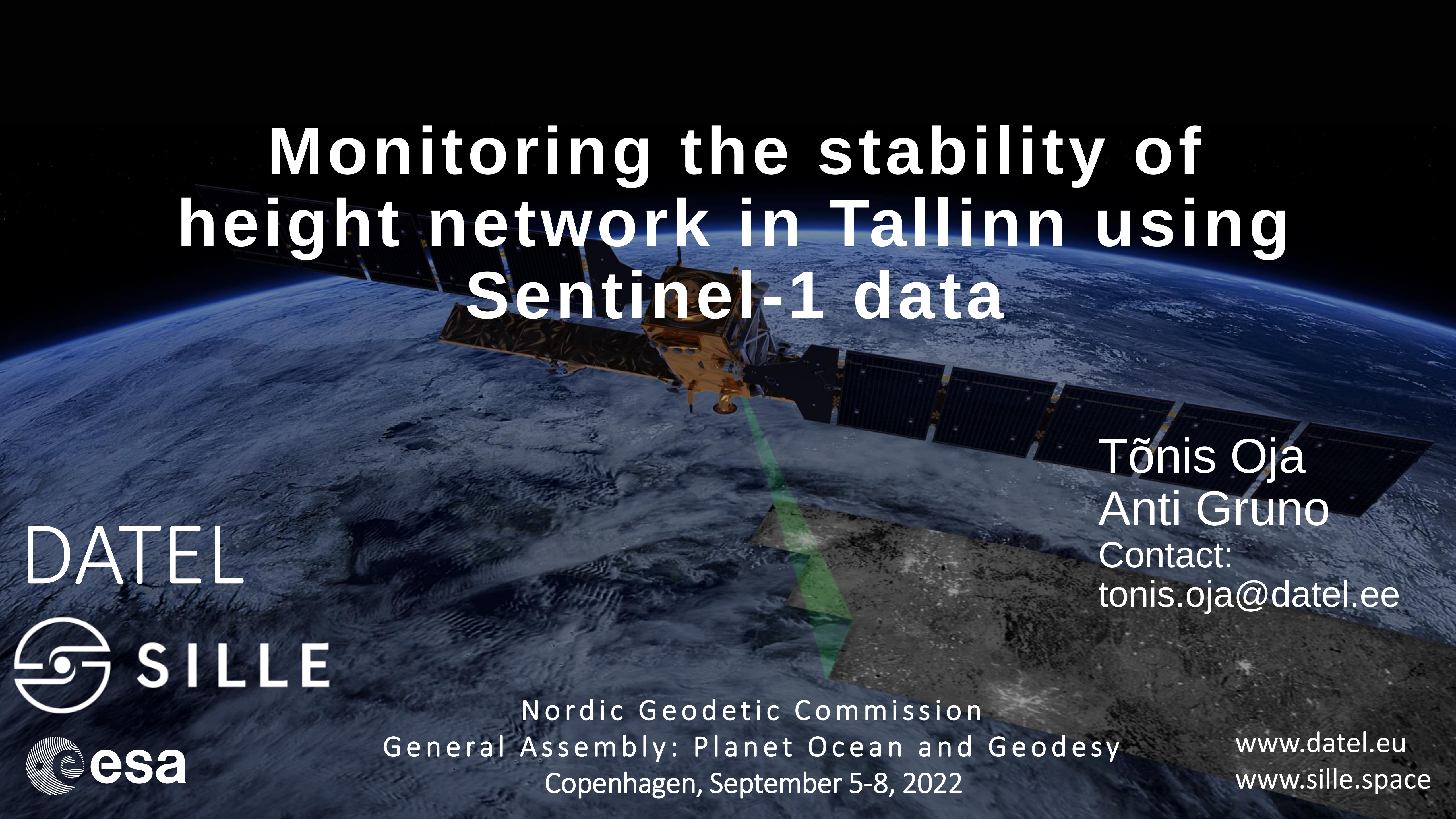


# Monitoring the stability of height network in Tallinn using Sentinel-1 data

Tõnis Oja
Anti Gruno
Contact:
tonis.oja@datel.ee

DATEL

SILLE

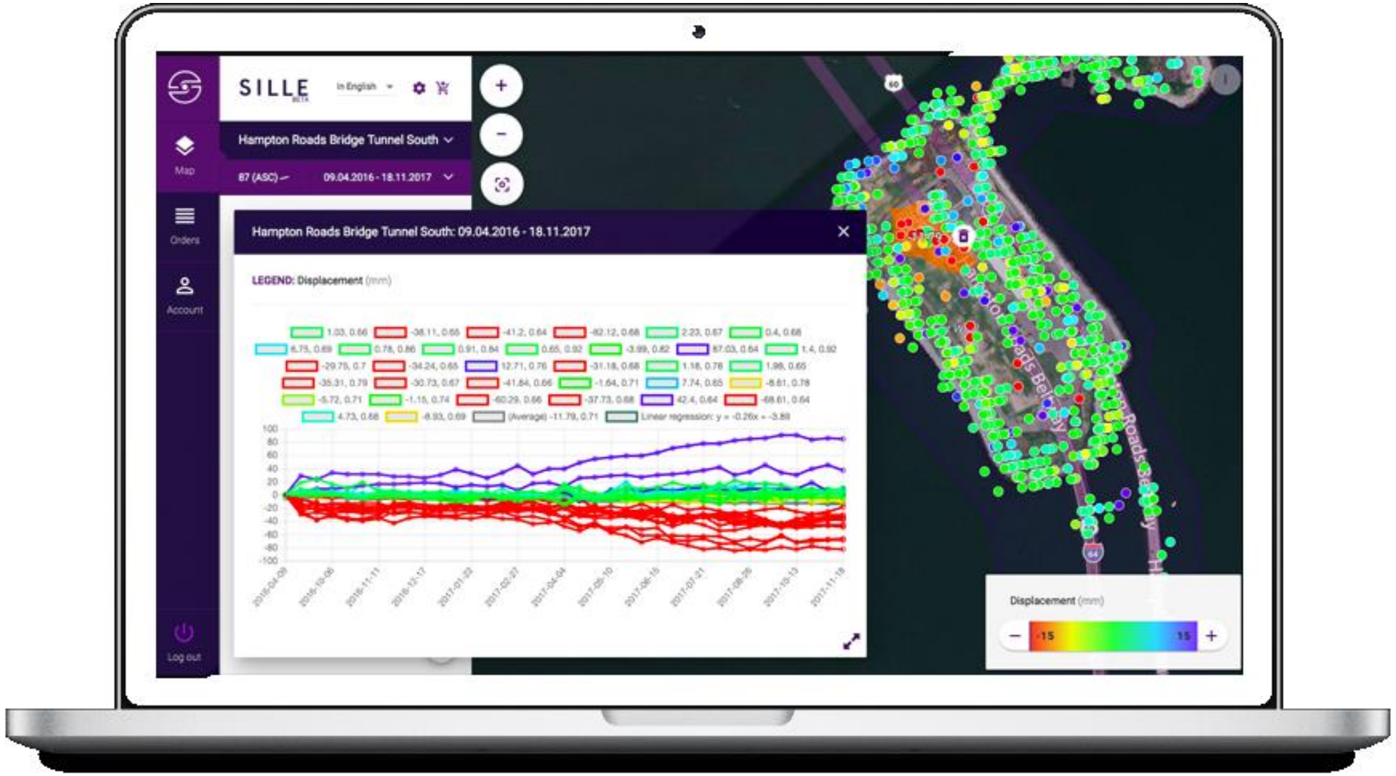
esa

Nordic Geodetic Commission
General Assembly: Planet Ocean and Geodesy
Copenhagen, September 5-8, 2022

www.datel.eu
www.sille.space

# Sille.Space – satellite-based monitoring e-service

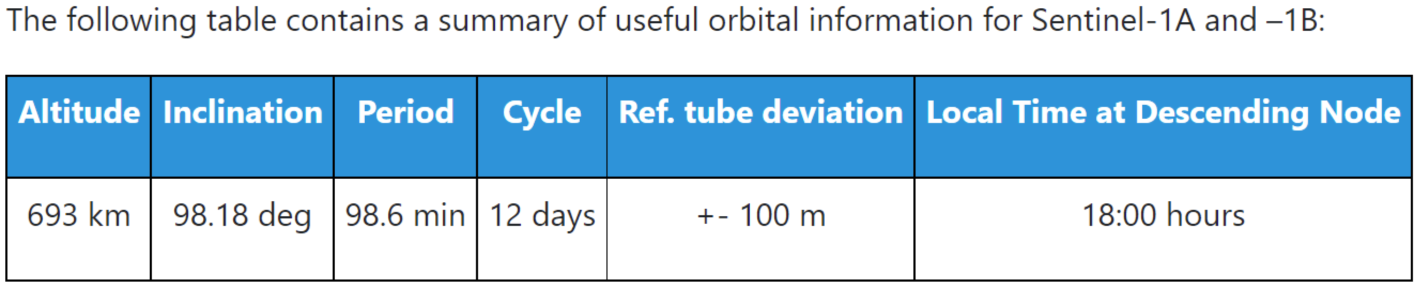
- Hazards, changes, processes and damage can be identified and monitored:
  - Infrastructure in urban areas
  - Buildings, dams
  - Mining, landslides
  - Ports, airports
  - Tunnels, railways
  - Power-/pipelines
  - Groundwater/oil extraction
  - …



www.sille.space

# Sille.Space – satellite-based monitoring e-service

- Satellite-based monitoring service:
  - Combines databases (clients, data, results), analysis tools (sarproz, GMT), map interface (MapServer), ...
  - Method: multitemporal SAR interferometry (InSAR)
  - Data: ESA Sentinel-1 C-SAR images
    - IW Mode, spatial and temporal resolution: 5x20 m, 6/12-day cycle



