



THE NEXT GENERATION OF LAND UPLIFT AND GLACIAL ISOSTATIC ADJUSTMENT MODELS FOR NORTHERN EUROPE

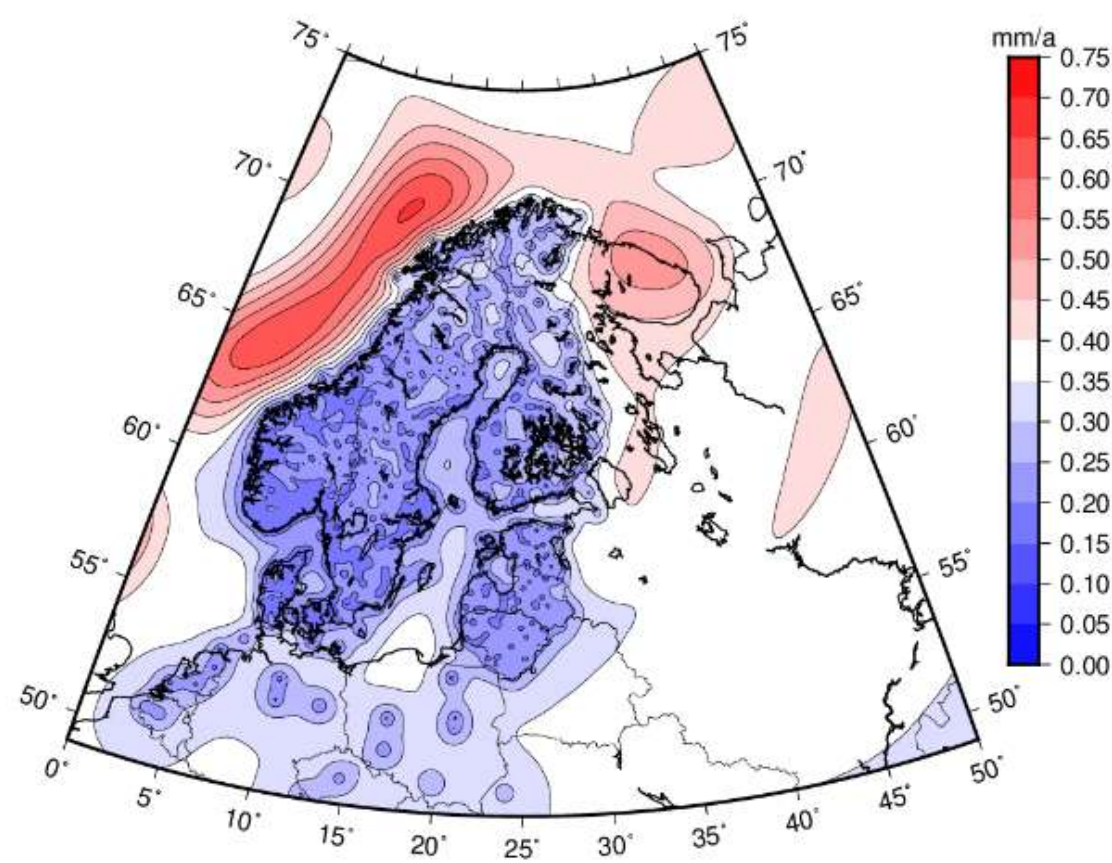
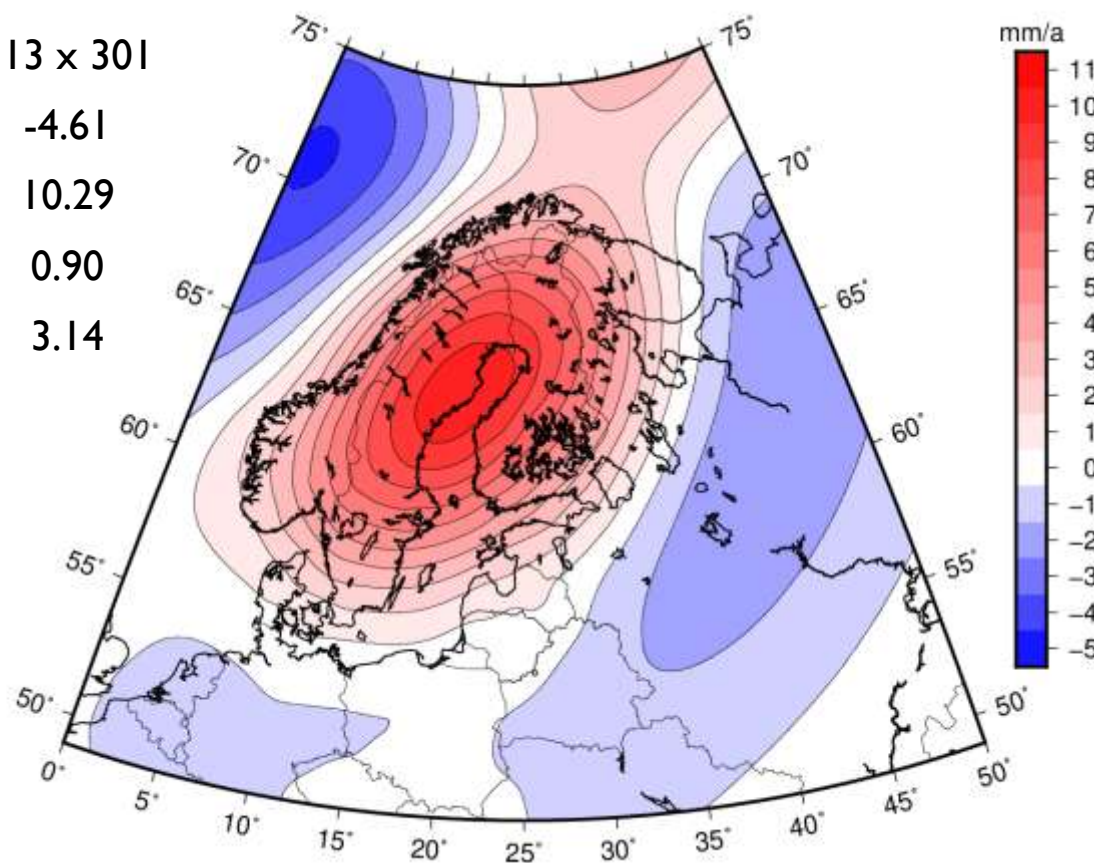
HOLGER STEFFEN

