A New Vertical Land Movements Data Set from a Reprocessing of GNSS at Tide Gauge Stations

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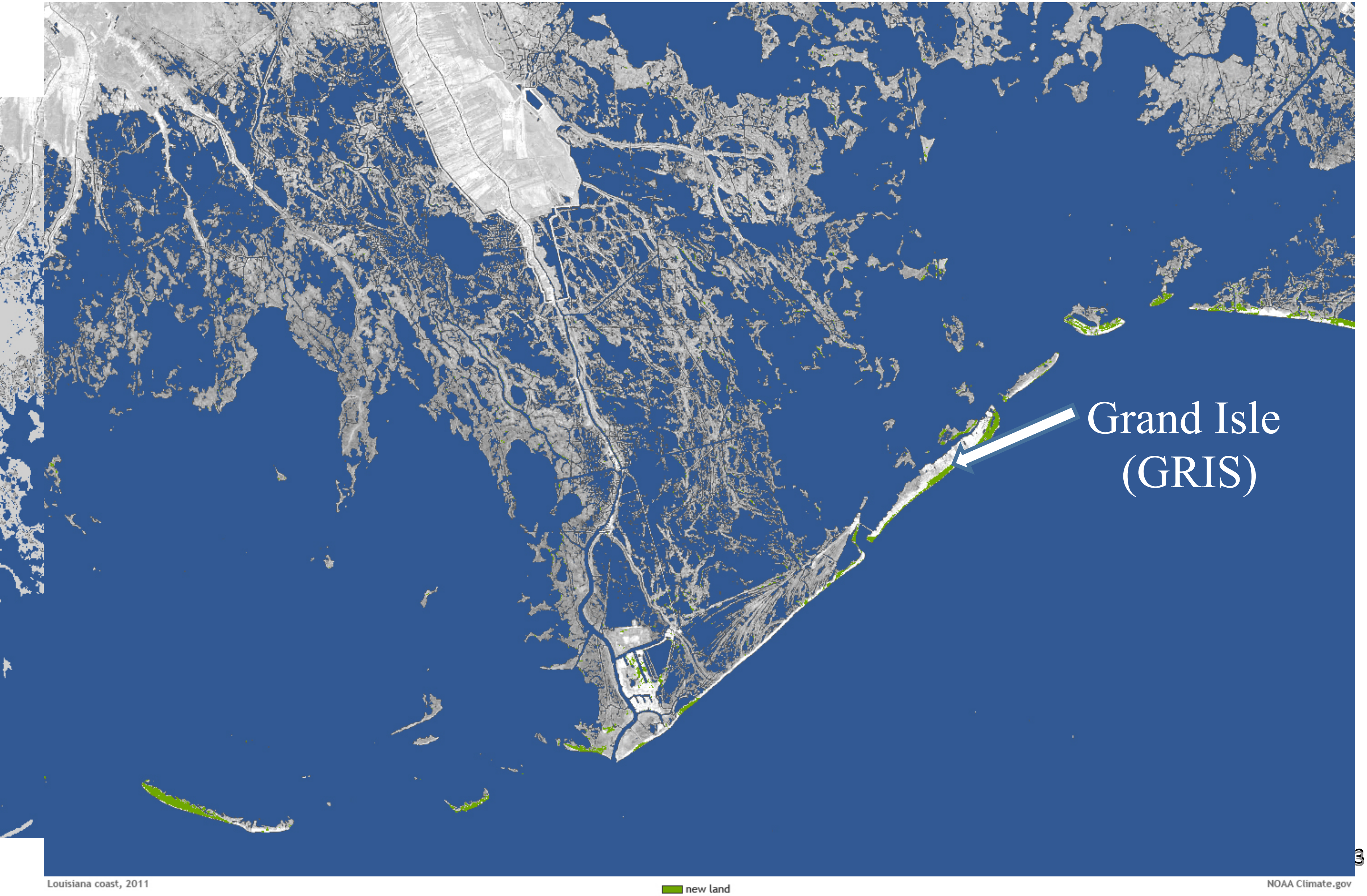
IAG/CPGPS International Conference on GNSS+ (ICG+ 2016)
Advances, Opportunities and Challenges
July 27-30, 2016, Shanghai, China