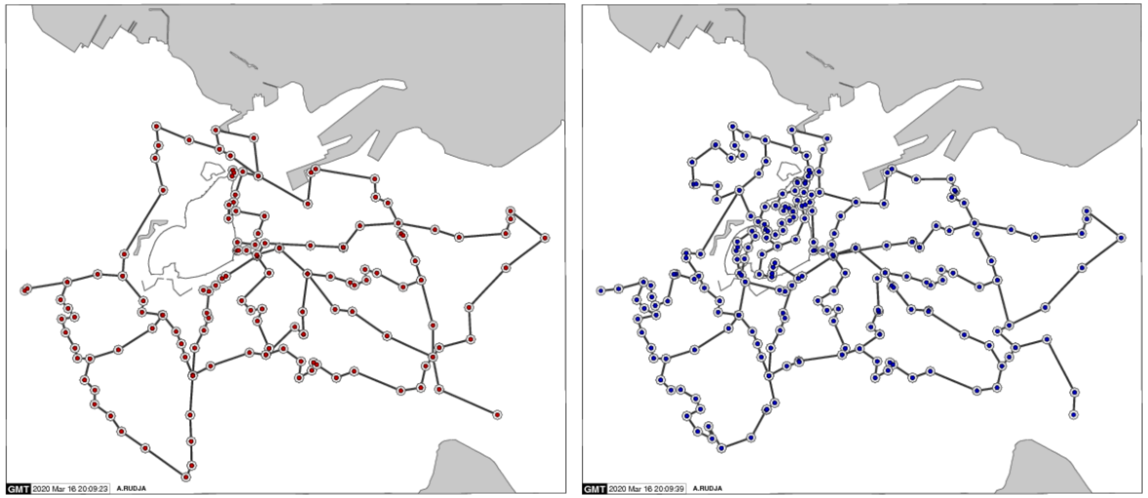
The following table contains a summary of useful orbital information for Sentinel-1A and –1B:

| Altitude | Inclination | Period | Cycle | Ref. tube deviation | Local Time at Descending Node |
|---|---|---|---|---|---|
| 693 km | 98.18 deg | 98.6 min | 12 days | +- 100 m | 18:00 hours |

*SENTINEL-1 C-SAR instrument*
sentinel.esa.int

# Study area

- The aim of InSAR analysis was to monitor the stability of benchmarks (BMs) in Tallinn city center
  - Repeated levellings of 116 BMs
    - Uncertainty of heights: $u(H_{\mathrm{lev}}) = 0.23\text{-}0.31$ mm
    - Uncertainty of velocities: $u(v_{\mathrm{lev}}) = 0.03$ mm/y



Precise leveling campaigns of the Tallinn height network undertaken in 2007/2008 and 2019

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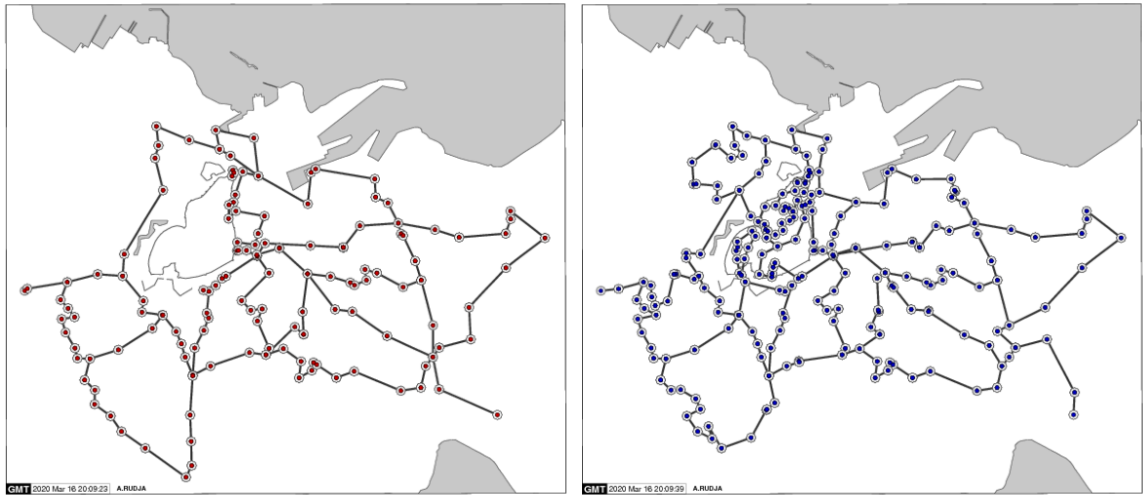
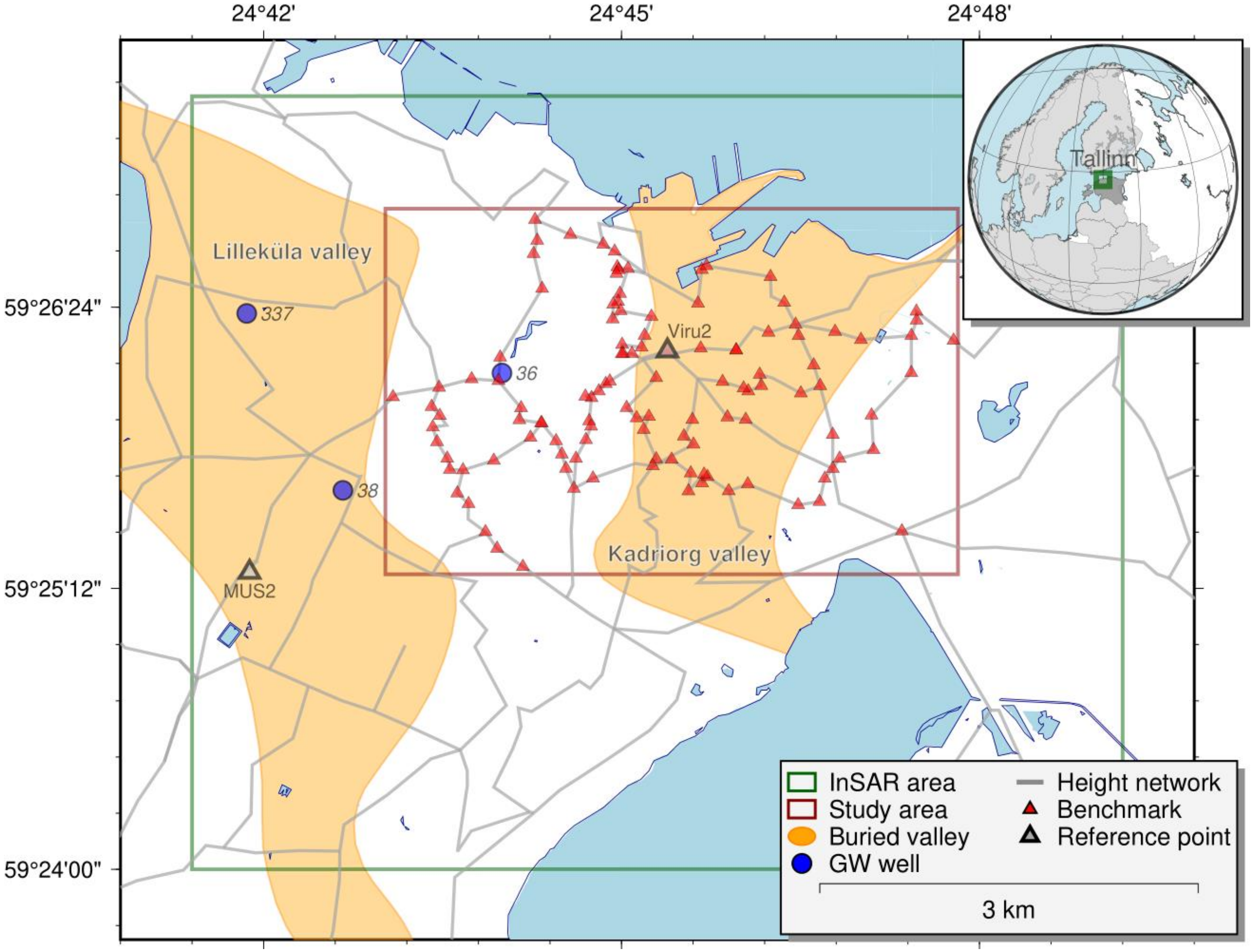


Precise leveling campaigns of the Tallinn height network undertaken in 2007/2008 and 2019



# InSAR analysis

- Sentinel-1 data + persistent scatterer interferometry (PSI)
  - Line-of-sight (LOS) velocities from ASC, DESC orbits
  - Time frame: Jun 2016 – Nov 2021 (5.4 y)
  - Velocity solutions with about 250 and 50 images for long- and short-term periods (~1 yr)
  - Filtering: ASI+sCoh. > 1.4, tCoh. > 0.7

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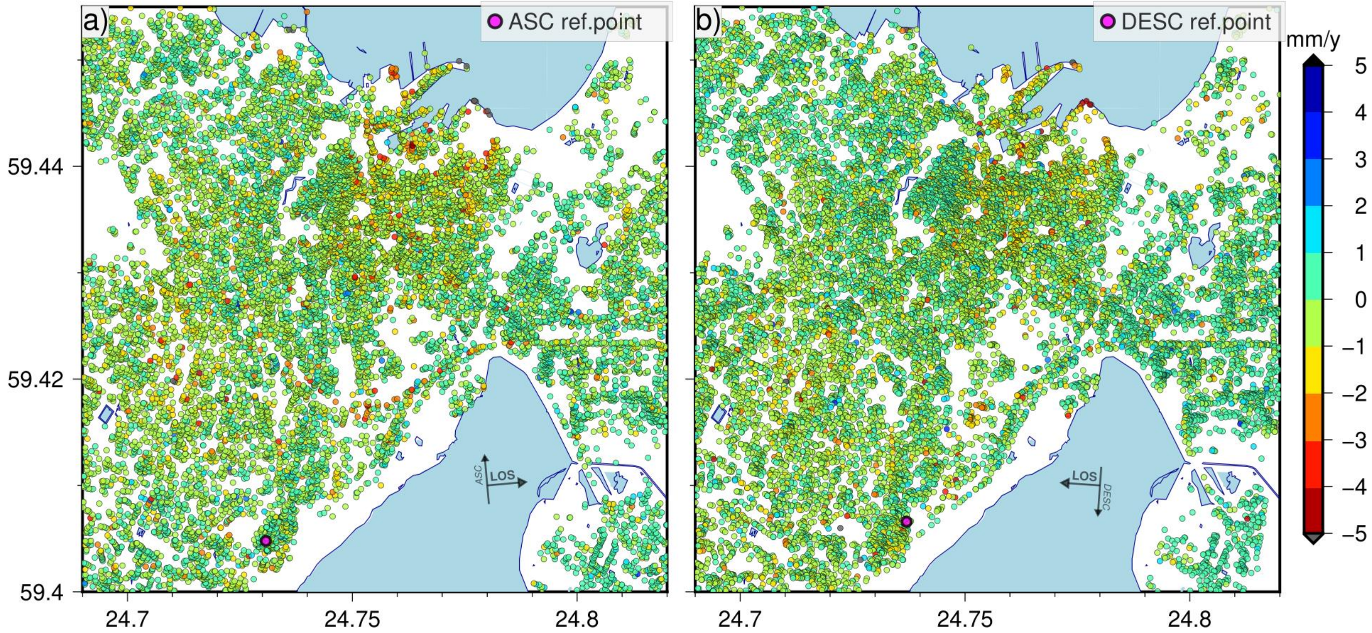