JONAS ÅGREN, ANDRZEJ ARASZKIEWICZ, TOBIAS ARNELL, VALENTINA R. BARLETTA, MICHAEL DÄHNEN,
PASI HÄKLI, PINGPING HUANG, LOTTI JIVALL, ULLA KALLIO, TINA KEMPE, HALFDAN P. KIERULF,
KSENIJA KOSENKO, KAMIL KOWALCZYK, SONJA LAHTINEN, SIMO MARILA, JAANUS METSAR, TONG NING,
MAARIA NORDMAN, JOKUBAS OGINTAS, DALIA PRIZGINIENE, MATTHEW J.R. SIMPSON, REBEKKA STEFFEN,
LEV TARASOV, OLAV VESTØL, METTE WEBER, VENTS ZUŠEVIC

NKG2016LU_ABS AND ITS UNCERTAINTY

Citations (15 Sep 26):
 Google Scholar 234
 Scopus 155
 Web of Science 132

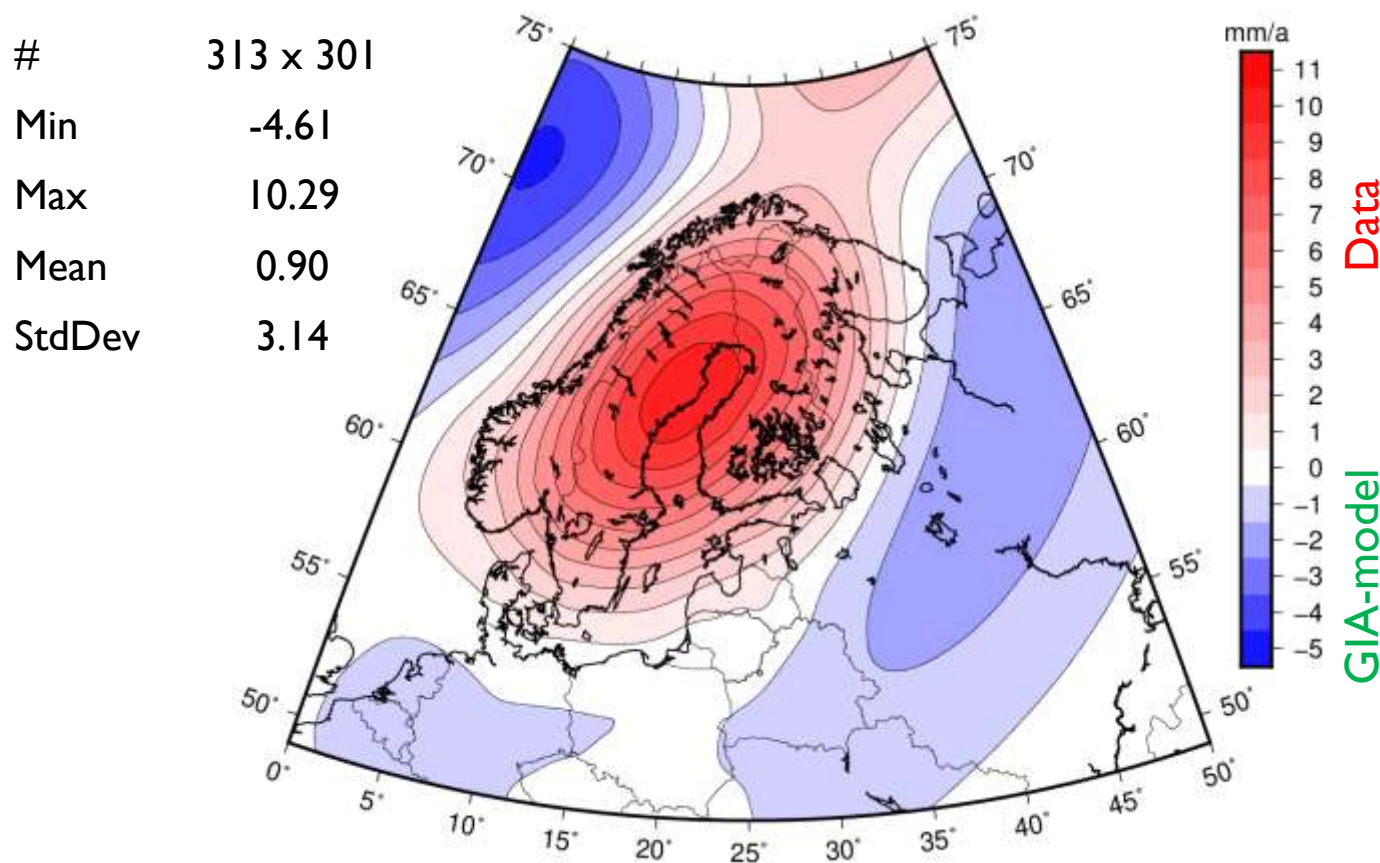
313 x 301
 Min -4.61
 Max 10.29
 Mean 0.90
 StdDev 3.14