Overview

- Brief update on IGS Tide Gauge Benchmark Monitoring (TIGA) Working Group combination
- British Isles continuous GNSS Facility and University of Luxembourg TIGA Analysis Center (TAC) Solution: BLT
- Results
  - Evaluations and first interpretations based on BLT solution
- Conclusions

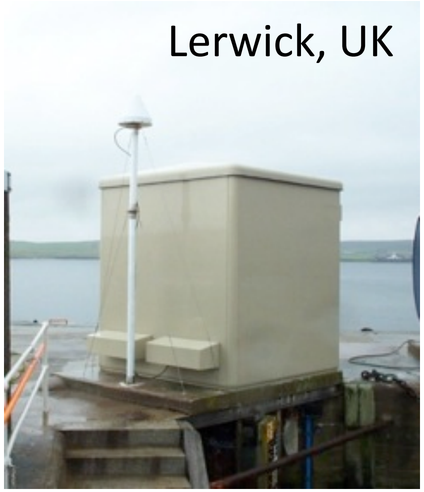
Land loss in the Gulf of Mexico 1932 -2011

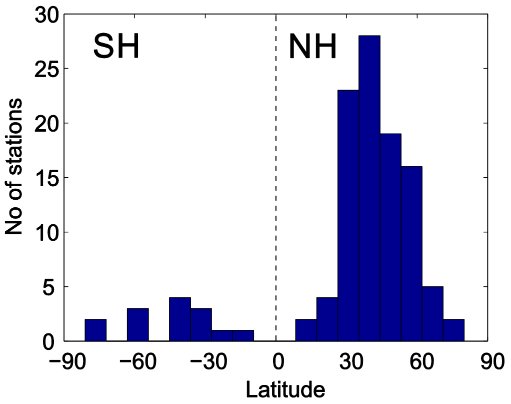


The IGS Tide Gauge Benchmark Monitoring (TIGA) Working Group

Goals and Objectives:

- To provide homogeneous sets of coordinates, velocities, robust uncertainties of continuous GNSS stations at or close to tide gauges (GNSS@TG)
- To establish and expand a global GNSS@TG network for satellite altimeter calibration studies and other climate applications
- To contribute to the IGS realization & densification of a global terrestrial reference frame
    - 2 TACs contributed to ITRF2014
- Promote the establishment of more continuous GNSS@TG, in particular in the southern hemisphere
- Promote the establishment of local ties between GNSS antenna and tide gauge benchmarks (TGBMs)



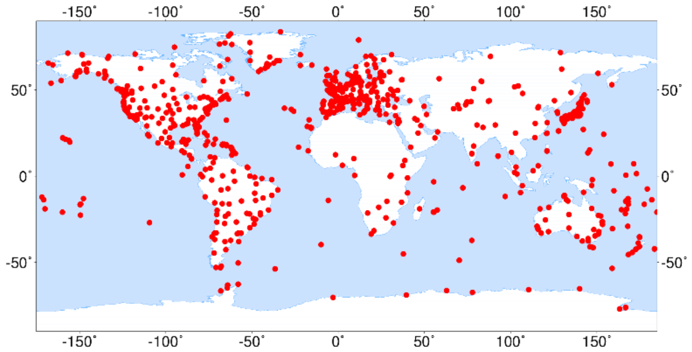


Current TIGA Analysis Centres (TAC)