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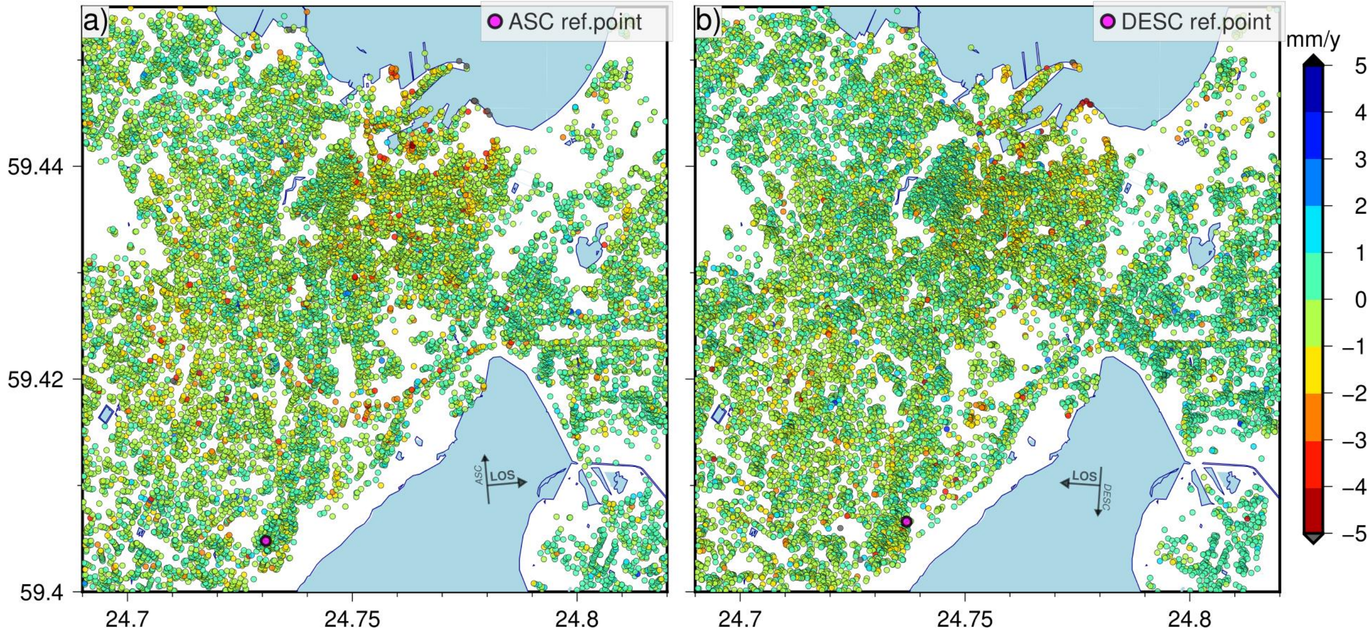


RESULTS:

LOS velocities of PS points in 2016.06 - 2021.11:

- ASC: 14452 p,
  MEAN VEL = -0.3 (min -12.7, max 3.7) mm/y
- DSC: 16305 p,
  MEAN VEL = -0.1 (min -11.2, max 4.3) mm/y

- Mean uncertainty ± 0.46 (min 0.42, max 0.87) mm/y

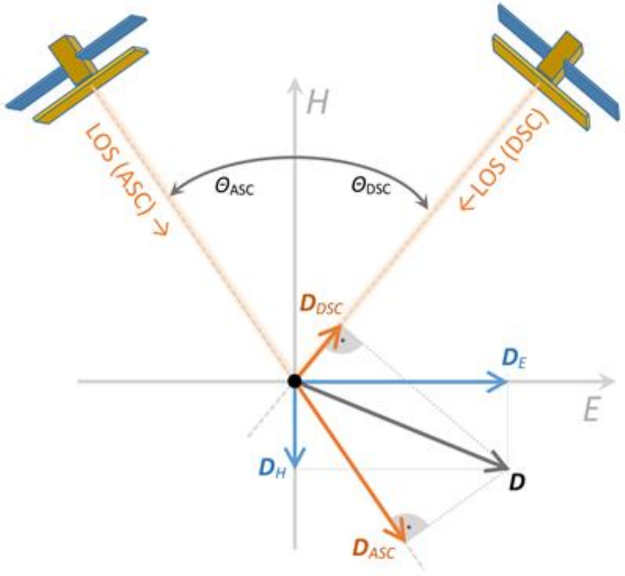
From linear regression: $\sigma^2_{\hat{\beta}_1} = \frac{SSR}{(n-2)\,S_{xx}}$

NB! Value about 5 times higher for short-term solutions

# From LOS (1D) to E, H (2D)

- Decomposition of LOS (*L*) to east-west (*E*), vertical (*H*): $s_L = s_E \sin\theta \cos\varphi + \cancel{s_N \sin\theta \sin\varphi} + s_H \cos\theta$
    - Solve linear system:

$$\begin{bmatrix} v_{L1} \\ v_{L2} \end{bmatrix} = \begin{bmatrix} \sin\theta_1 \cos\varphi_1 & \cos\theta_1 \\ \sin\theta_2 \cos\varphi_2 & \cos\theta_2 \end{bmatrix} \begin{bmatrix} v_E \\ v_H \end{bmatrix} = M \begin{bmatrix} v_E \\ v_H \end{bmatrix} \Longrightarrow \begin{bmatrix} v_E \\ v_H \end{bmatrix} = M^{-1} \begin{bmatrix} v_{L1} \\ v_{L2} \end{bmatrix}$$



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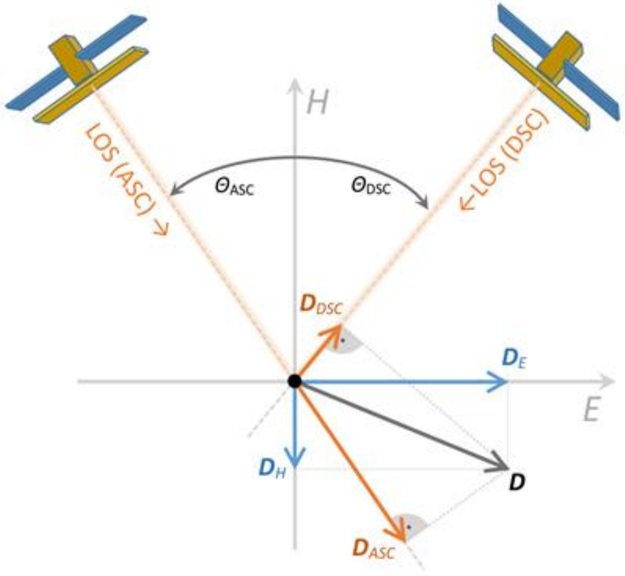
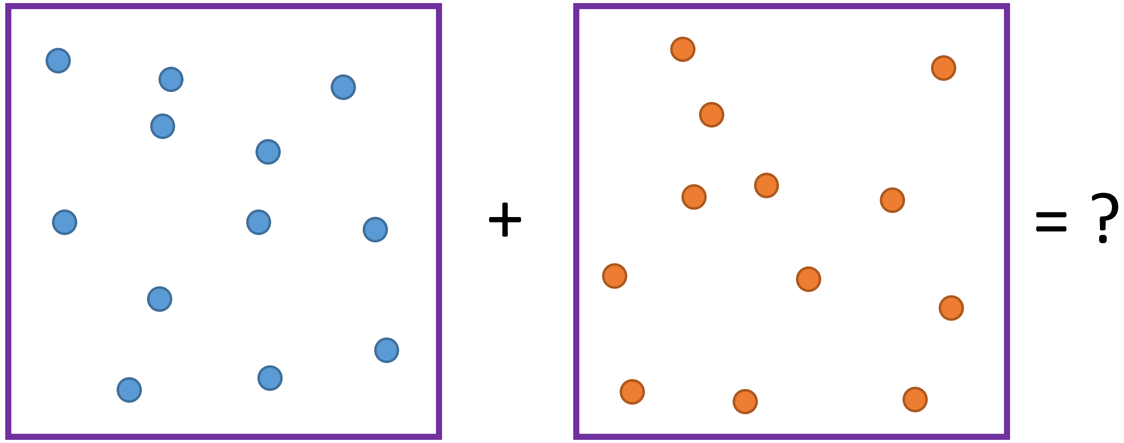


- How to combine different orbits?
  - L1 (ASC), L2 (DESC) points do not overlap spatially