Based on (GNSS) data until 2014; GNSS processing 11 years ago! Model released 10 years ago!

(Vestøl et al. 2019)

ISSUES WITH NKG2016LU



- No levelling data south of Baltic Sea (D, PL) nor in Russia
- (Very) sparse GNSS data south of the Baltic Sea, e.g., Germany, Poland, Lithuania
- Some GNSS data with rather short time span, we actually removed at least 50 stations that were processed
- 5 much better ice models were not used
- No elastic correction of GNSS data
- No spatial weighing of RSL and GNSS data
- New community-updated and quality-checked RSL data are available for the Baltic Sea
- GIF database available
- Unsatisfying fit of GIA model south of Baltic Sea
- LU-Model was calculated in the two-step approach

Based on (GNSS) data until 2014; GNSS processing 11 years ago! Model released 10 years ago!

TOWARDS BIFROST2025 AND NKG202XLU

- Integrate levelling data from Germany and Poland
- Use 10 more years of GNSS data (1/1/2000-31/12/2024)
- Add more Lithuanian, German and Polish GNSS data (500+)
- Expand area to include UK (also GIA-affected) and Faroe Islands (~80)
- Better knowledge about some previous outliers (trees – see Lahtinen et al. 2019)
- Better knowledge about elastic effects due to climate change-related processes
- GIA modelling with better ice models, 3D earth and new 3D modelling code plus improved observations for fitting
- Use one-step approach introduced in Vestøl et al. (2019)
- **Which GNSS processing code shall we use?**



PROCESSING DETAILS

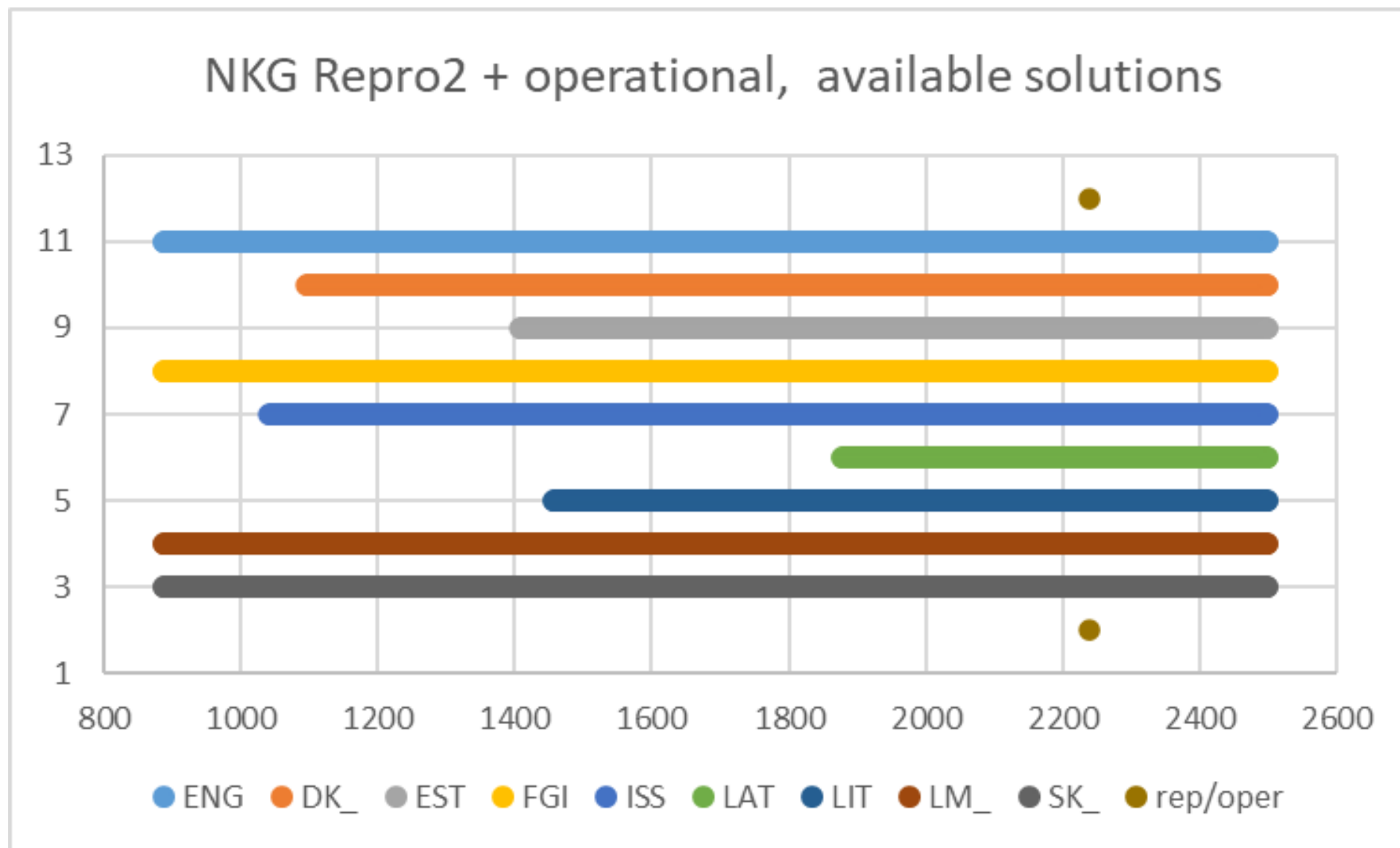
	Bernese-NKGRepro2*	Bernese-BIFROST	GAMIT	GipsyX
Stations	NKG GNSS AC standard	NKG standard + selected extra from GAMIT/GipsyX list	NKG standard + extra EPN/IGS + northern (D + PL) + UK + Faroe Islands	
# stations§	439	637	1071	
Time span	1/1/1997-03/01/2025	1/1/1997-31/12/2022	1/1/2000-31/12/2024	
Reference Frame	IGS20			
Systems	GPS+GLO+GAL	GPS		
Tide model	FES2014b			
Mapping function	VMFI			
Cut-off angle	3	7		

