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NKG2020 transformation

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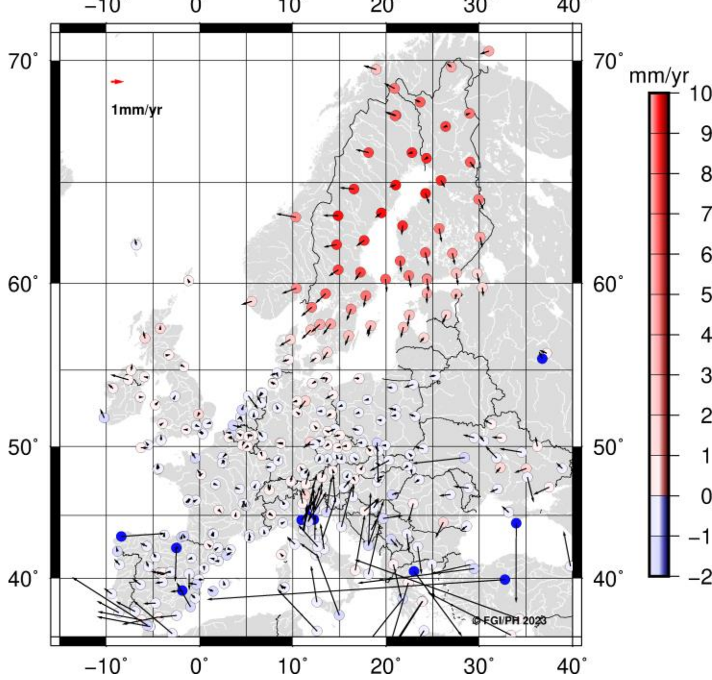
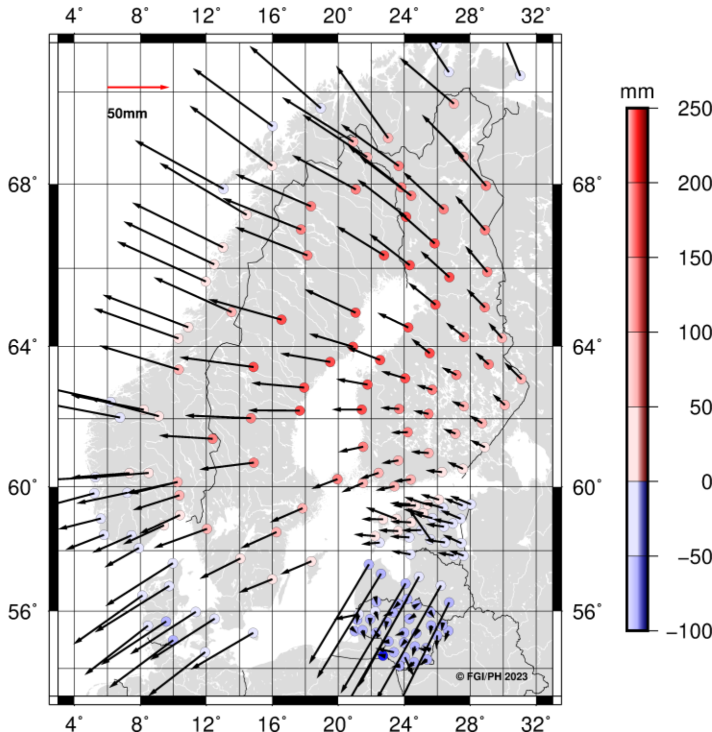
Background

- Glacial Isostatic Adjustment (GIA) causes intraplate deformations in the Nordic and Baltic countries
  - Up to 1cm/yr in vertical and a few mm/yr in horizontal (see ETRF2014 velocities from EPN_ETRF2014_C2235 in the top figure)
- ETRS89 as a plate-fixed frame minimizes time-variability of coordinates via standardized EUREF transformation
  - It considers only the rigid Eurasian plate motion but not any intra- or interplate deformations → residuals may reach a few dm (see ITRF2014@2023.0 -> Nat. ETRFyy in the bottom figure)
  - Intraplate corrections not recommended (based on ETRS89 definition) but recognized necessary for some cases
- GIA has been one of the most important study subjects for the Nordic Geodetic Commission (NKG), e.g.:
  - Several land uplift models and NKG transformation approach



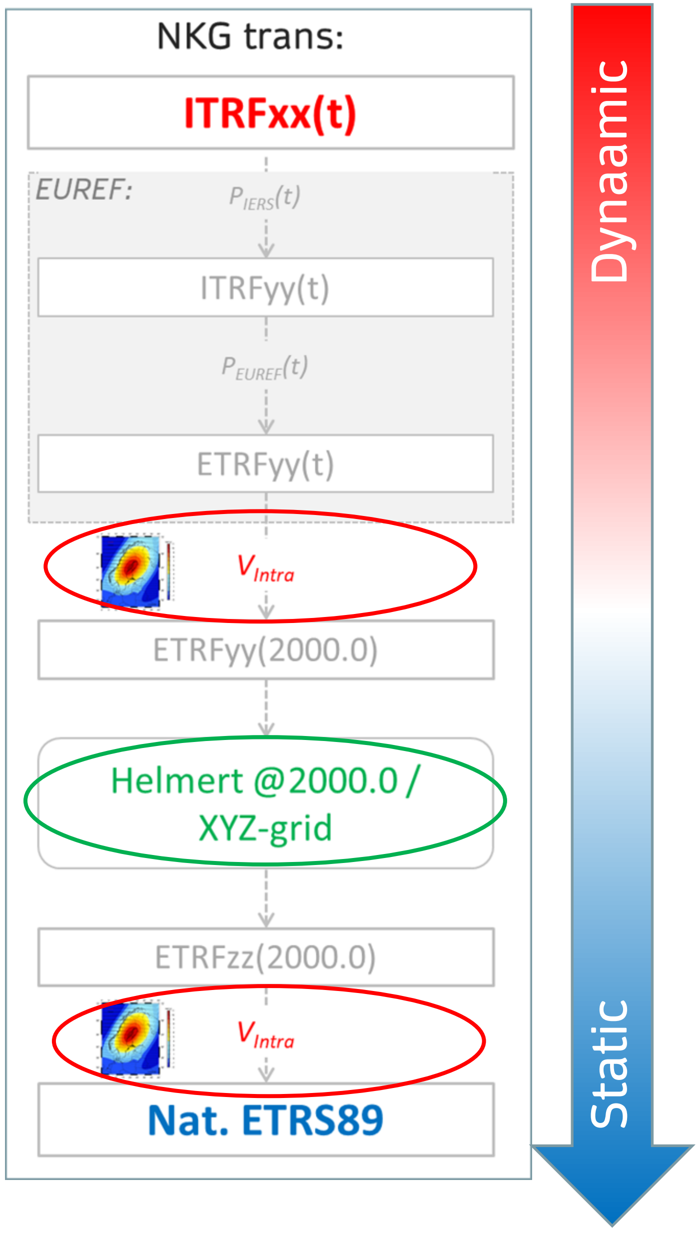


NKG transformation

- **Storing of geodata**: national, static reference frame (Nordic-Baltic region: ETRS89 realizations)
- **Positioning (coordinates)**: most accurate, global, dynamic reference frame (ITRFyy)
- **Transformation** considers crustal motions between these two reference frames (”two-frame approach”, ”semi-dynamic RF”):
  - Basis: EUREF transformation
  - Deformation model: intraplate corrections
  - National transformation parameters: differences btw pan-European and national realizations