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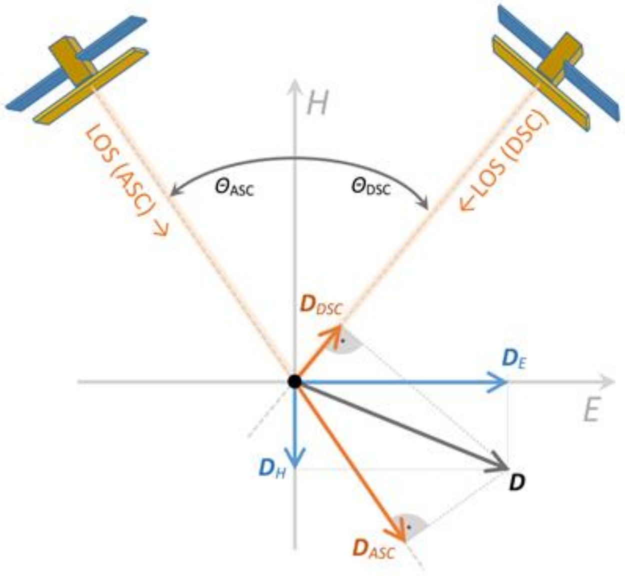
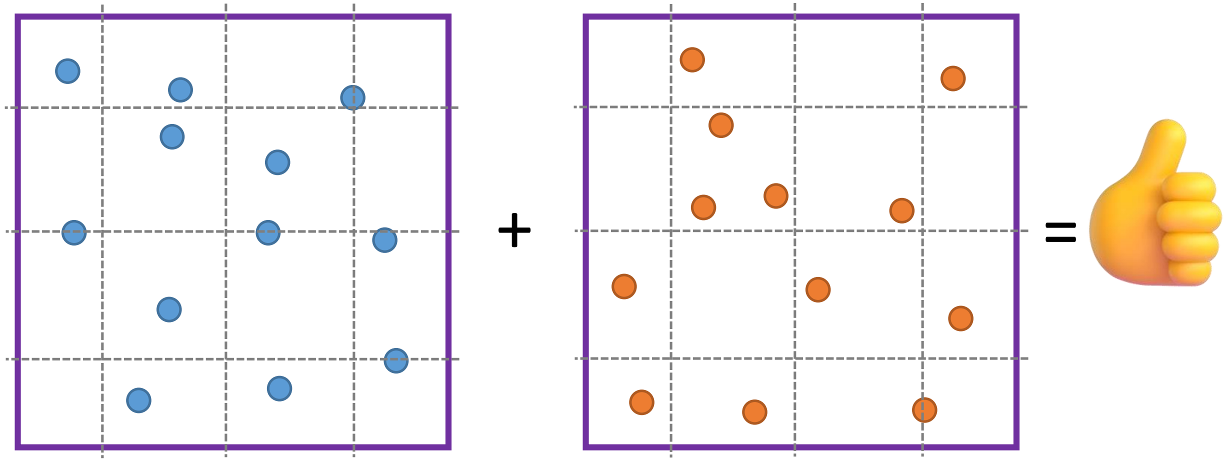


- How to combine different orbits?
  - *L*1 (ASC), *L*2 (DESC) points do not overlap spatially
  - Gridding

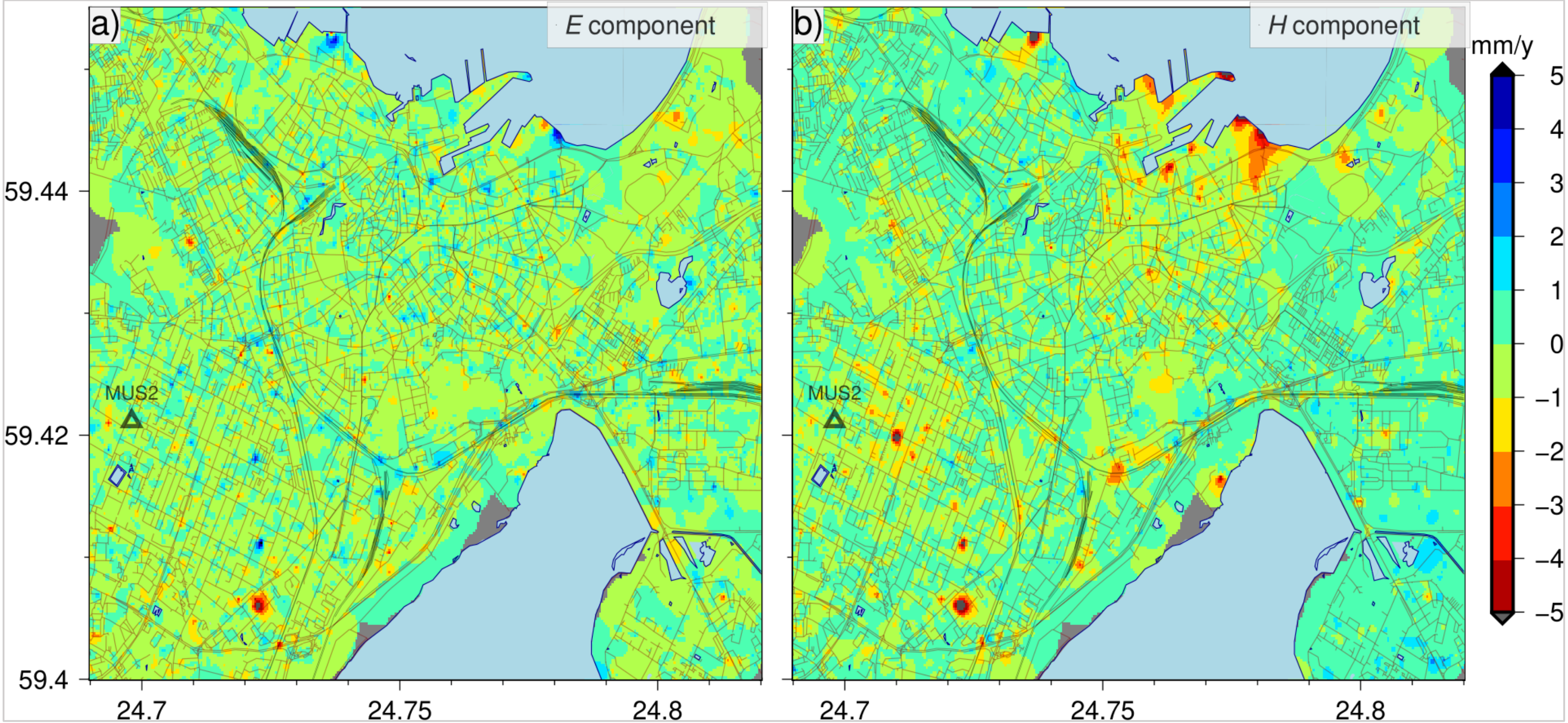


# From LOS (1D) to E, H (2D)

GMT - The Generic Mapping Tools, an open source software, https://www.generic-mapping-tools.org/

- Gridding of LOS velocity models with GMT
  - `blockmean`: dLon/dLat = 1.44”/0.72” = 0.0004°/0.0002° (~23/22 m)
  - `surface` (2D splines, T=0.3)
  - grid nodes with a distance more than 300 m from the nearest PS points were set to NaN
- *E*, *H* models with `grdmath`: $[v_\mathrm{E}\ v_\mathrm{H}]^T = M^{-1}\ [v_\mathrm{LOS1}\ v_\mathrm{LOS2}]$
- Variance grids: $[D(v_\mathrm{E})\ D(v_\mathrm{H})]^T = M^{-1}\ [D(v_\mathrm{LOS1})\ D(v_\mathrm{LOS2})]^T\ (M^{-1})^T$
- Reference for *E*, *H* models: $v_{2D}$ = 0.0 mm/y at pGNSS “MUS2”
  - VEL (2012.3 – 2021.9, dT = 9.6 a) in IGS14 (from http://geodesy.unr.edu/NGLStationPages/stations/MUS2.sta): $v_E$ = –0.17 ± 0.19 mm/y and **$v_H$ = 3.14 ± 0.79** mm/y

# Long term solution



**Velocity solutions** for east-west (*E*) and vertical (*H*) components (2016-2021) decomposed from the LOS velocities. The solutions have been fixed at the location of “MUS2” permanent GNSS station

# Long term *E*, *H* solutions

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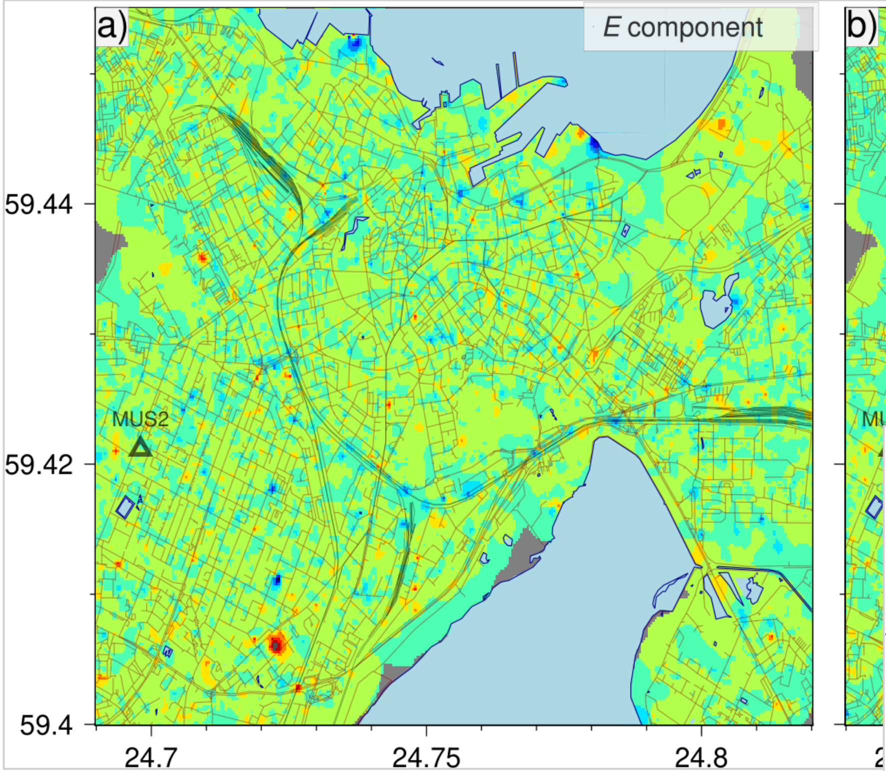