* Following EPN Repro guidelines

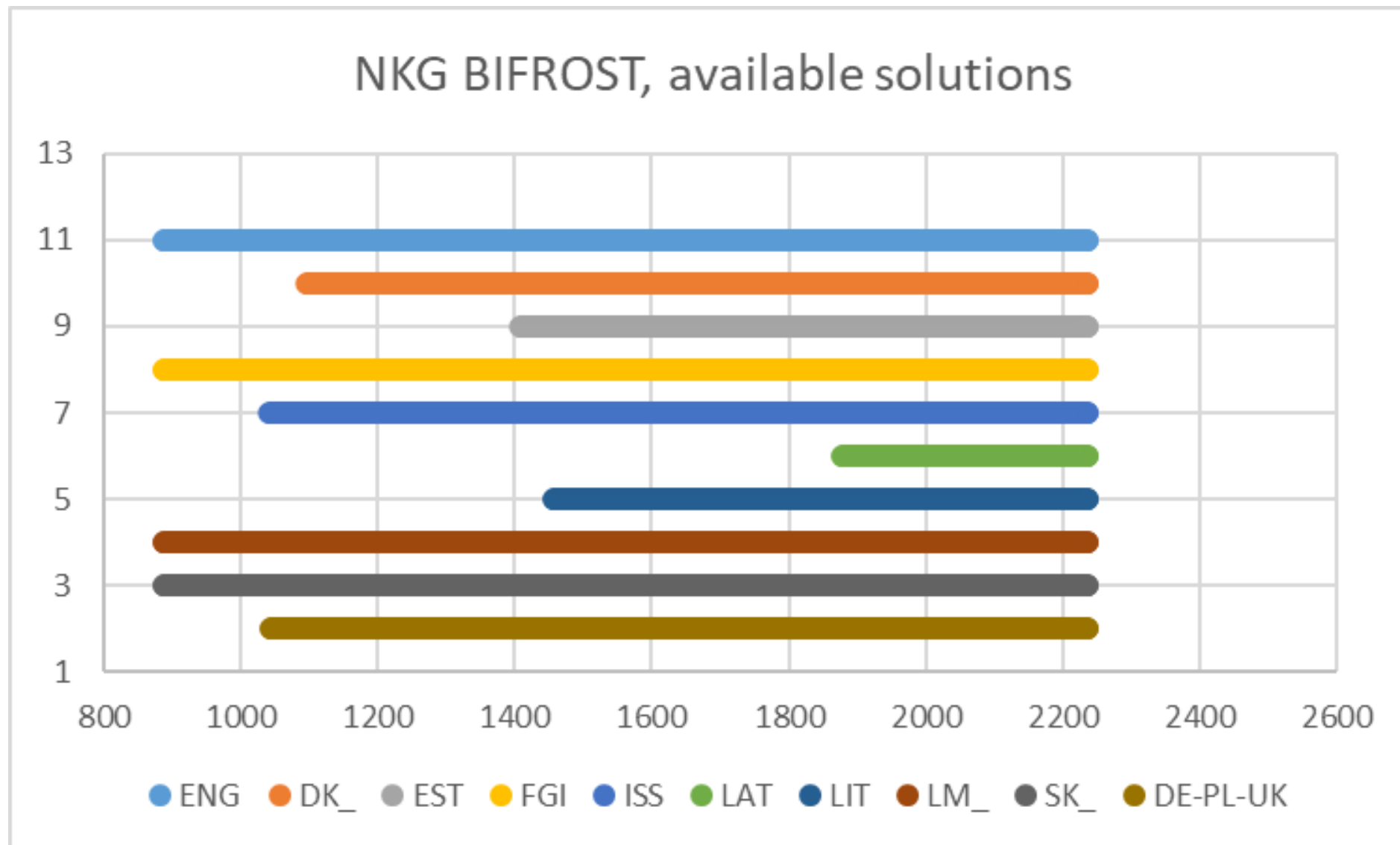
§ Unique station codes, will likely be updated