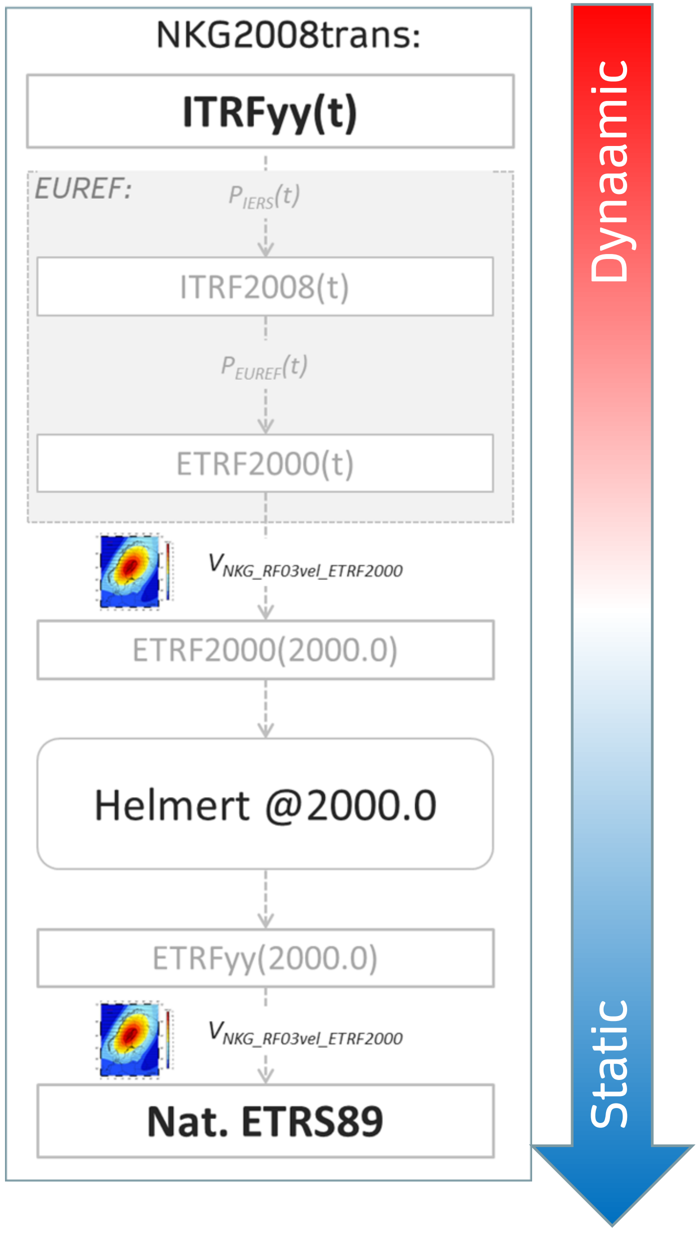
→ **Accurate link between global (ITRFyy) and Nordic-Baltic (ETRFyy) reference frames**

- E.g. for reference frame maintenance and monitoring
- Released versions: NKG2008, **NKG2020**



NKG2008 transformation

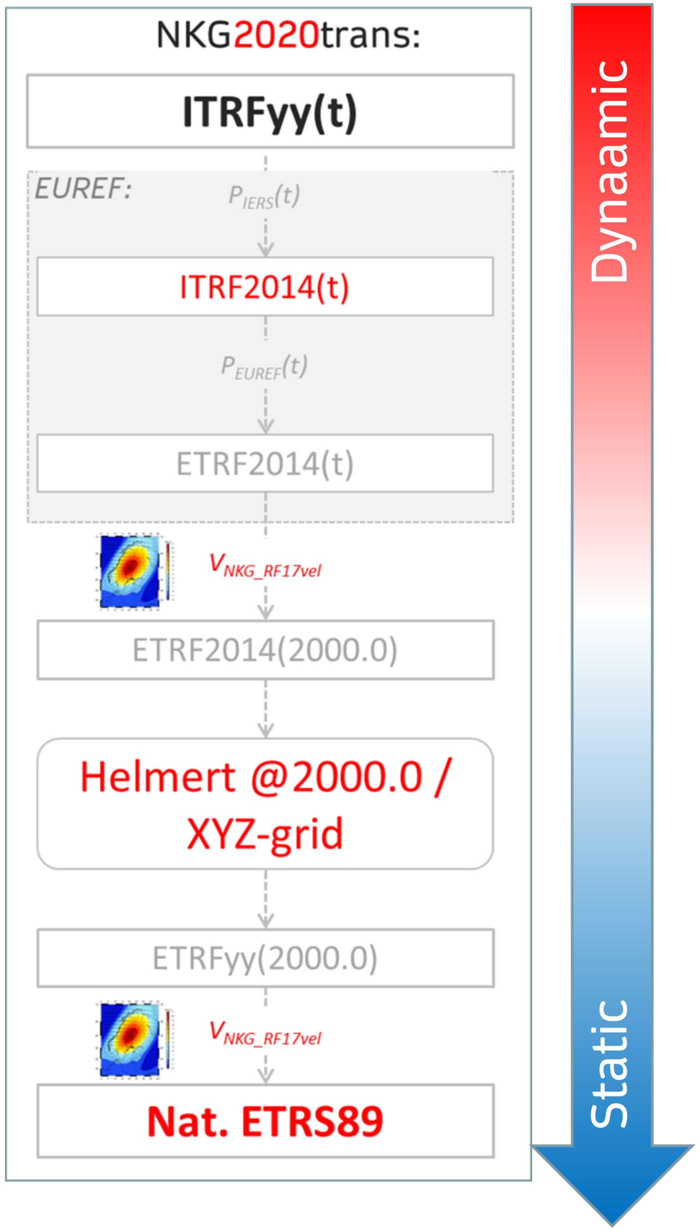
- Released in 2016
  - https://doi.org/10.1515/jogs-2016-0001