TAC	Host Institutions	Software package	Contributors
BLT	British Isles continuous GNSS Facility (BIGF) and University of Luxembourg (UL), UK and Luxembourg	BSW52	F. N. Teferle A. Huneganw R. M. Bingley D. N. Hansen
DGF	Deutsches Geodätisches Forschungsinstitut (DGFI), Germany	BSW52	L. Sánchez
GFZ	GeoForschungsZentrum, Potsdam (GFZ), Germany	EPOS.P8	T. Schöne Z. Deng
ULR	Centre Littoral de Geophysique, Universite de La Rochelle (ULR), la Rochelle, France	GAMIT/ GLOBK Version 10.5	M.Gravelle A.Santamaría-Gómez, G. Wöppelmann

TIGA Combination

- The **main TIGA product** is an IGS-style **combination of** individual **TAC solutions**
- The **University of Luxembourg** is also a **TIGA combination center** (TCC)



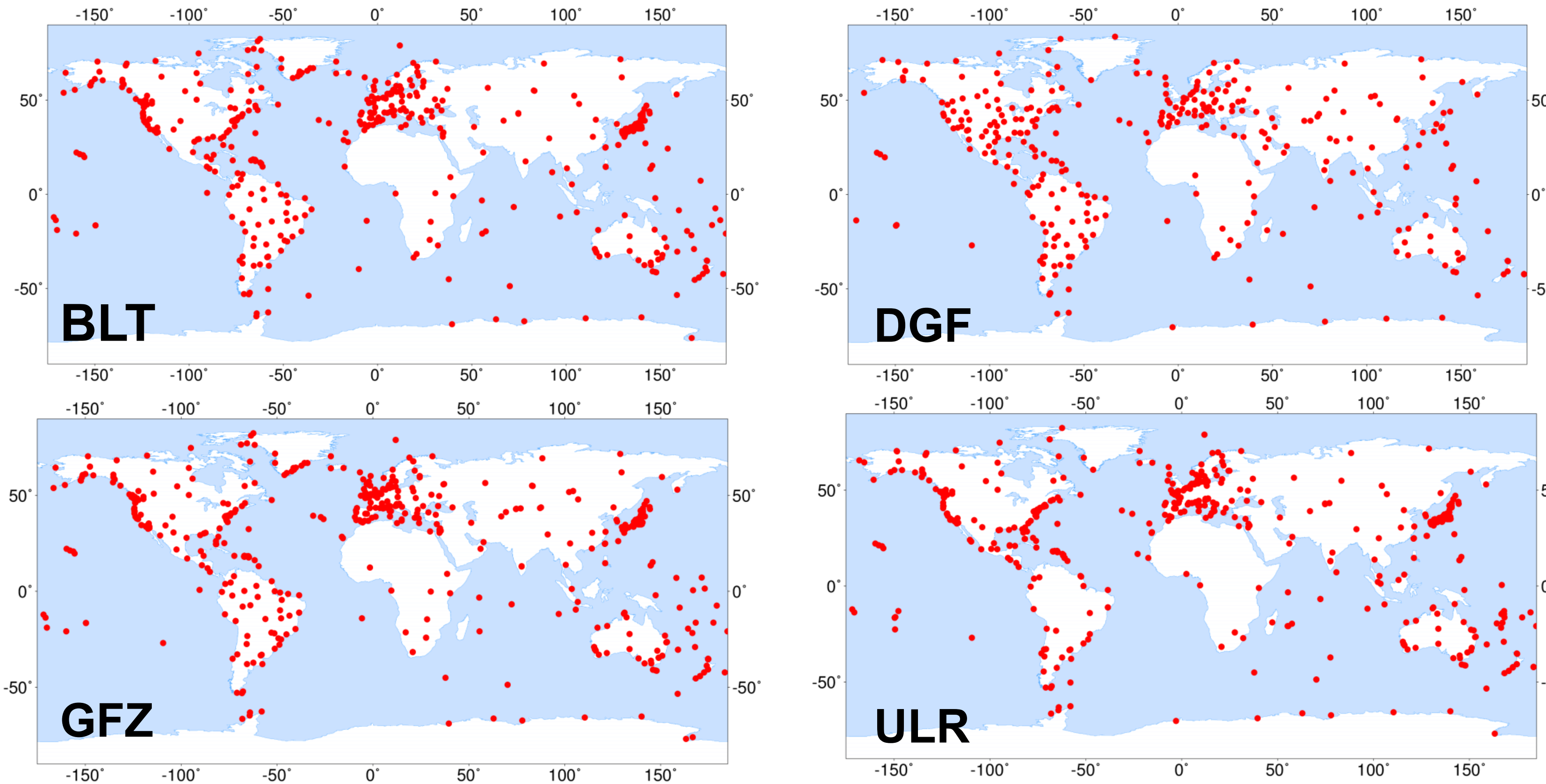
All tracking stations in the combined solution