Atmospheric loading considered in GAMIT, not used in Bernese and not possible in GipsyX. Can be removed for comparison at a later stage

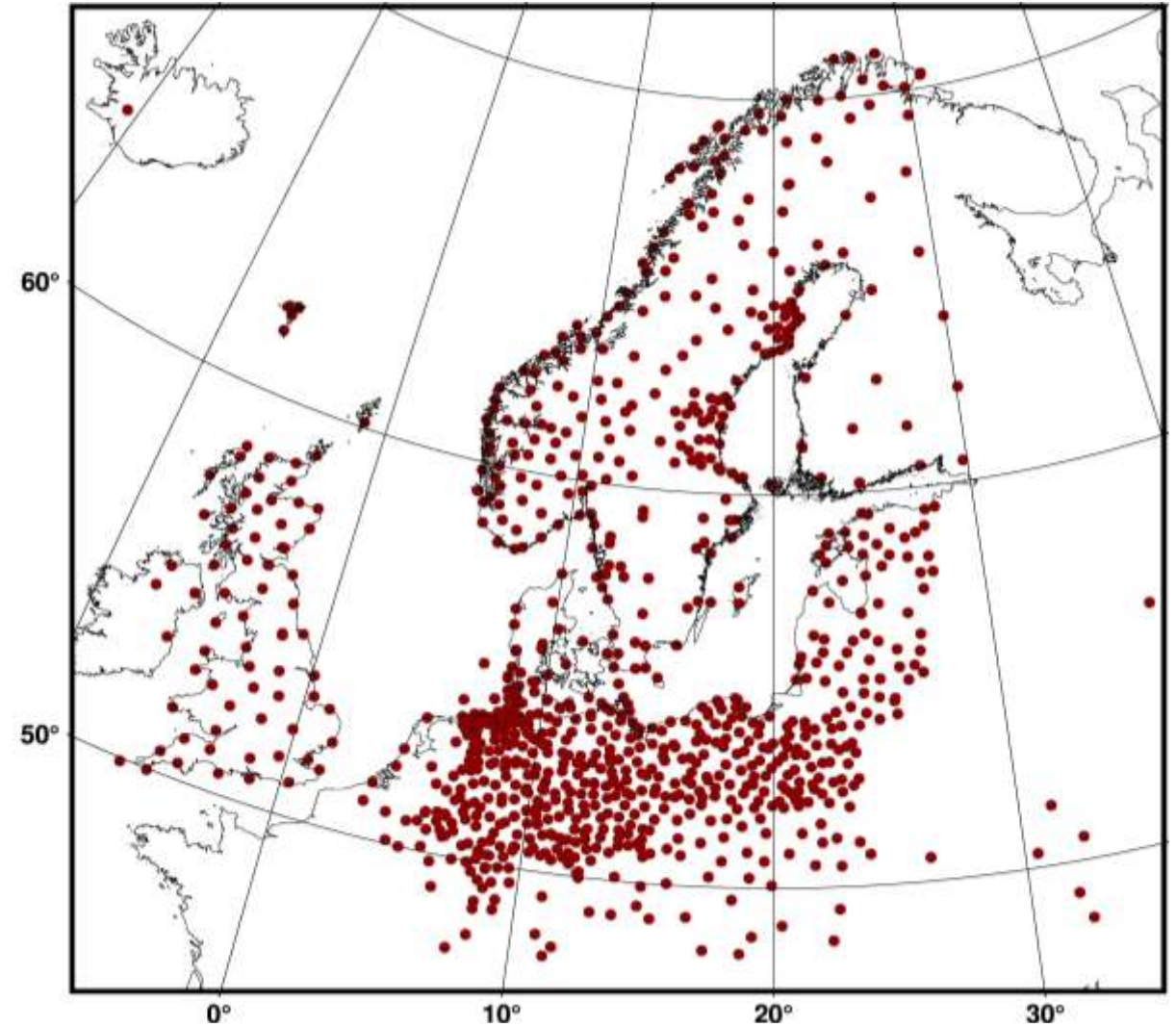
BERNESE NKG REPRO2



BERNESE NKG BIFROST



GNSS STATIONS FOR GAMIT OCH GIPSYX



TOWARDS THE INPUT FOR THE NEW MODELS

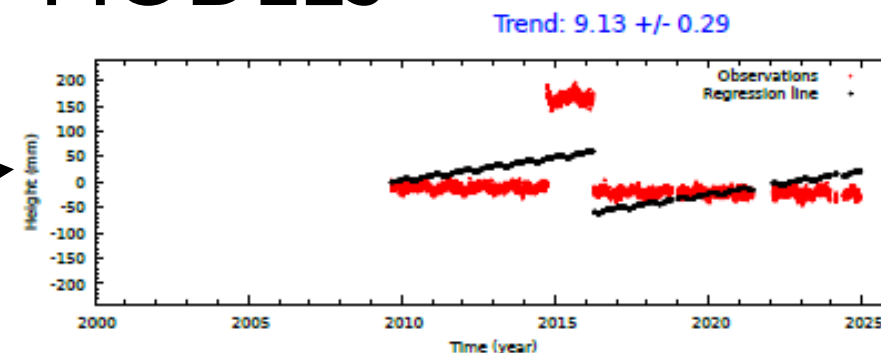
- Outlier detection for GNSS observations, partly iteratively
- Velocity calculation
- Selecting input for NKG202XLU & RF2X_vel
- Calculating NKG202XLU and RF2X_vel

NKG202XLU will be the vertical component of RF2X_vel!