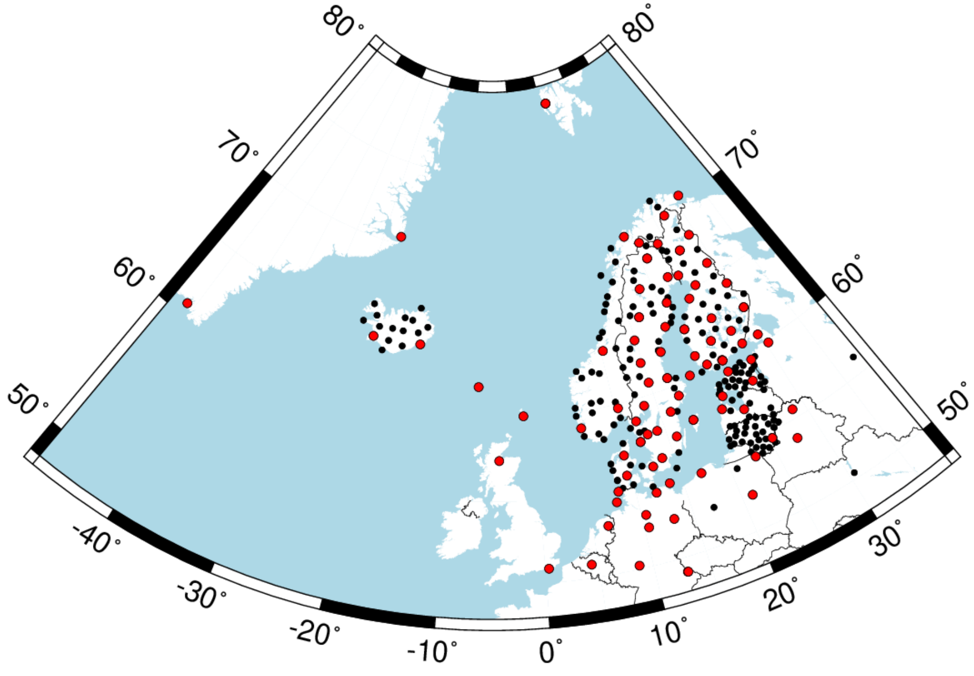
NKG2020 transformation

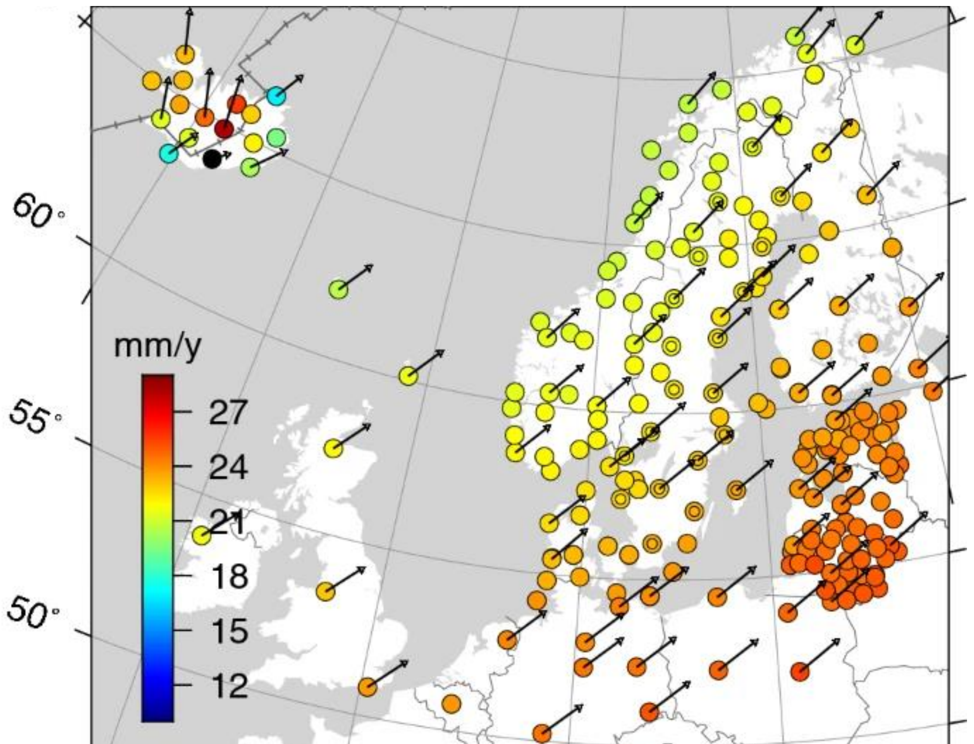
- Released in 2021
  - Uncertainty estimates and documentation in 2023
- Same methodology but all data updated:
  - ITRFyy coordinates: ITRF2014(2015.0) from **NKG Repro1**
  - National ETRFyy coordinates: revised and even some updated realizations
  - Deformation model: **NKG_RF17vel**
  - National transformations:
    - New Helmert parameters: Denmark, Estonia, Finland, Latvia, Lithuania and Sweden
    - New method: **correction grid** for Norway

→Major update
  - Supersedes NKG2008 transformation



NKG Repro1

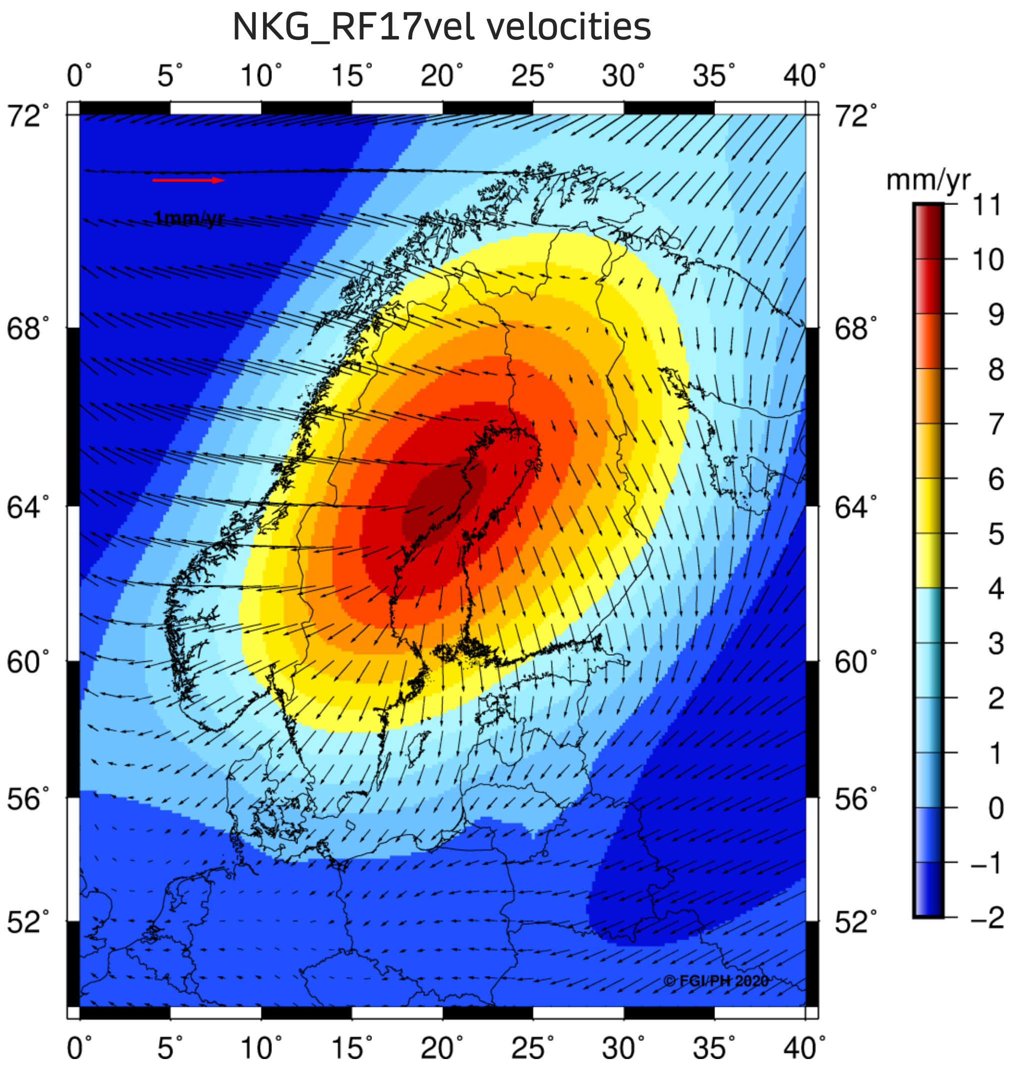




- NKG GNSS AC: Service of the Nordic Geodetic Commission (NKG)
  - Nordic-Baltic collaboration, started 2012
  - 250-300 CORS stations
  - **Goal:** determine common, harmonized, densified and continuous ITRF solution (coordinates, velocities and their uncertainties) to Nordic-Baltic countries
  - Processing:
    - Operational processing with a few weeks delay
    - Reprocessing of data history (repro): NKG Repro1 (2019)
    - Cumulative solutions: NKG Repro1 upd 2020 (2021), NKG Repro1_C2237 (2023)
- NKG Repro1
  - Data span (1997-2017)
  - Processing: Bernese, combination: CATREF, velocity uncertainties: Hector
  - **Result: high-quality GNSS station ITRF2014 coordinates, velocities and their uncertainties**

NKG_RF17vel model (2D+1D)