- Daily TIGA repro2 SINEX combination
- Modelling of station position time series. Specifically:

    - Offsets, depending on TAC solutions
    - Computationally intensive, depends on the use of UL HPC infrastructure

- Long-term stacking
- Software packages for combination: CATREF, GLOBK

Current (repro 2) TACs Global Networks



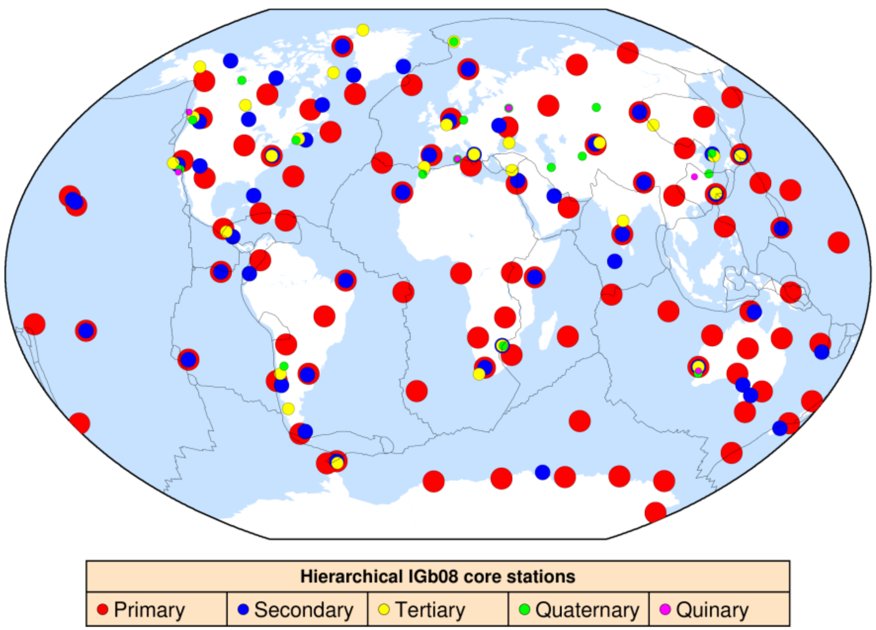
TIGA Data Centre: University of La Rochelle (ULR), www.sonel.org