The GIA model of both models will be the same!

TOWARDS THE INPUT FOR THE NEW MODELS

- Outlier detection for GNSS observations, partly iteratively
 1. Visual inspection of time series, update of station information, removal of "bad" data by processors
 2. *Difference to other solutions (time series, velocities)*
 3. Difference to a smoothed surface (collocation approach similar to EuVeM2022) – value at observation point
 4. *Leave-one-out cross validation (LOOCV)*
 5. Automatic LOOCV-like check during the one-step approach
 6. *Automatic check with smoothed solution as for RFI 7_vel*
- Velocity calculation
- Selecting input for NKG202XLU & RF2X_vel
- Calculating NKG202XLU and RF2X_vel



TOWARDS THE INPUT FOR THE NEW MODELS

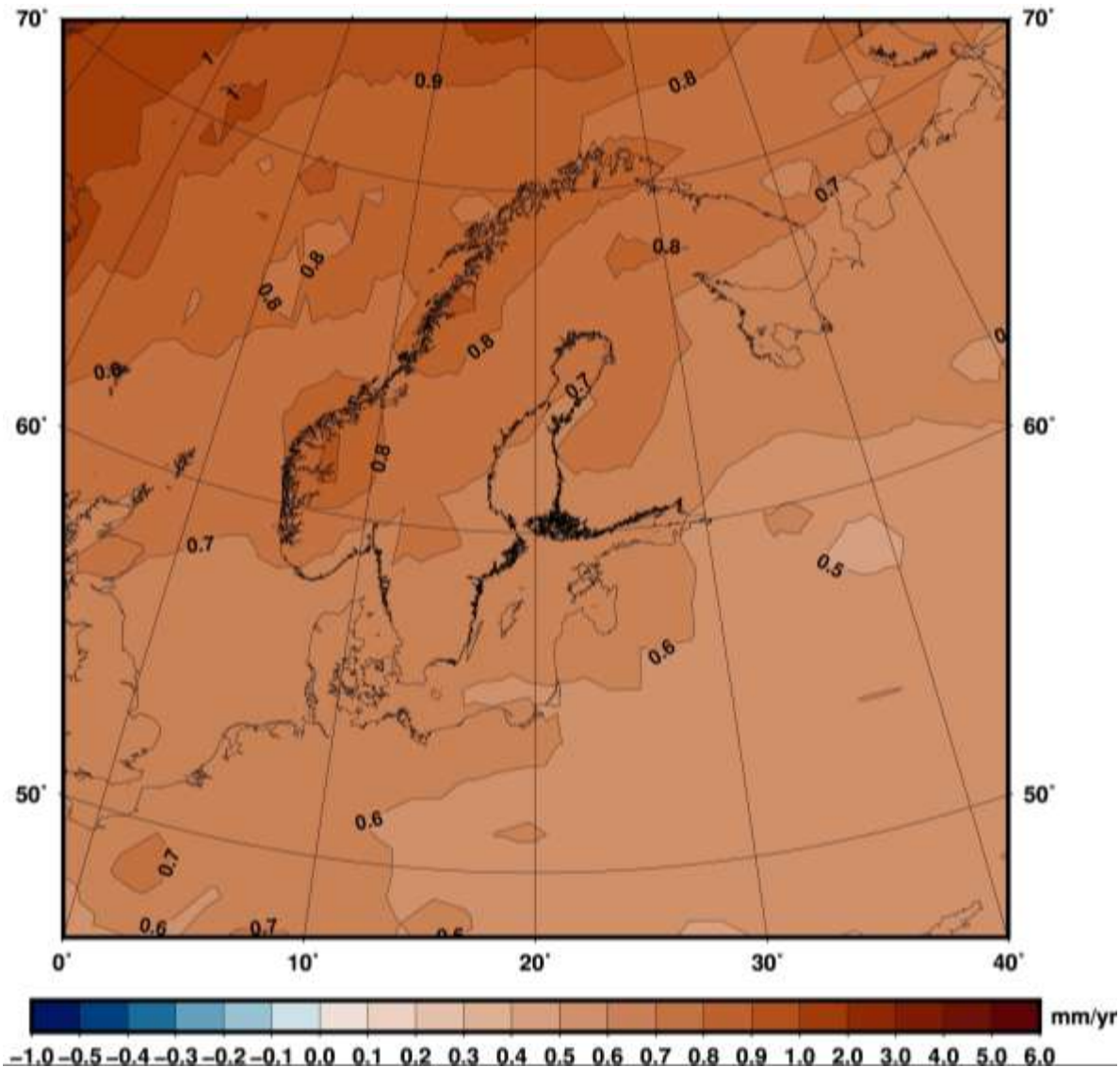
- Outlier detection for GNSS observations, partly iteratively
- Velocity calculation
 - Different software for calculation:
 - tsview (GAMIT/GLOBK; Herring, 2003)
 - MIDAS (Blewitt et al., 2016)
 - CATREF (Altamimi et al.)
 - Hector (Bos et al., 2013)
 - least-square regression
 - ...
 - GAMIT result for testing the different software and determining how large differences are
- Selecting input for NKG202XLU & RF2X_vel
- Calculating NKG202XLU and RF2X_vel

⇒ many 3D velocity estimates!