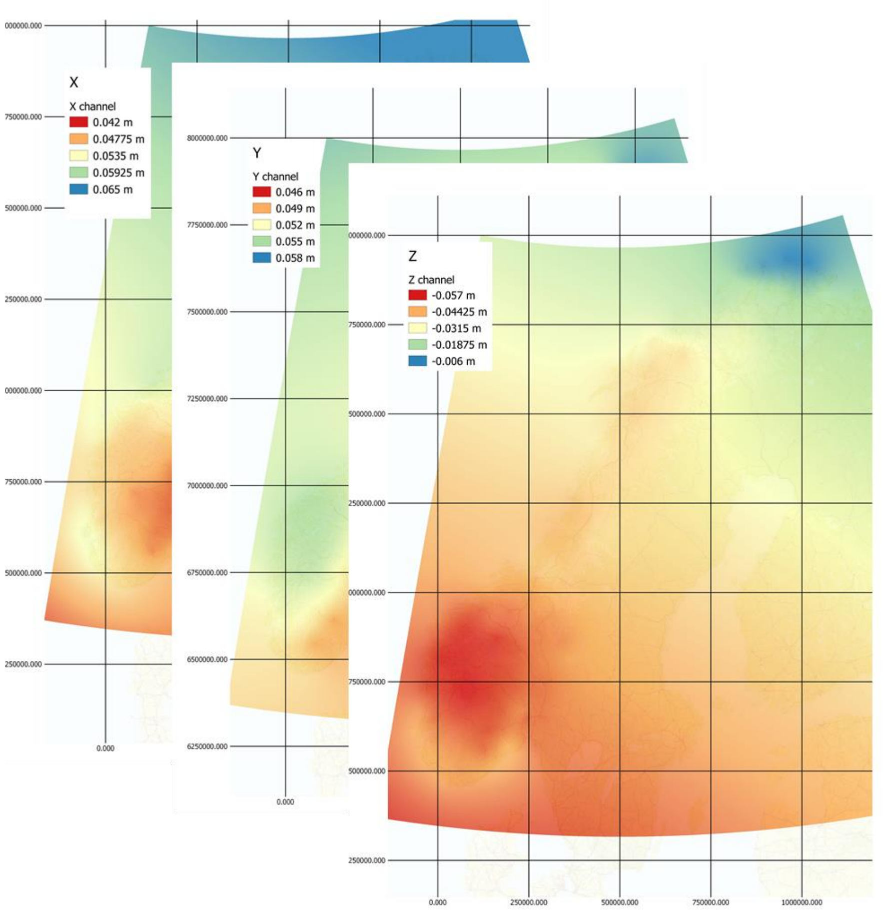
- NKG intraplate deformation (land uplift) model
- Data:
  - GNSS velocities and uncertainties: NKG Repro1, BIFROST2015
  - Levelling data (1D model only)
  - GIA velocities: NKG2016GIA
- Horizontal and [vertical]() velocity grids (2D+1D) for 3D applications
- Major improvement over the previously used NKG_RF03vel model



Horizontal: black vectors, vertical: color map

National transformations

- Helmert transformation for most countries but a new method of a correction grid was employed in the Norwegian transformation
  - Helmert residuals were considered too large and therefore more accurate method was needed
- The correction grid was created with the least-squares collocation (LSC) including systematic (Helmert) and stochastic (signal) parts
  - Corrections (systematic + stochastic parts) were stored in XYZ-grid (see the figure)
- Significant improvement in post-transformation fit
  - 0.7, 0.7, 2.7 mm (rms), and extreme values ~9mm (compared to pure Helmert residuals ~25mm)



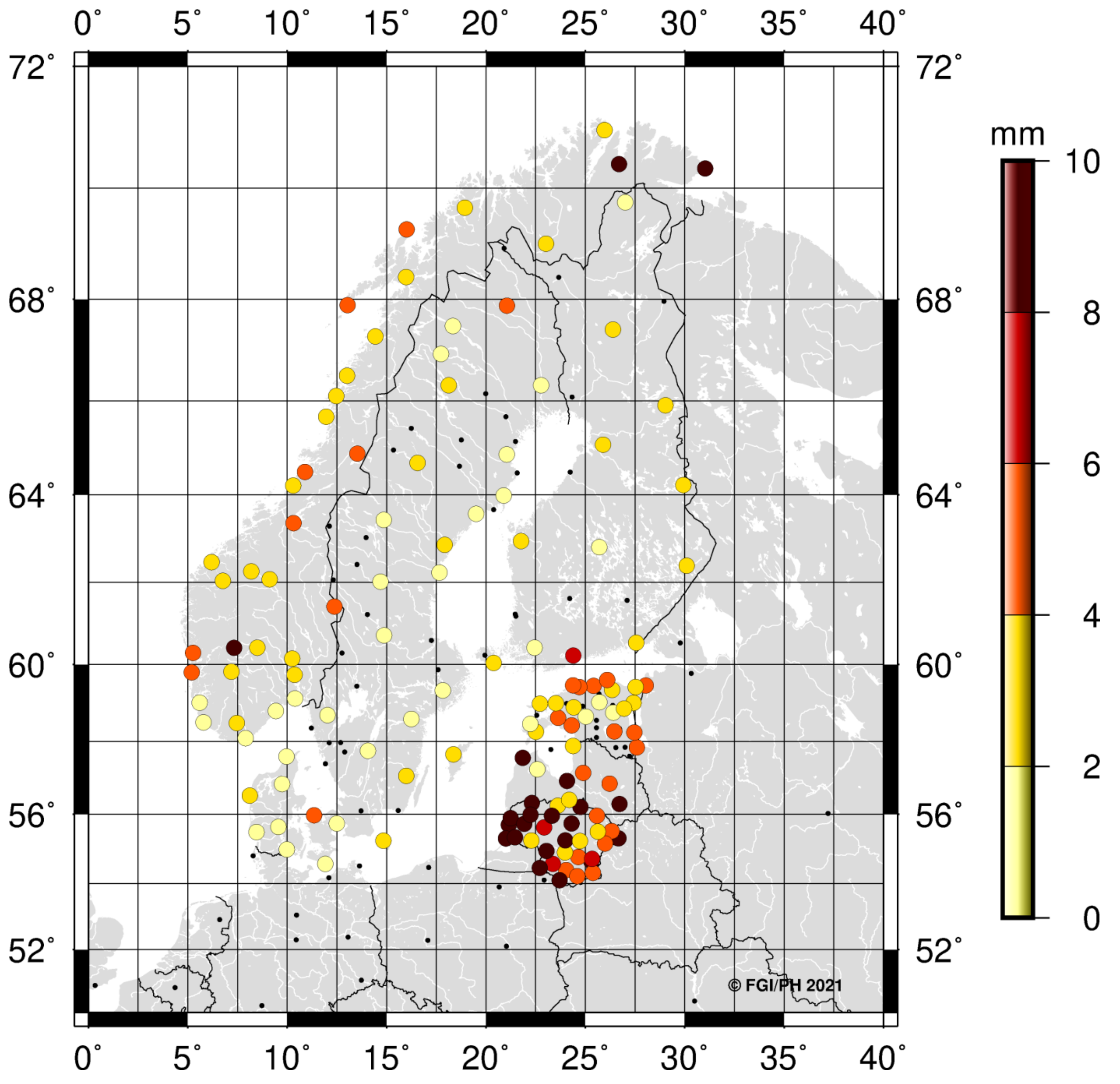
NKG2020 residuals

(from the parameter estimation)

- NKG Repro1 (ITRF2014@2015.0) coordinates used for estimating the transformation parameters
- Residuals (overall, for comparison purposes): 1.9mm, 1.8mm, 3.3mm for N, E, U respectively