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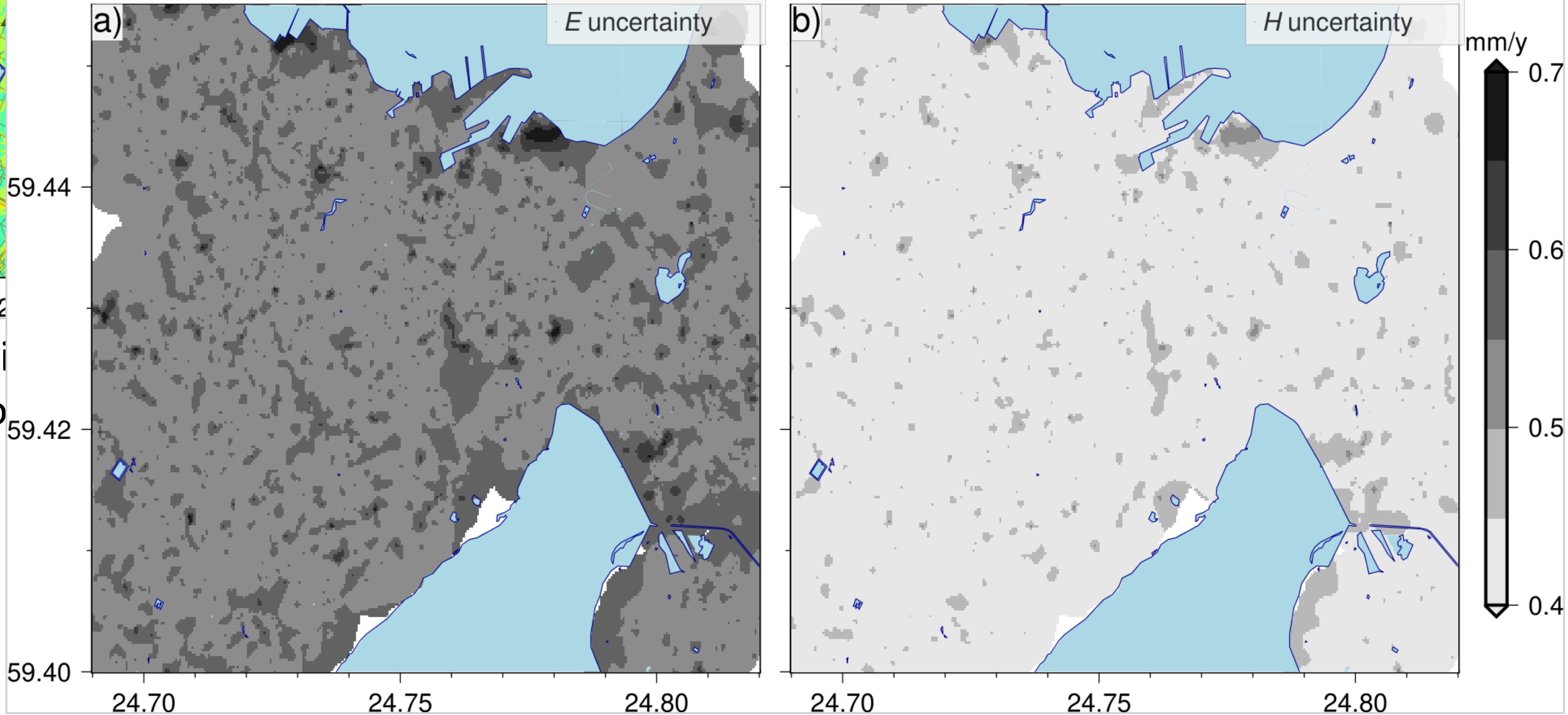
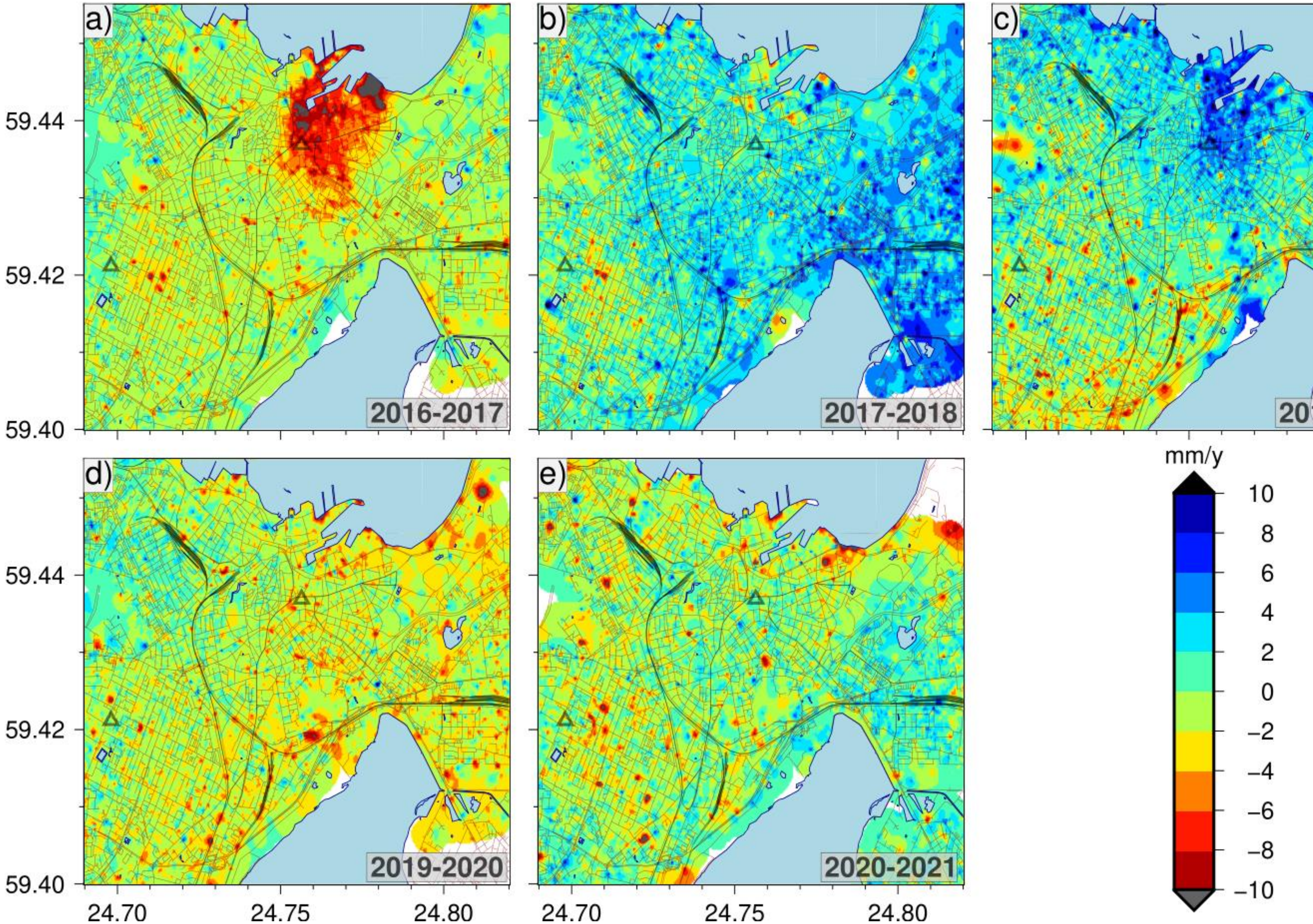


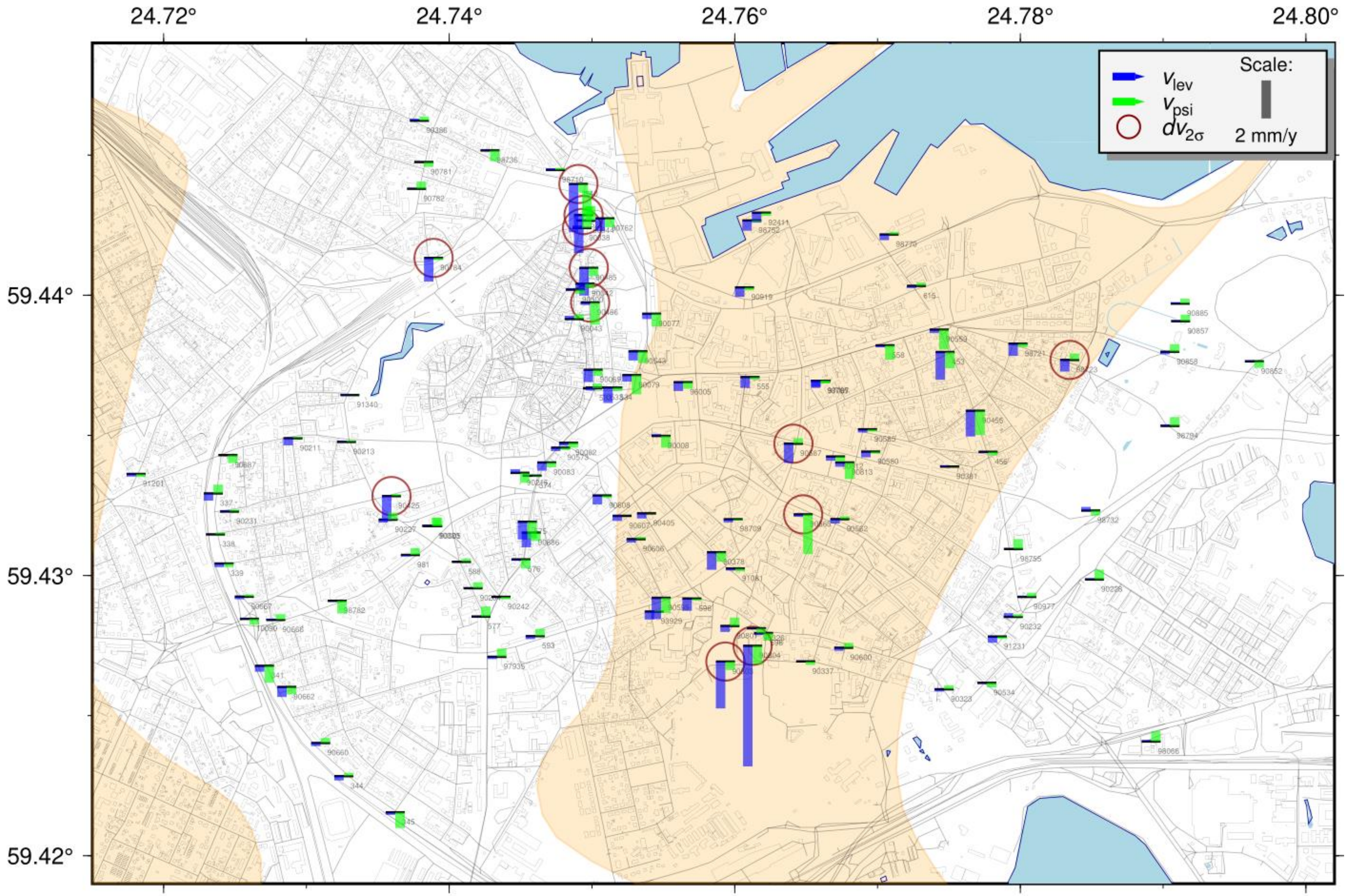
**Uncertainty grids** of *E*, *H*
velocity solutions (2016-2021)