TOWARDS THE INPUT FOR THE NEW MODELS

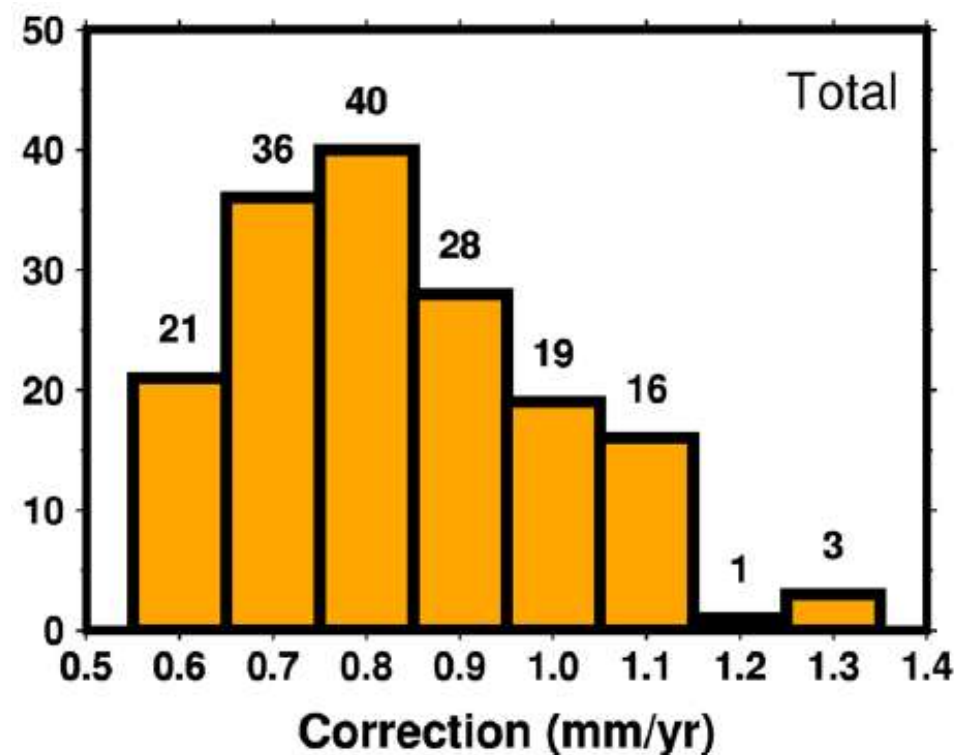
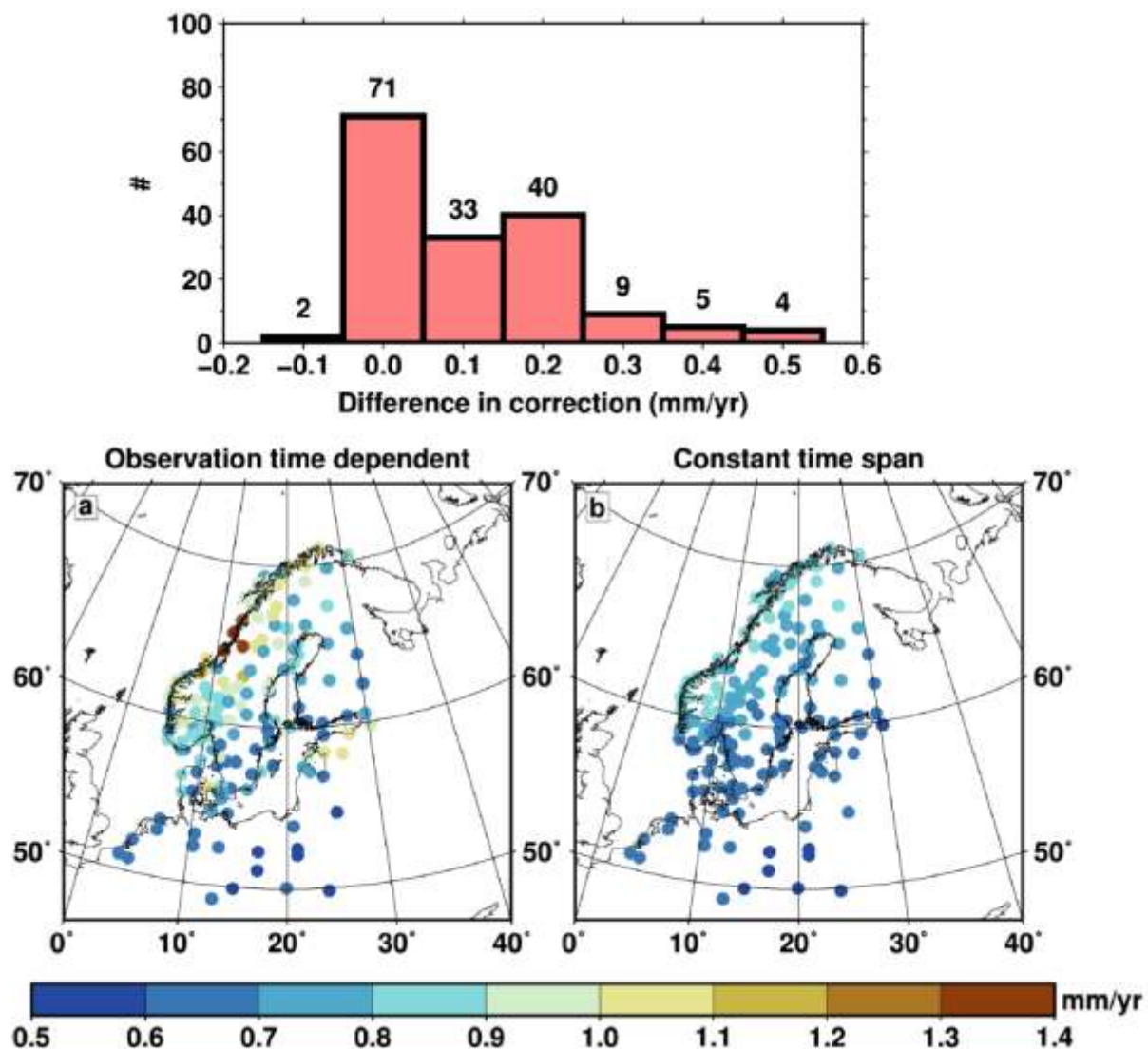
- Outlier detection for GNSS observations, partly iteratively
 - Velocity calculation
 - Selecting input for NKG202XLU & RF2X_vel
 - Only one set of input data (GIA model, levelling data, 3D velocity estimates) for the new models; we do only provide alternatives (e.g. 3D velocity estimates) as part of the corresponding BIFROST2025 publication
 - GNSS data:
 - Correcting time-dependent elastic deformation of velocities based on GRACE results
-
- Calculating NKG202XLU and RF2X_vel