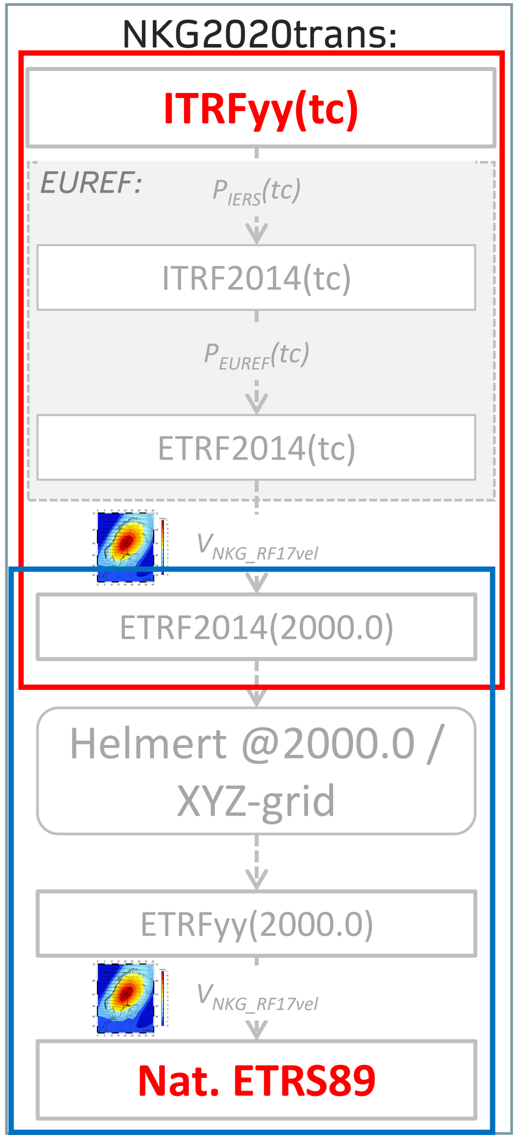
*Table 3. Rms of transformation residuals (NEU). * Norwegian transformation is based on correction grid and therefore has no Helmert residuals. Here rms refers to coordinate differences between transformed NKG Repro1 and official ETRS89 coordinates (in brackets values from the initial Helmert transformation). ** Total used only for overall uncertainty estimation in Section 5 and for this consistency purposes some outliers rejected.*

rms	n	dN [mm]	dE [mm]	dU [mm]
DK	10	0.42	0.46	1.82
EE	23	1.85	2.18	2.36
FI	12	1.53	1.77	2.63
LT	31	3.54	3.22	12.60
LV	7	1.38	3.11	6.09
NO*	189	0.7	0.7	2.7
	(35)	(2.83)	(2.09)	(5.70)
SE	69	0.87	0.70	2.12
Total**	179	1.86	1.82	3.33



NKG2020 uncertainty

- Helmert transformation residuals (and coordinate differences after correction grid)
  - A few mm accuracy (uncertainty) for most countries
  - Gives a picture of the expected uncertainty level but valid only for the coordinates used to determine the transformation parameters
- NKG2020 transformation has several steps that contain their uncertainties
  - Part of the steps time-dependent → also NKG2020 uncertainty time-dependent
  - Uncertainty can be divided into constant and time-dependent parts
- Uncertainty can be estimated in several ways, here empirical approach selected
  - Estimated with different data sets



NKG2020 uncertainty: constant part

- Constant part of the uncertainty estimated with four data sets:
  - NKG Repro1_upd2020, EPN_IGb14_C2220, ITRF2020, IGS20 (not shown due to only a few common stations)
  - Epoch: 2015.0 (same as for parameter estimation)
  - Reference frame: ITRF2014 (IGb14), ITRF2020 (+IGS20)
- Accuracy: approximately same level for all solutions and compared to the residuals
  - Constant part (overall, for comparison purposes): 1.7mm, 1.8mm, 3.6mm for N, E, U respectively
  - Additional component (to the residuals) from other data sets to total uncertainty budget negligible but directly proportional to the used data sets, here high-quality solutions used
- NKG2020 transformation works also for ITRF2020 with the same accuracy

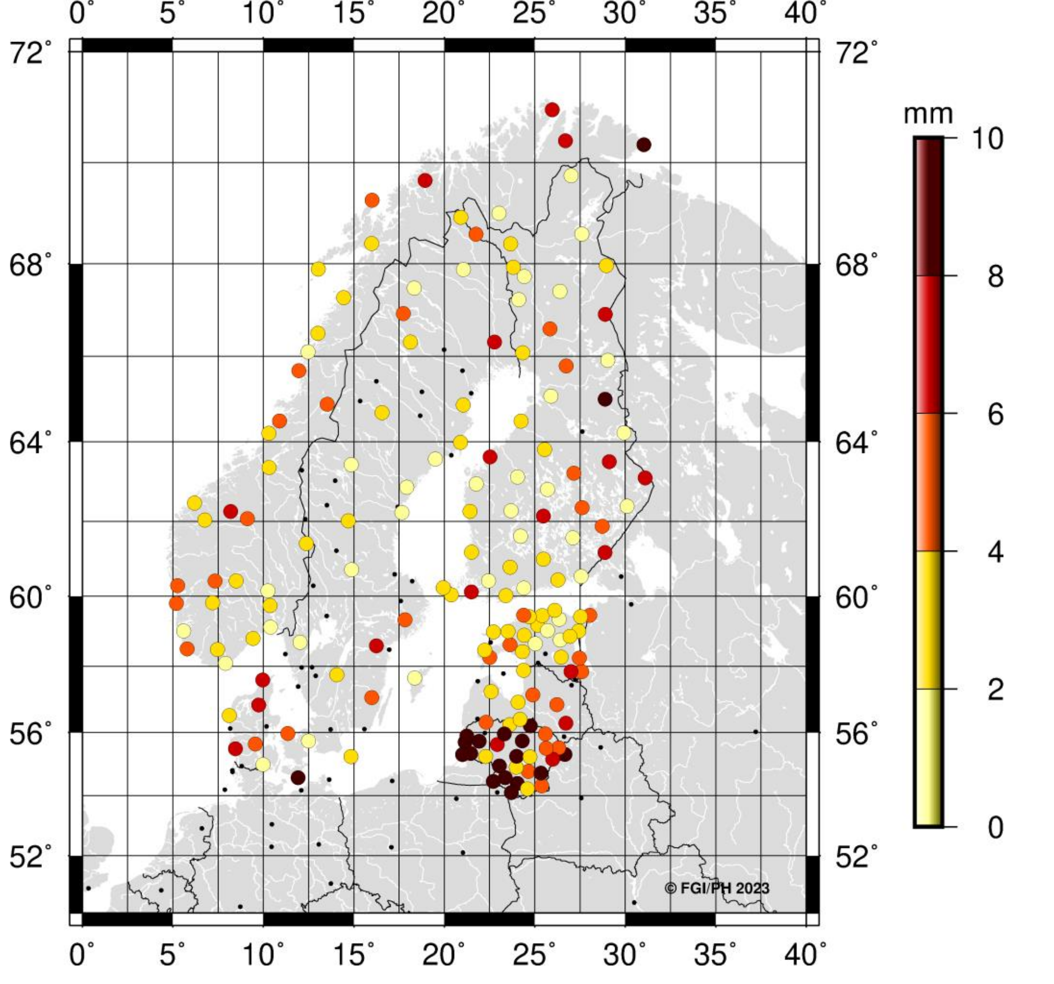


*Table 6. NKG Repro1 upd2020: IGb14@2015.0, EPN_IGb14_C2220: IGb14@2015.0 and ITRF2020@2015.0 transformed to national ETRS89 realizations. rms of coordinate differences. * Norway w/ correction grid*

rms	NKG Repro1 upd2020: IGb14@2015.0				EPN_IGb14_C2220: IGb14@2015.0				ITRF2020@2015.0			
Country	n	dN [mm]	dE [mm]	dU [mm]	n	dN [mm]	dE [mm]	dU [mm]	n	dN [mm]	dE [mm]	dU [mm]
DK	10	0.84	1.94	5.45	3	0.51	1.71	3.21	5	1.19	2.06	2.77
EE	25	1.89	2.10	2.10	4	3.01	2.93	2.54	1	2.50	2.50	0.00
FI	46	1.05	1.34	3.53	19	0.64	0.40	1.36	3	1.18	1.09	2.81
LV	6	0.96	3.29	2.38	1	5.10	2.60	25.20	0			
LT	29	3.56	4.21	9.39	1	6.50	2.30	36.10	1	6.70	1.30	41.50
NO*	35	2.01	1.39	3.35	5	2.49	2.87	2.59	6	2.88	2.75	3.30
SE	67	1.17	1.18	2.67	30	1.26	1.44	2.49	21	1.39	1.19	3.26
Total	**222**	**1.69**	**1.78**	**3.59**	**64**	**1.47**	**1.59**	**2.41**	**39**	**1.79**	**1.84**	**3.31**