# Short term *H* solutions



A series of vertical velocity models from yearly InSAR analyses to monitor short-term deformation changes in Tallinn city center

# Comparison 1



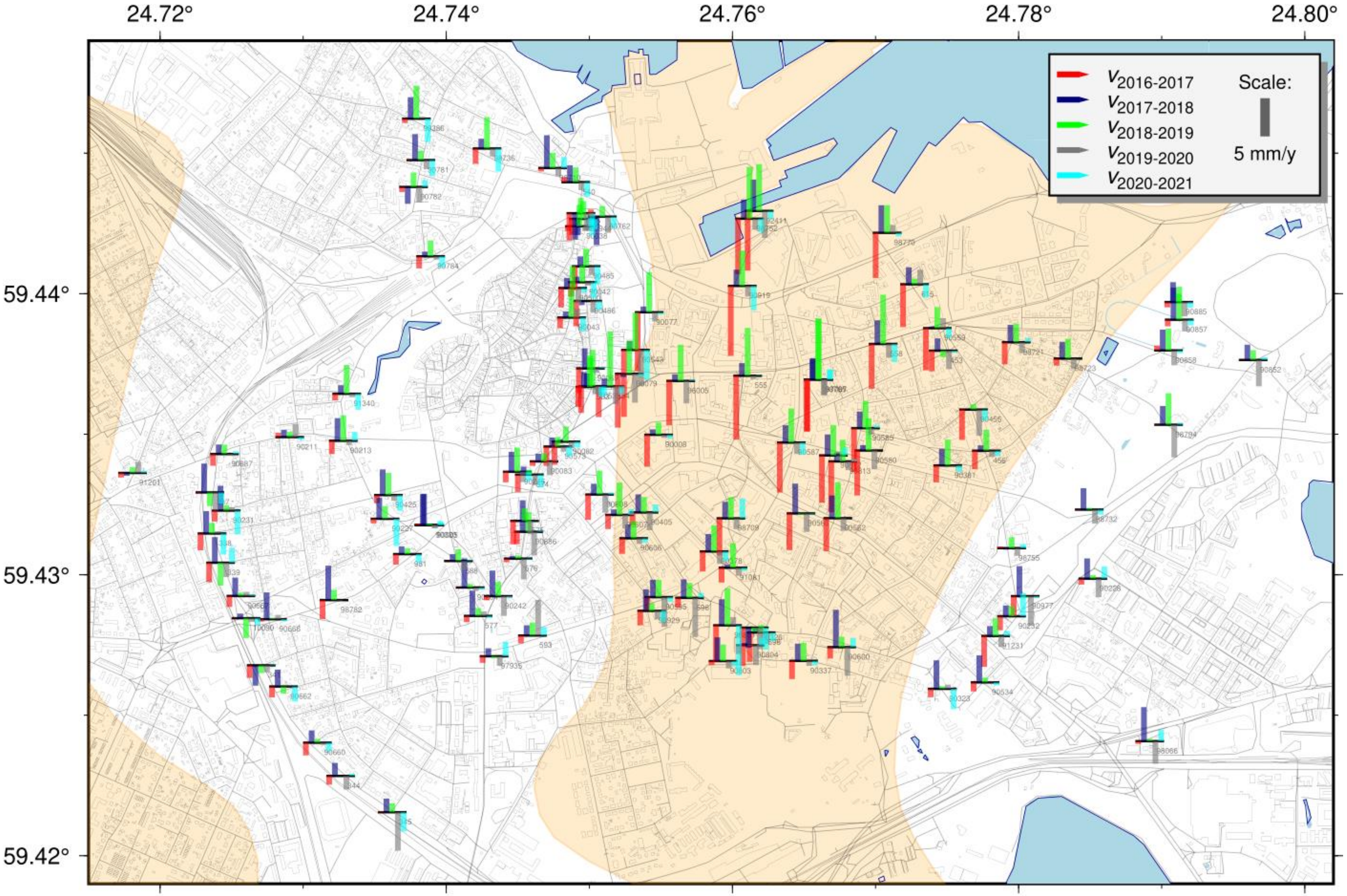
The comparison of the leveled (2007-2019) and InSAR velocities (2016-2021) at 116 BMs of the Tallinn height network

Testing statistical significance of differences **d*v*** = $v_{lev} - v_{psi}$ between leveled and InSAR velocities:

O – significant **d*v*** at 12 BMs (10%)

Mean uncertainty (2σ):
$u(v_{lev})$ = 0.06 mm/y
$u(v_{psi})$ = 0.84 mm/y
***u*(d*v*) = ± 0.84 mm/y**

# Comparison 2

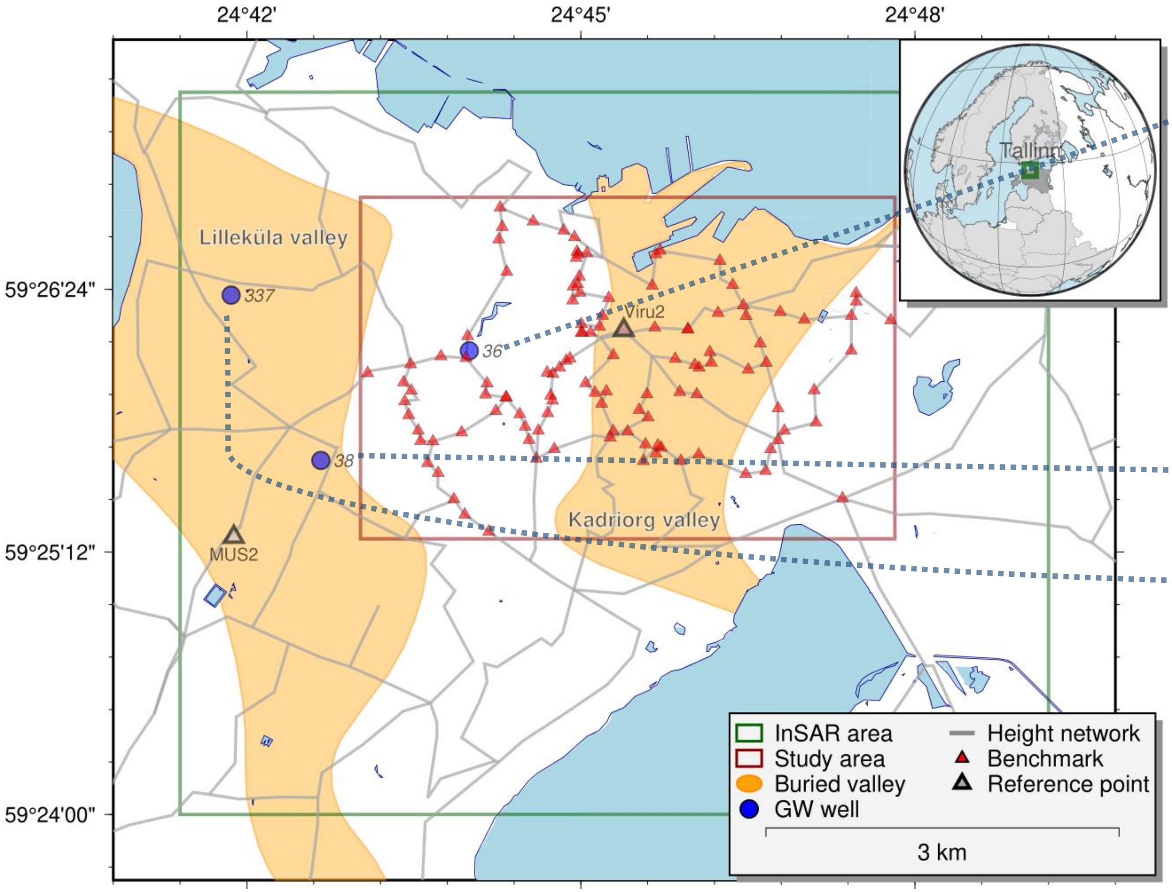


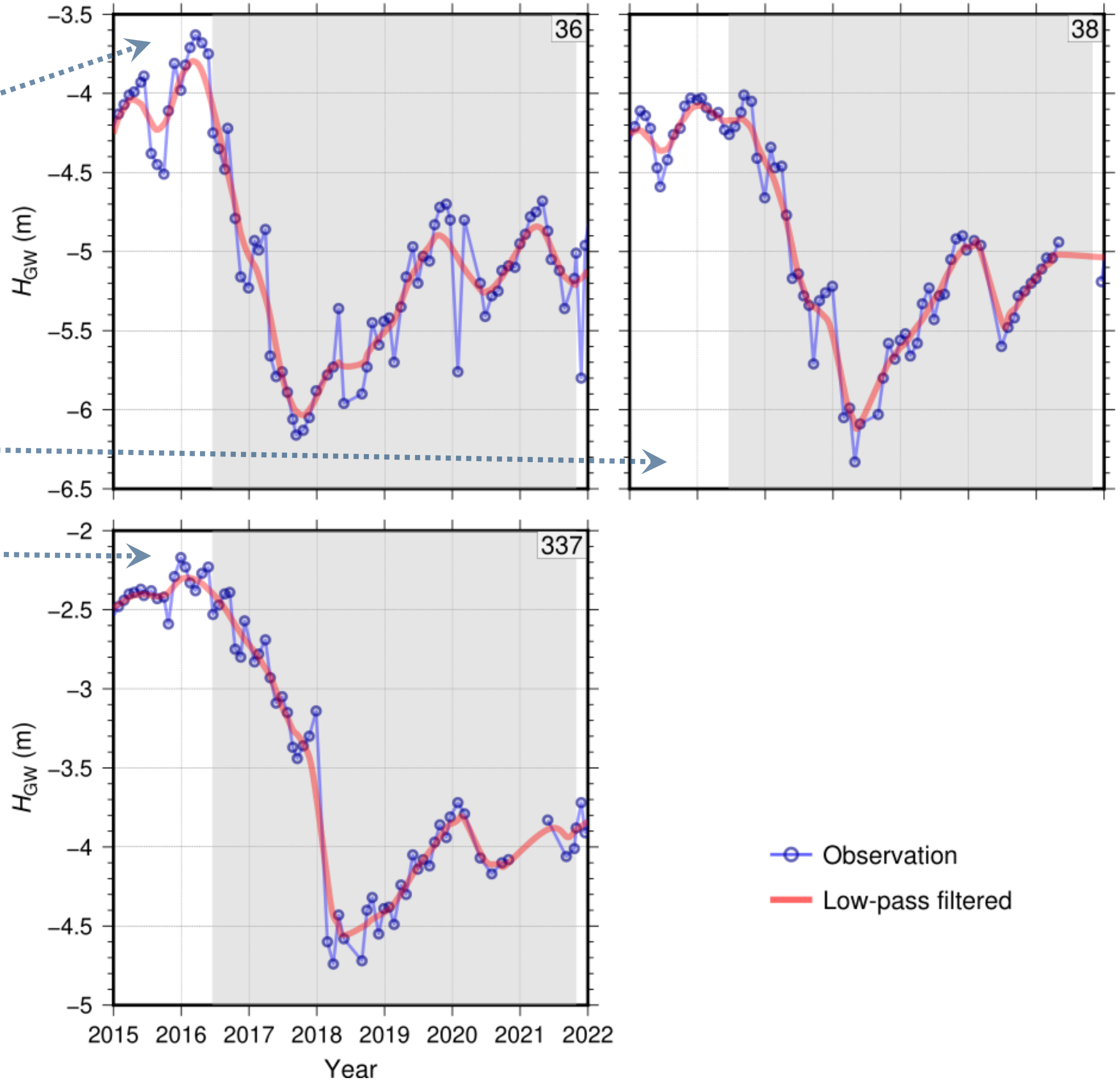
Velocities from yearly InSAR solutions at the benchmarks of Tallinn height network