THE SUM OF ELASTIC EFFECTS IN EUROPE



(Kierulf et al., 2021)

INFLUENCE OF OBSERVATION TIME SPAN



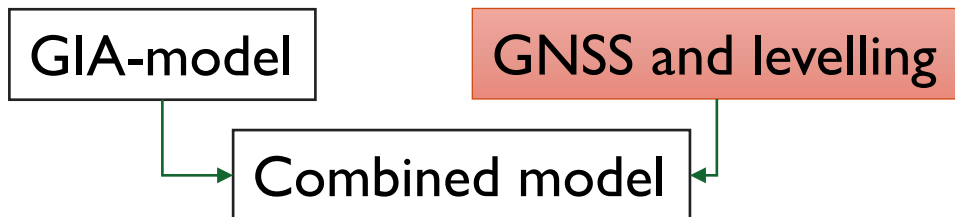
(Kierulf et al., 2021)

TOWARDS THE INPUT FOR THE NEW MODELS

- Outlier detection for GNSS observations, partly iteratively
- Velocity calculation
- Selecting input for NKG202XLU & RF2X_vel
 - Only one set of input data (GIA model, levelling data, 3D velocity estimates) for the new models; we do only provide alternatives (e.g. 3D velocity estimates) as part of the corresponding BIFROST2025 publication
 - GNSS data:
 - Correcting time-dependent elastic deformation of velocities based on GRACE results
 - Different velocity estimates are compared after least-square collocation to identify best input
 - Levelling data:
 - All in place (i.e. NKG area plus Germany and Poland)
 - GIA model:
 - 1D modelling using various ice and earth models for identification of best 1D GIA model
 - 1D GIA model used as initial step for 3D GIA model with 3D viscosity structure from seismic tomography model REVEAL (Thrastarson et al., 2024)
 - GIA model will be used for all new NKG models
- Calculating NKG202XLU and RF2X_vel

TOWARDS THE INPUT FOR THE NEW MODELS

- Outlier detection for GNSS observations, partly iteratively
- Velocity calculation
- Selecting input for NKG202XLU & RF2X_vel
- Calculating NKG202XLU and RF2X_vel



1. Remove observation-time-dependent elastic contribution from GNSS observations

$$\dot{h}_{total-elastic} = \dot{h}_{GIA} + \dot{h}_{geology_{region+local}} + \dot{h}_{unmodelled\ errors}$$

2. Identify best GIA model by fitting it to elastic-corrected GNSS, RSL, "elastic-corrected" GRACE/AG
3. Update GIA model with elastic-corrected GNSS + levelling (elastic-corrected?)
4. Add grid of elastic contribution for the maximum observation time span on the updated GIA model $\Rightarrow$ this results in a deformation model that shows the average land uplift from 2000.0-2025.0

DRAFT SCHEDULE

- End of September 2026: GNSS processing finished
- End of October 2026: Observation time-dependent elastic correction for each station ready
- End of December 2026: all outliers identified and uncertainty determination for velocities from different software; determination of elastically corrected input GNSS velocities; GIA model defined
- January 2027: produce new models
- Jan-Feb 2027: test/check new models
- March 2027: decide on new models or start round of small improvements