NKG2020 uncertainty: time-dependent part

- Time-dependent part of the uncertainty evaluated with position time series: NKG Repro1_upd2020
  - Length of time series: 3.3-23.5 years, average: 13 years
  - Data cleaned: same discontinuities and data rejections as for NKG Repro1_upd2020, number of solutions in TS: 1-6
  - Daily ITRF2014 coordinates transformed with NKG2020 transformation and compared to national ETRS89 coordinates → residual time series
- Residual time series analyzed with Hector
  - Residual velocities optimally close to zero (see example in the figure)
  - Remaining non-zero velocities indicate either uncertainties in the NKG_RF17vel deformation model or uncertainties or some local effects in the station velocities

Good stations look like this:

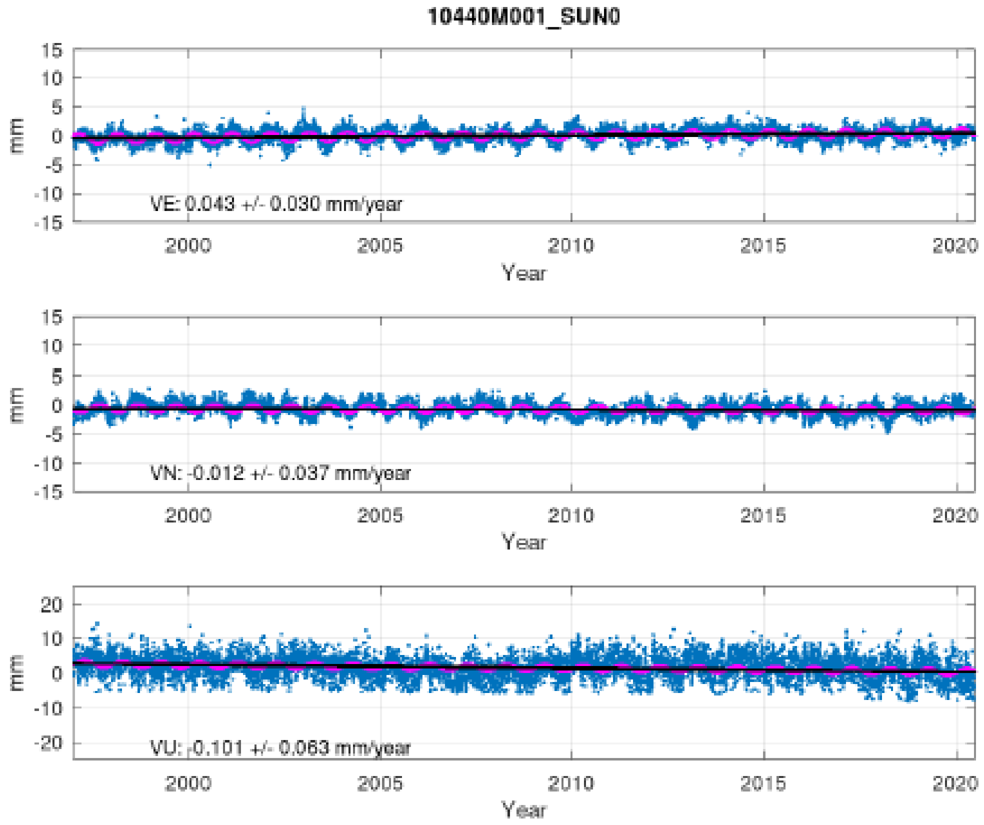
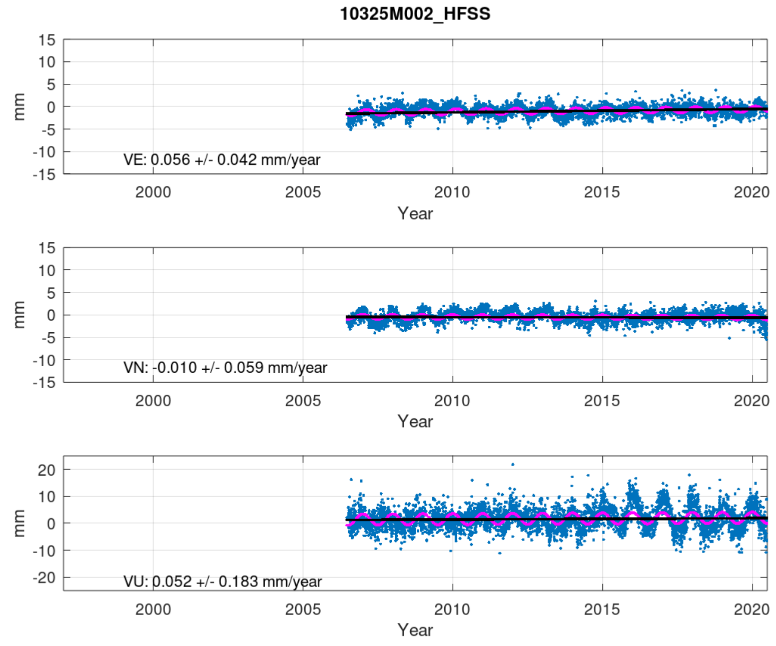
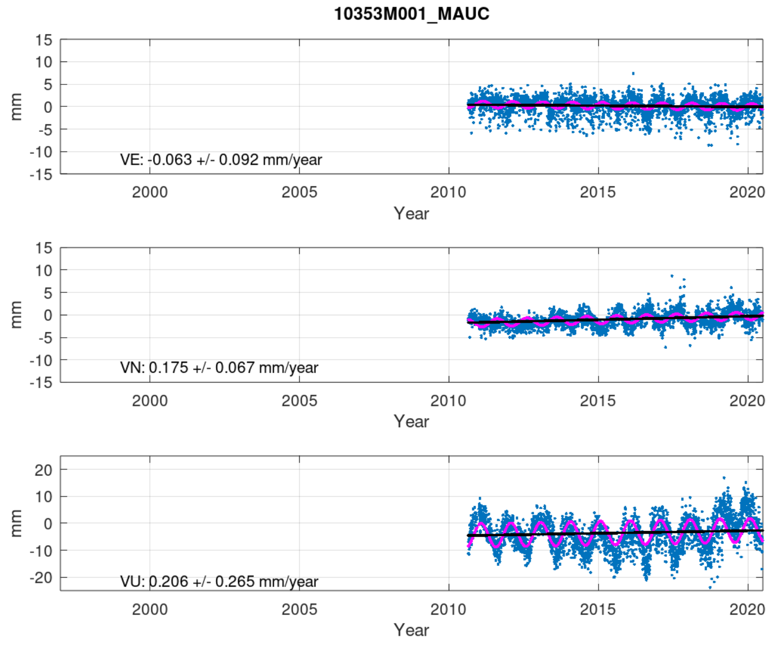
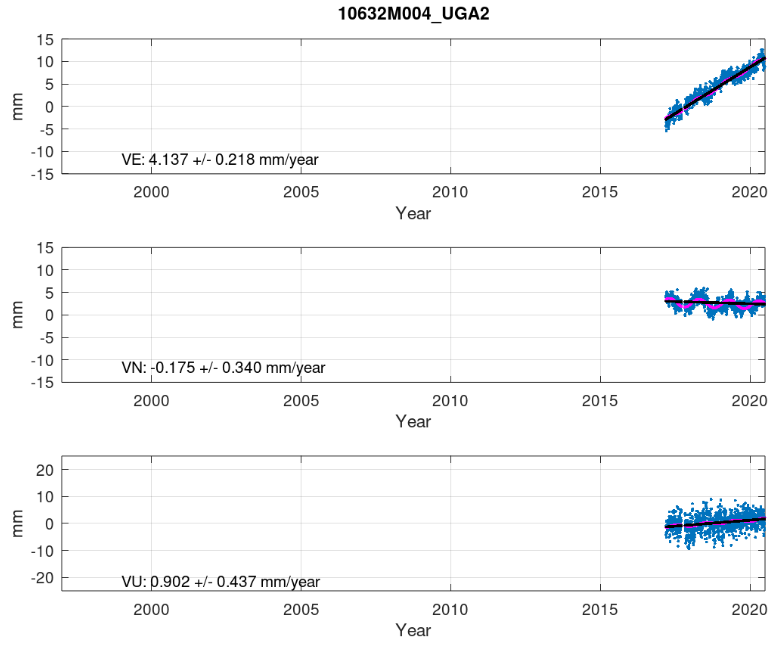
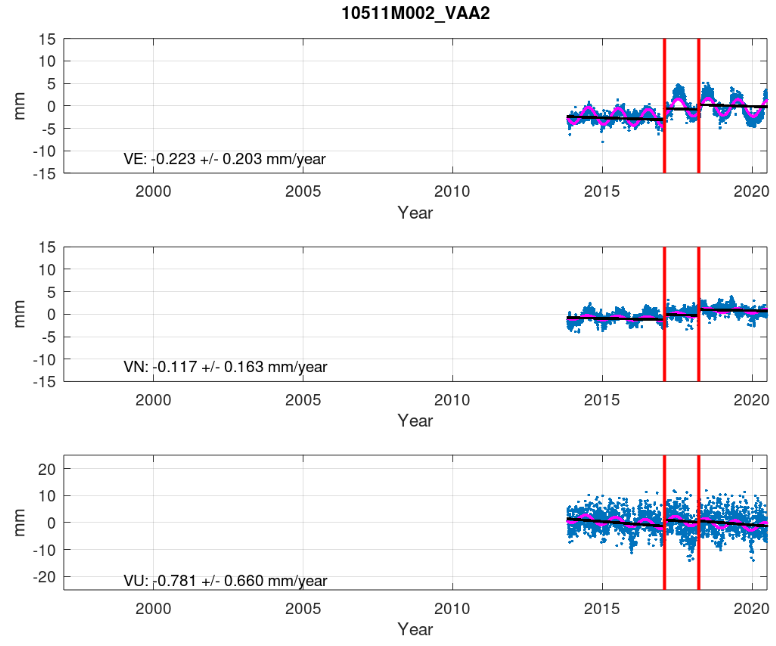