# The source of nonlinear VLM

- Important to understand these findings to evaluate InSAR results
- Historical studies based on repeated leveling:
  - Maps of vertical land movement (VLM) compiled by Zhelnin (1958), Lutsar (1965), Vallner and Lutsar (1966), Kall and Torim (2003)
    - The sinking of the Tallinn city center was noticed in 1951
    - In 1960s, the highest subsidence rates up to 30 mm/year were observed
    - From 1964 onwards, the sinking rate decreasing, the leveling repeated within 1986-2000 showed that sinking stopped or reversed into rising
  - A correlation has been found between the leveling results, the geological structure and **groundwater level changes**
    - Largest VLM rates over **the ancient valleys buried under quaternary sediments**

# Groundwater level in Tallinn

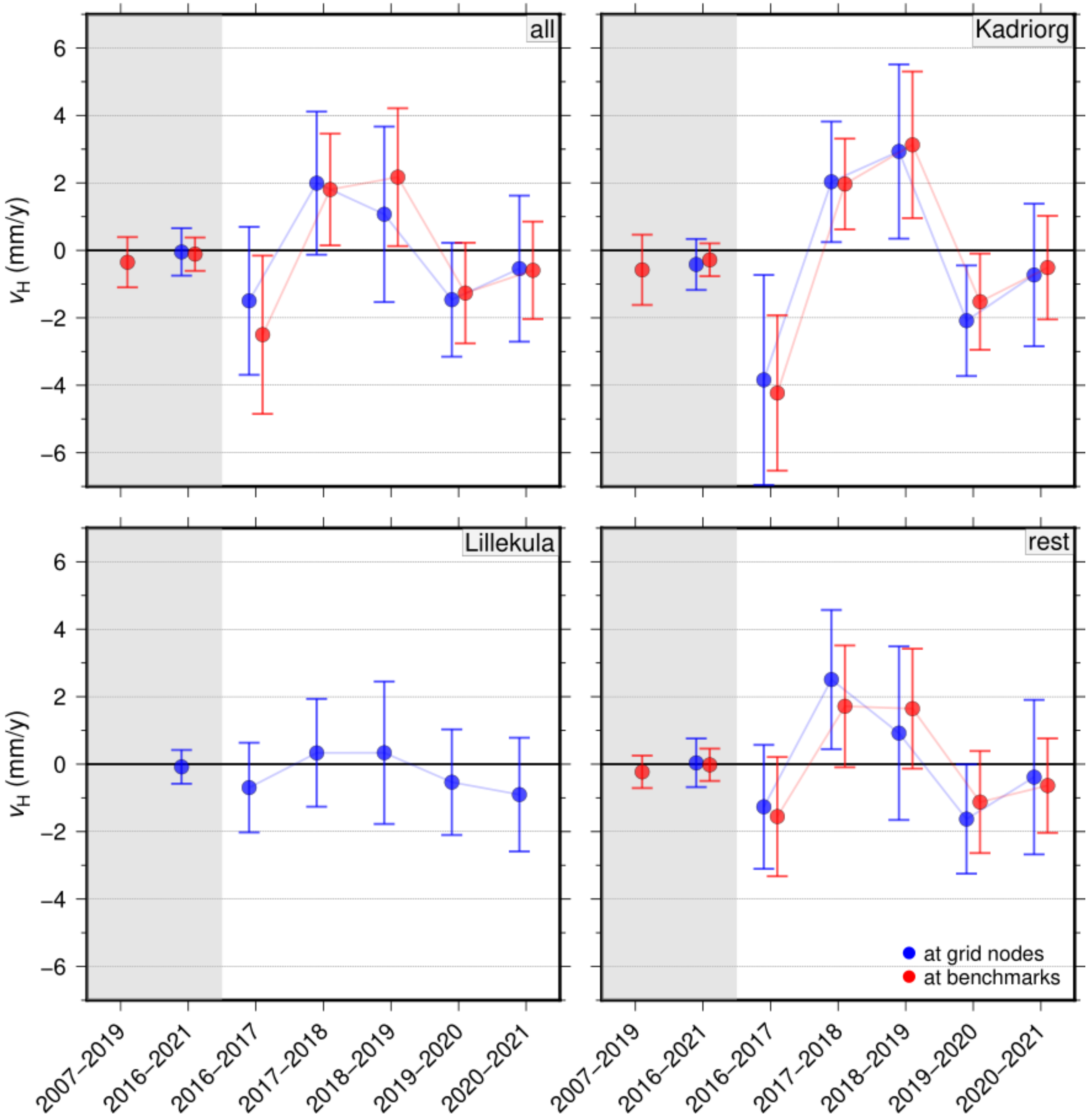




Groundwater level variations in Tallinn in 2015-2022 (KESE 2022). For smoothing a Gaussian filter with 1 yr long window length was used. The gray area presents the time period covered by the InSAR measurements.

# Statistics over different areas

- Mean value with standard deviation (represented by error bars) was estimated over
  - The nodes of InSAR vertical velocity grids (blue)
  - The leveled and InSAR derived velocities at the benchmarks (red)
- The gray background separates long-term solutions (leveling, InSAR) from yearly solutions (InSAR)
- The statistics were estimated for all study area (all), Kadriorg and Lilleküla buried valleys, and the rest (valleys excluded)



# Conclusions

- InSAR is suitable to monitor the stability (and accuracy) of geodetic infrastructure
  - Long-term InSAR results were consistent with repeated leveling
  - Differences not significant at 104 BMs (90%)

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  - Q: The effect on the city environment and infrastructure of Tallinn?

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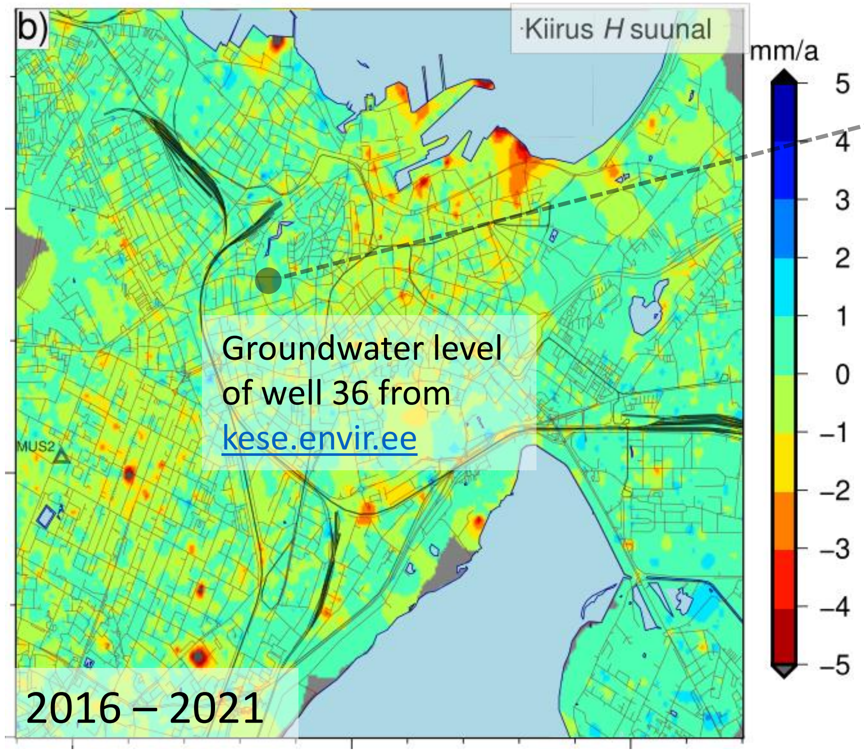
  - Q: The effect on the city environment and infrastructure of Tallinn?
- A: New InSAR analysis complemented with terrestrial geodetic measurements, rigorous hydrogeological modeling and additional geological, hydrological data would be a useful tool to model processes and predict the land motion in Tallinn
- Paper submitted:
  - Oja, T., and Gruno, A. (2022) Monitoring of millimeter-scale deformations in Tallinn using repeated leveling and PS-InSAR analysis of Sentinel-1 data. Advances in Geodesy and Geoinformation