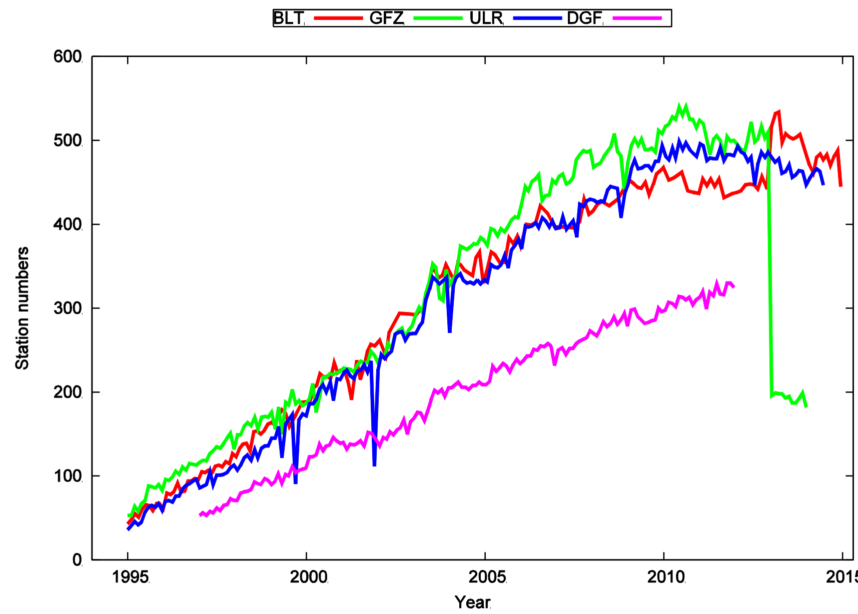
The TIGA repro2 Campaign

- Re-analysis of GNSS data collected by the IGS/TIGA network since 1995 to the end of 2014, using the latest models and methodology

- Main updates since the last reprocessing of IGS and adapted by TACs:
  - Common set of stations (IGb08 core)
  - Daily data integrations
  - IGS08.atx antenna PCV/PCO
  - IGb08 frame
  - IERS 2010 Conventions
  - New yaw attitude models during eclipsing seasons
  - A priori modeling of Earth radiation pressure and antenna thrust