Figure 12. Example of the residual time series and velocities for SUN0 station in Sweden.



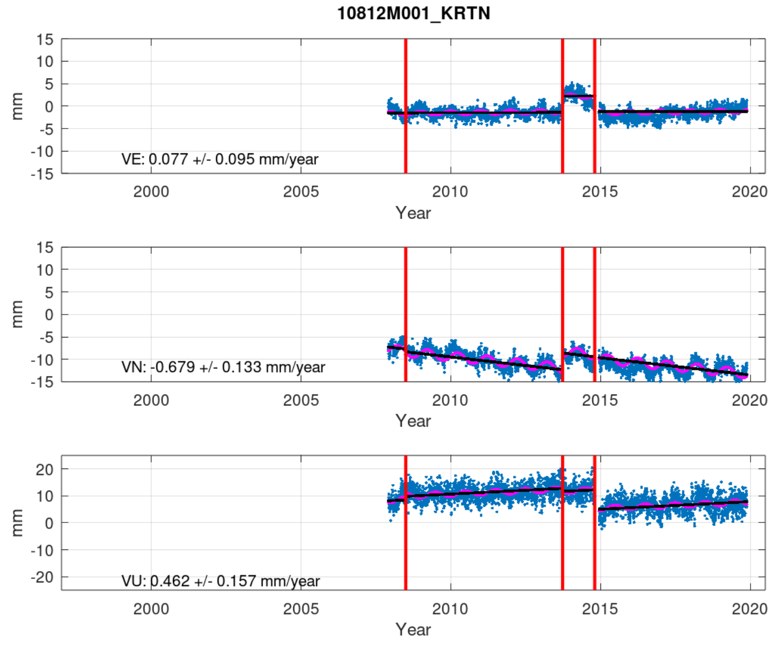






But there are other kinds of stations as well

- Discontinuities, short time series, local effects,...



NKG2020 uncertainty: time-dependent part

- Consequently, it is difficult to give one definite answer of the transformation accuracy over time.
  - The longest time series and/or longest uninterrupted time series suggest that the transformation is almost time-invariant.
  - At the other end, the residual velocities are dominated by inaccuracies and local effects in station velocities.
  - Somewhere in between the uncertainties of the model and station velocities are converging to describe the actual time-variable accuracy for our purpose.
- Simple outlier detection applied to residual velocities (instead of thorough station-wise analysis)
- Time-dependency (overall, rms): 0.1, 0.1, 0.3 mm/yr for N, E, U respectively
  - These values suggest a few millimeter stability over 10 years that can be considered very good result

Table 7. Statistics of the residual velocities in the national ETRS89 realizations. Outlier detection performed.

Res.vel. (n=148)	dN [mm/yr]	dE [mm/yr]	dU [mm/yr]
Min:	-0.42	-0.37	-1.02
Max:	0.44	0.39	0.58
Mean:	0.02	0.01	-0.16
Stdev:	0.12	0.13	0.30
rms:	0.12	0.13	0.34
95%:	0.30	0.27	0.72