# Thank you for your attention!
# Questions?

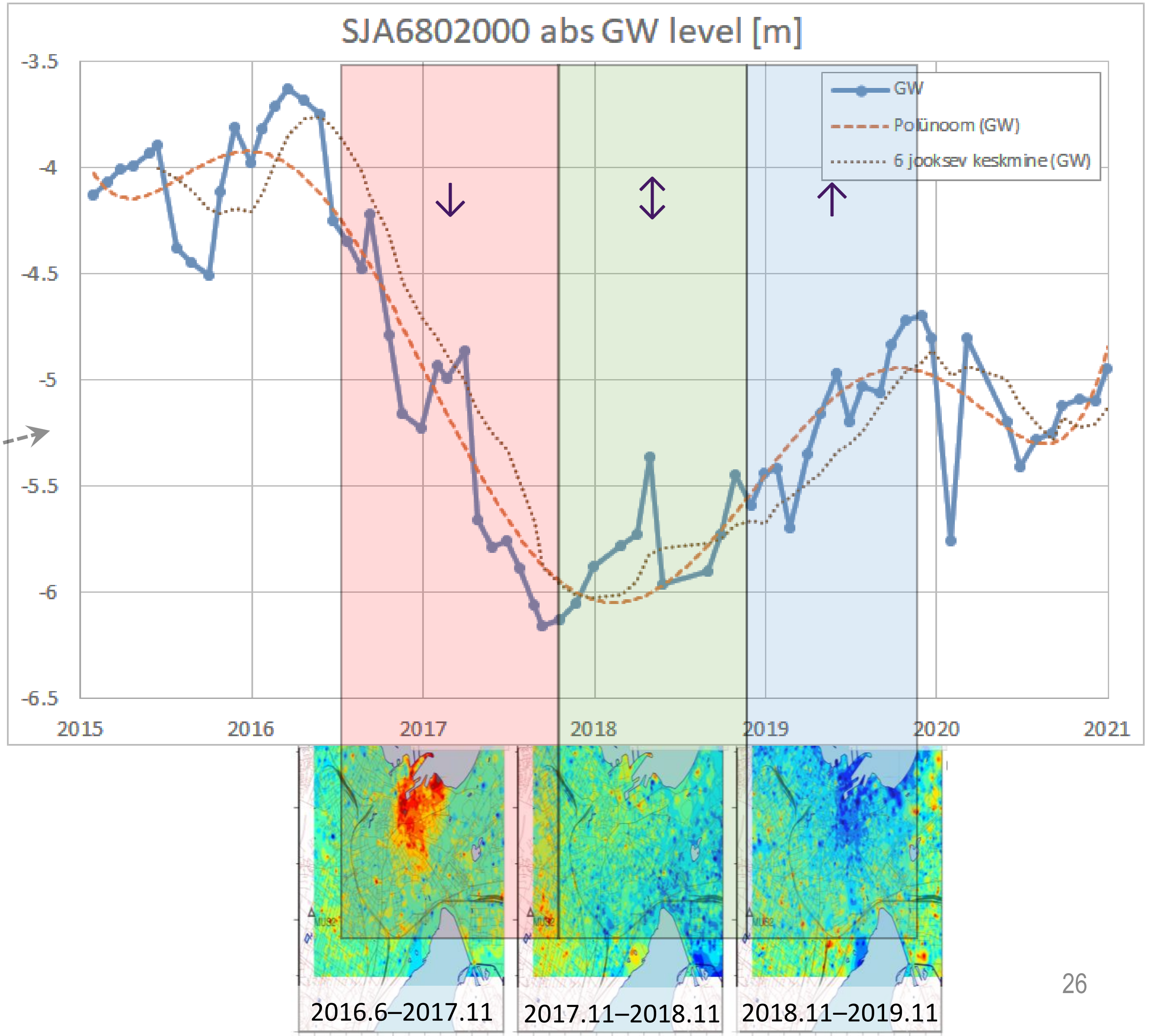
**Tonis.Oja@datel.ee**
**Anti.Gruno@datel.ee**

# Groundwater level in Tallinn (2)

- Possible sources
  - Geology (buried valleys, bedrock escarpments)
  - Hydrology (groundwater level variations)



Groundwater level of well 36 from [kese.envir.ee](kese.envir.ee)



2016.6–2017.11

2017.11–2018.11

2018.11–2019.11

# Buried valleys in Tallinn

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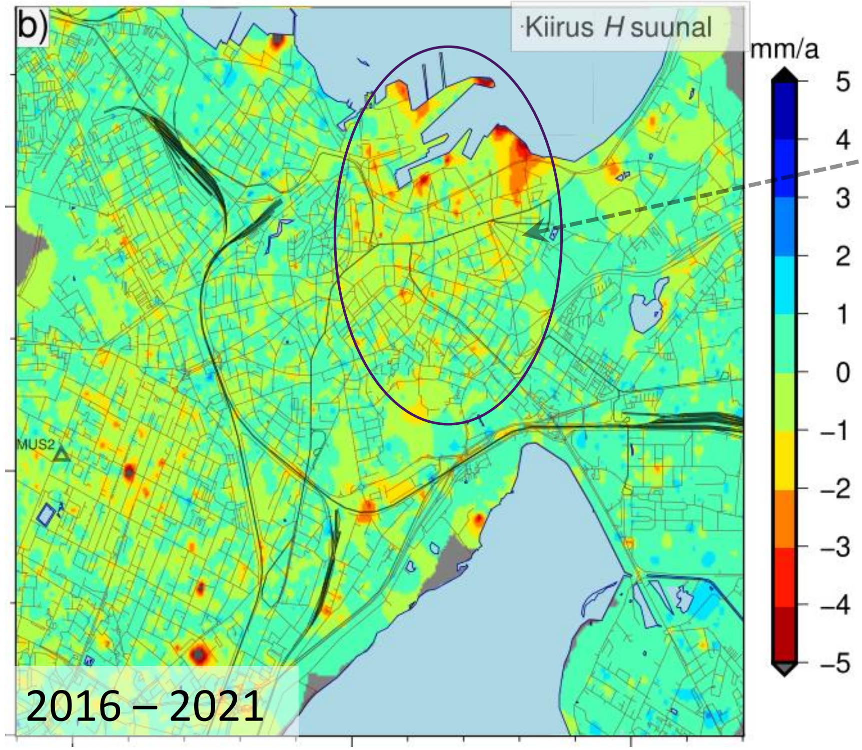
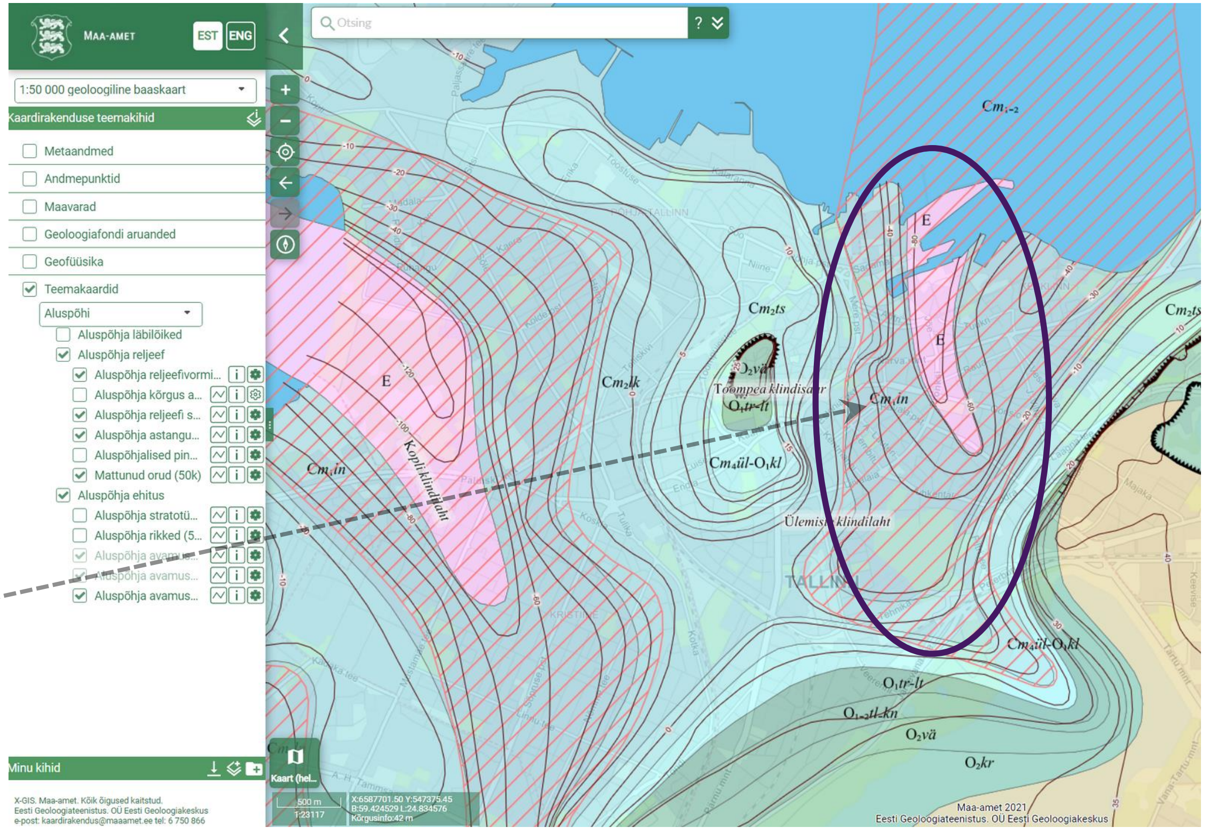


2016 – 2021



1:50 000 geoloogiline baaskaart

Kaardirakenduse teemakihid

- ☐ Metaandmed
- ☐ Andmepunktid
- ☐ Maavarad
- ☐ Geoloogiafondi aruanded
- ☐ Geofüüsika
- ☑ Teemakaardid
  - Aluspõhi
    - ☐ Aluspõhja läbilõiked
    - ☑ Aluspõhja reljeef
      - ☑ Aluspõhja reljeefivormi...
      - ☐ Aluspõhja kõrgus a...
      - ☑ Aluspõhja reljeefi s...
      - ☑ Aluspõhja astangu...
      - ☐ Aluspõhjalised pin...
      - ☑ Mattunud orud (50k)
    - ☑ Aluspõhja ehitus
      - ☐ Aluspõhja stratotü...
      - ☐ Aluspõhja rikked (5...
      - ☑ Aluspõhja avamus...
      - ☑ Aluspõhja avamus...
      - ☑ Aluspõhja avamus...

Minu kihid

X-GIS. Maa-amet. Kõik õigused kaitstud.
Eesti Geoloogiateenistus. OÜ Eesti Geoloogiakeskus
e-post: kaardirakendus@maaamet.ee tel: 6 750 866

X:6587701.50 Y:547375.45
B:59.424529 L:24.834576
Kõrgusinfo:42 m

Maa-amet 2021
Eesti Geoloogiateenistus. OÜ Eesti Geoloogiakeskus

Geological base map 1:50000
Estonian Land Board 2021
[geoportaal.maaamet.ee](geoportaal.maaamet.ee)