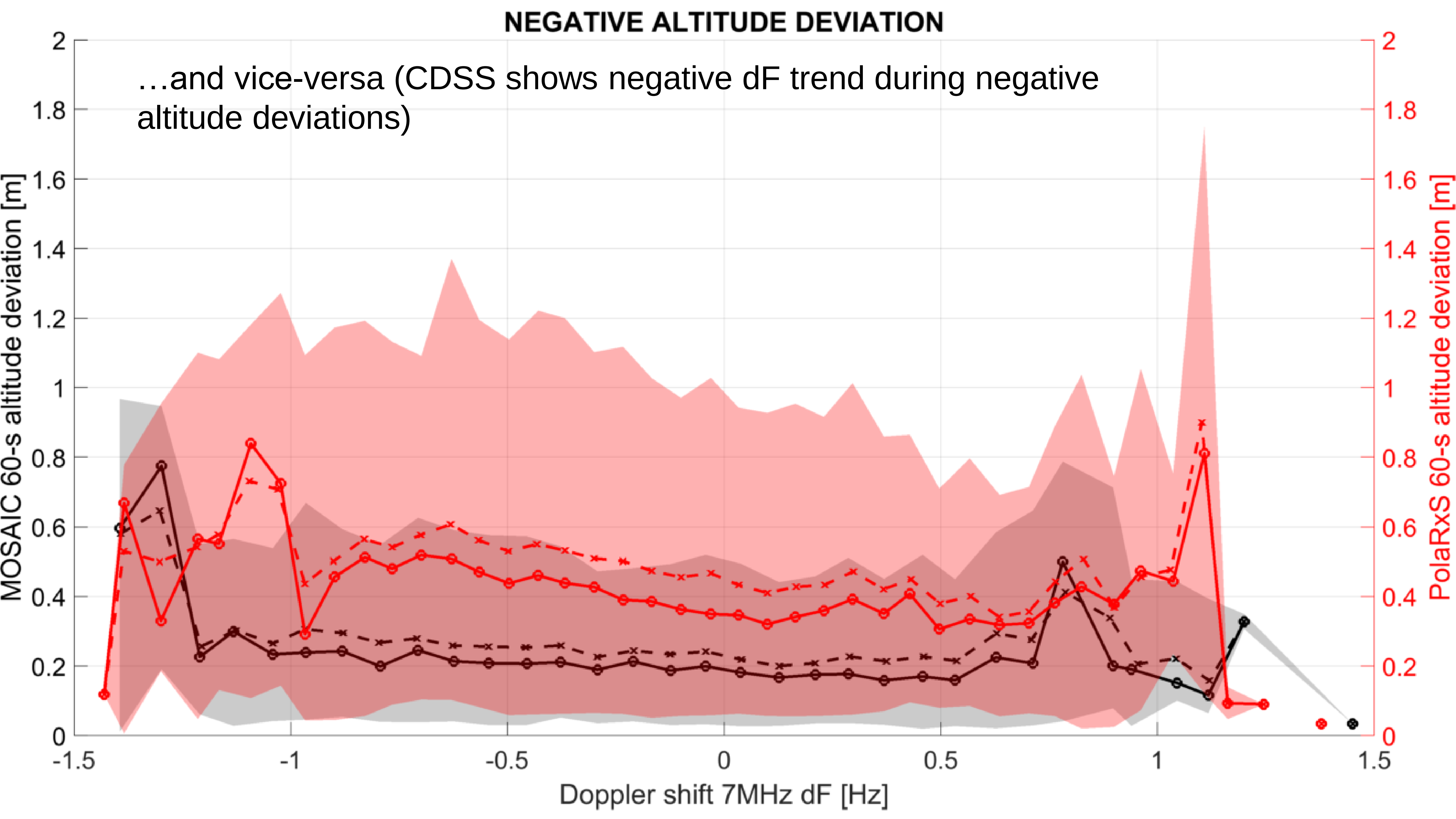


MSTIDix activity indicator (in LI [m]): generally shows effect of the MSTIDs
MOSAIC 60-s 3D position deviation [m]
PolaRxS 60-s 3D position deviation [m]
MSTID index AMPLITUDE [LI m]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
0.005
0.01
0.015
0.02
0.025
0.03
0.035


ROTI / dTEC not very helpful for indicating positioning deviations
MOSAIC 60-s 3D position deviation [m]
PolaRxS 60-s 3D position deviation [m]
average delta TEC [TECU/min]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4



POSITIVE ALTITUDE DEVIATION
HF Continuous Doppler Sounding System (CDSS) shows positive dF (trend) during positive altitude deviations…
MOSAIC 60-s altitude deviation [m]
PolaRxS 60-s altitude deviation [m]
Doppler shift 7MHz dF [Hz]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1.5
-1
-0.5
0
0.5
1
1.5



NEGATIVE ALTITUDE DEVIATION
…and vice-versa (CDSS shows negative dF trend during negative altitude deviations)
MOSAIC 60-s altitude deviation [m]
PolaRxS 60-s altitude deviation [m]
Doppler shift 7MHz dF [Hz]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1.5
-1
-0.5
0
0.5
1
1.5

Results and plans

- Positioning deviations were related to some ionospheric disturbance indicators, low-cost GNSS receiver solutions (specifically uBlox ZED-F9P) are even more prone to these effects.

- Positioning with SBAS, w/o SBAS: differences, sources of some being investigated V/HPL (m). Actual error level estimator needed for some use cases.

- HF Czech Continuous Doppler Sounding Systems (CDSS) correlates the best, having positive dF during positive altitude deviations (and vice-versa).

- The time resolution of 1 minute of ROT and the time interval of 5 minutes of ROTI allows observing ionospheric plasma irregularities with the horizontal scales of ~5 – ~15km at the mid-latitudes. (ROT-based degraded positioning indicators to be tailor-made for specific use cases, dTEC C05 - in 1Hz obtained from MOSAIC receiver using geostationary BeidouC05.)

- Planned tests of variants of Gradient ionospheric index (GIX)