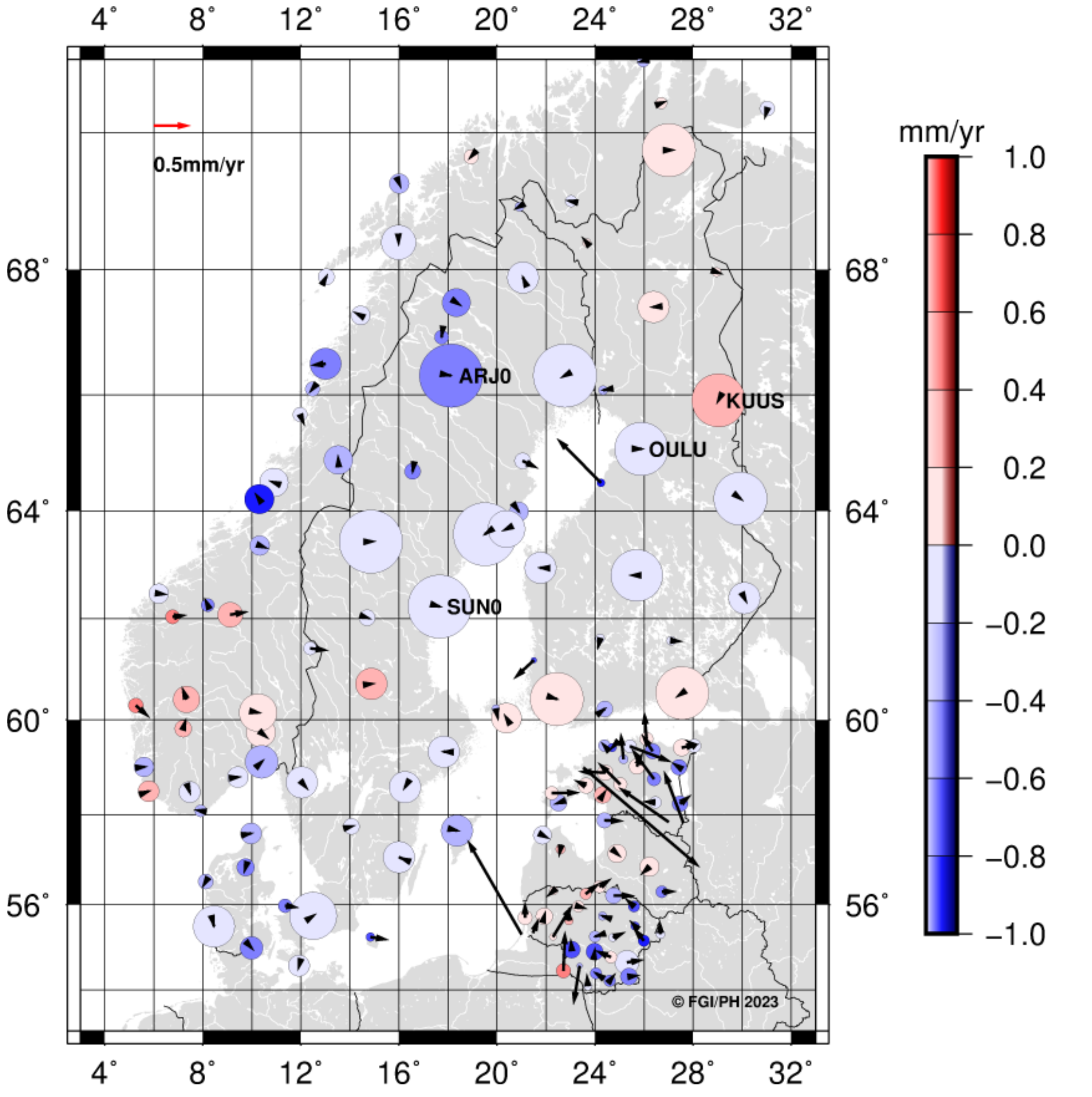


Figure 11. Same as Figure 9 but the circle sizes showing the ratio of observations and offsets (number of observations divided by number of solutions). Results before outlier analysis ~~in the left-hand side and after in the right-hand side~~. This describes the length of uninterrupted time series. Increasing number of offsets affects the quality of time series.

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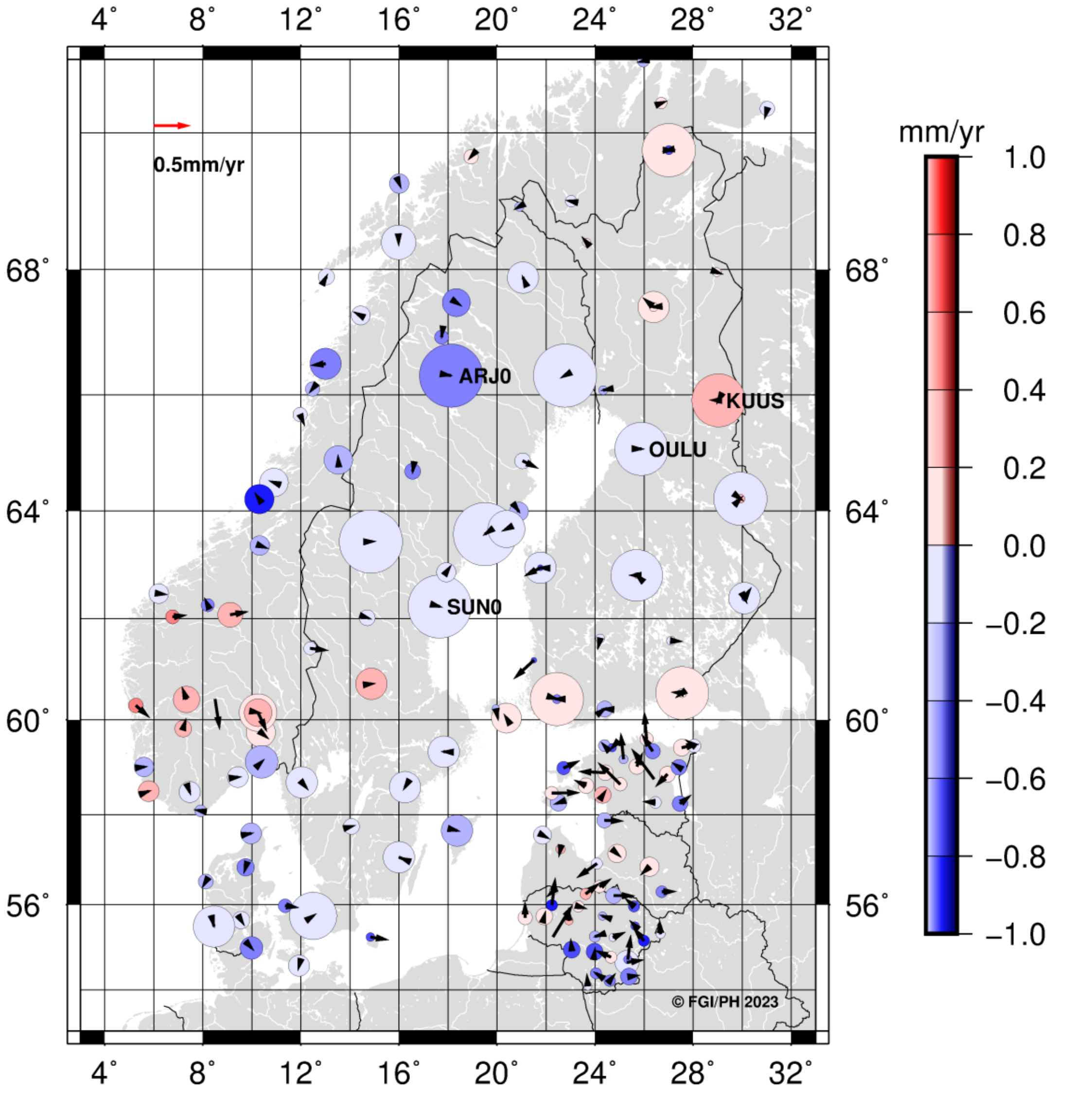

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Standardization (of reference frames and transformations)

- Globalization and increasing demands for accuracy in geodata analysis increase the need for standardization on reference frames and transformations
  - Ensures seamless and errorless analysis without misinterpretations
- In order to make NKG2020 transformation widely and easily available to users, we:
  - have implemented the NKG2020 transformation to open-source transformation software PROJ (8.0.1 onwards)
  - are working on registering the NKG2020 transformation to EPSG and ISO geodetic registries

Conclusions

- We have released a new version, NKG2020 transformation, that supersedes previous version NKG2008.
- NKG2020 transformation serves as a link between ITRFyy and Nordic-Baltic ETRFyy realizations at a few millimeter-level, also over time.
  - Overall, we found the empirical accuracy (uncertainty at epoch 2015.0): 1.7 mm +/- 0.1 mm/yr, 1.8 mm +/- 0.1 mm/yr and 3.6 mm +/- 0.3 mm/yr in North, East and Up components, respectively (1σ).
  - As a result, the accuracy degrades only a few millimeters in 10 years.
  - NKG2020 transformation was also shown to operate equally with the recently released ITRF2020.
- NKG2020 has been implemented in PROJ and in the future into EPSG and ISO registries
- Full documentation available soon (accepted): https://doi.org/10.1515/jogs-2022-0155

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