Processing details TAC: repro2

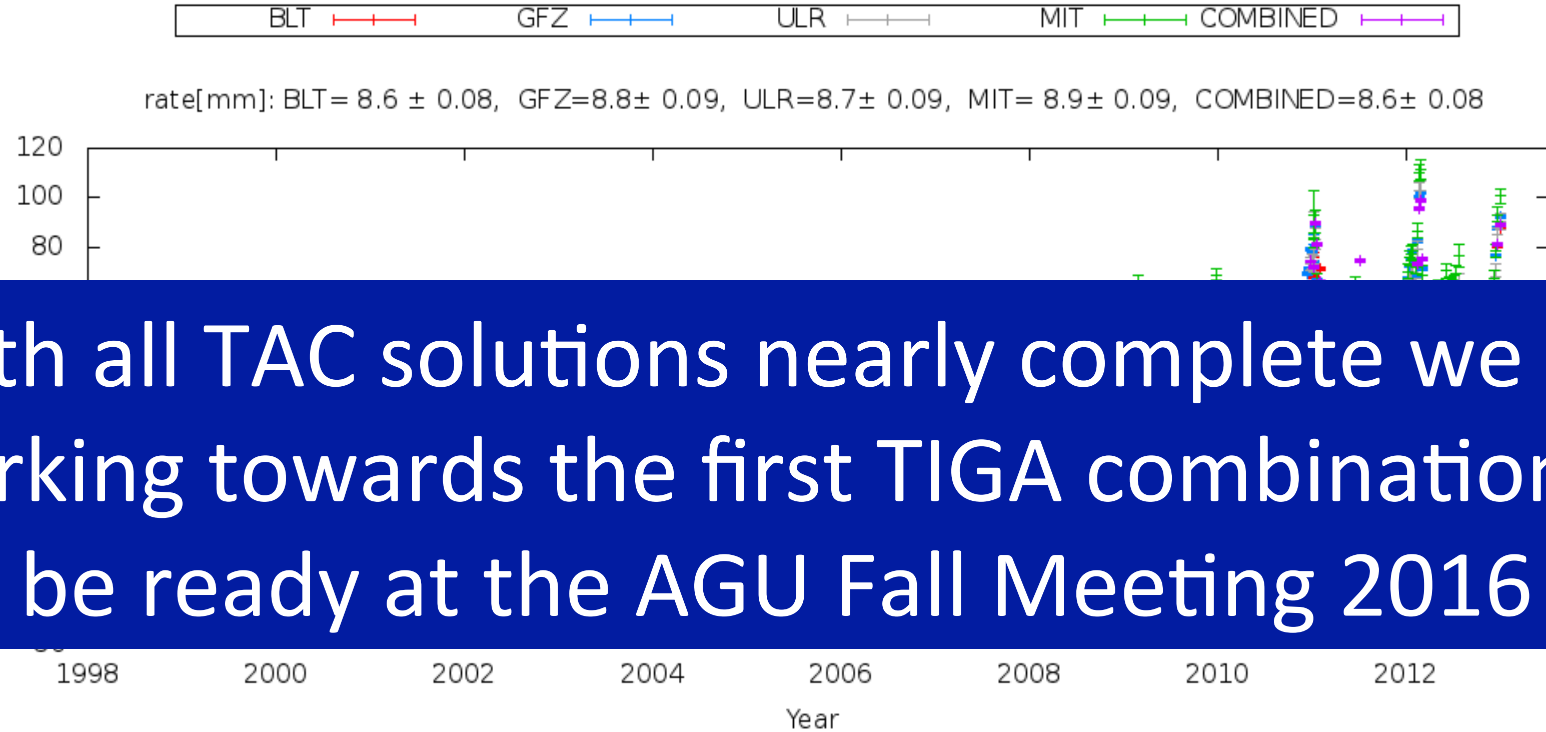




Global station network [core in red (91)] and substitutes sites [in blue (**52**), green (**27**), yellow (**17**) and brown (**6**)] in order of their priority used to align daily position estimates to the IGb08 reference frame.

- Most TACs process well over 400 stations since 2006
- At peak periods 550+ GPS stations are processed with many of them at or close to TGs

Preliminary TIGA Combination (with IGS AC MIT Solution): Height Time Series



With all TAC solutions nearly complete we are working towards the first TIGA combination to be ready at the AGU Fall Meeting 2016

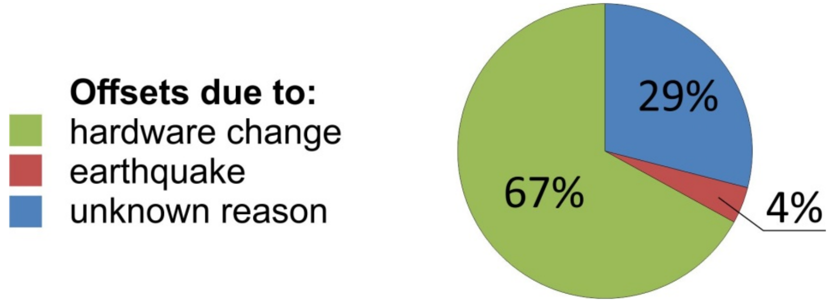
Example for VAAS, near the TG in Vasa, Finland. The combined solution provides a direct comparison of the TACs and a quality assurance for TACs and users.

Details of BLT repro2

Software	Bernese BSW5.2
Satellite Systems	GPS
Elevation cutoff angle	deg and elevation dependent weighting
Ionosphere	Ionospheric-free linear combination (L3) including 2nd orders corrections
Antenna PCV	IGS absolute elevation and azimuth dependent PCV igs08.atx file
Troposphere	1.GMF and DRY GMF mapping for the a priori values and while estimating hourly ZWD parameters using WET GMF 2. VMF mapping for the a priori values and ZWD estimate using WET VMF
Troposphere Gradients	Chen Herring for tropospheric gradient estimation
Conventions	IERS2010
Ocean tides	FES2004
Gravity Field	EGM2008
Ambiguity Resolution	Resolved to integers up to 6000 km using different techniques depending on the baseline length
Datum	No-Net-Rotation (NNR) and No-Net-Translation (NNT) with respect to IGb08
Network	Upwards 450 stations
Time period	1994 to 2015
Data	Double-differenced phase and code observations

GPS Time Series Analysis

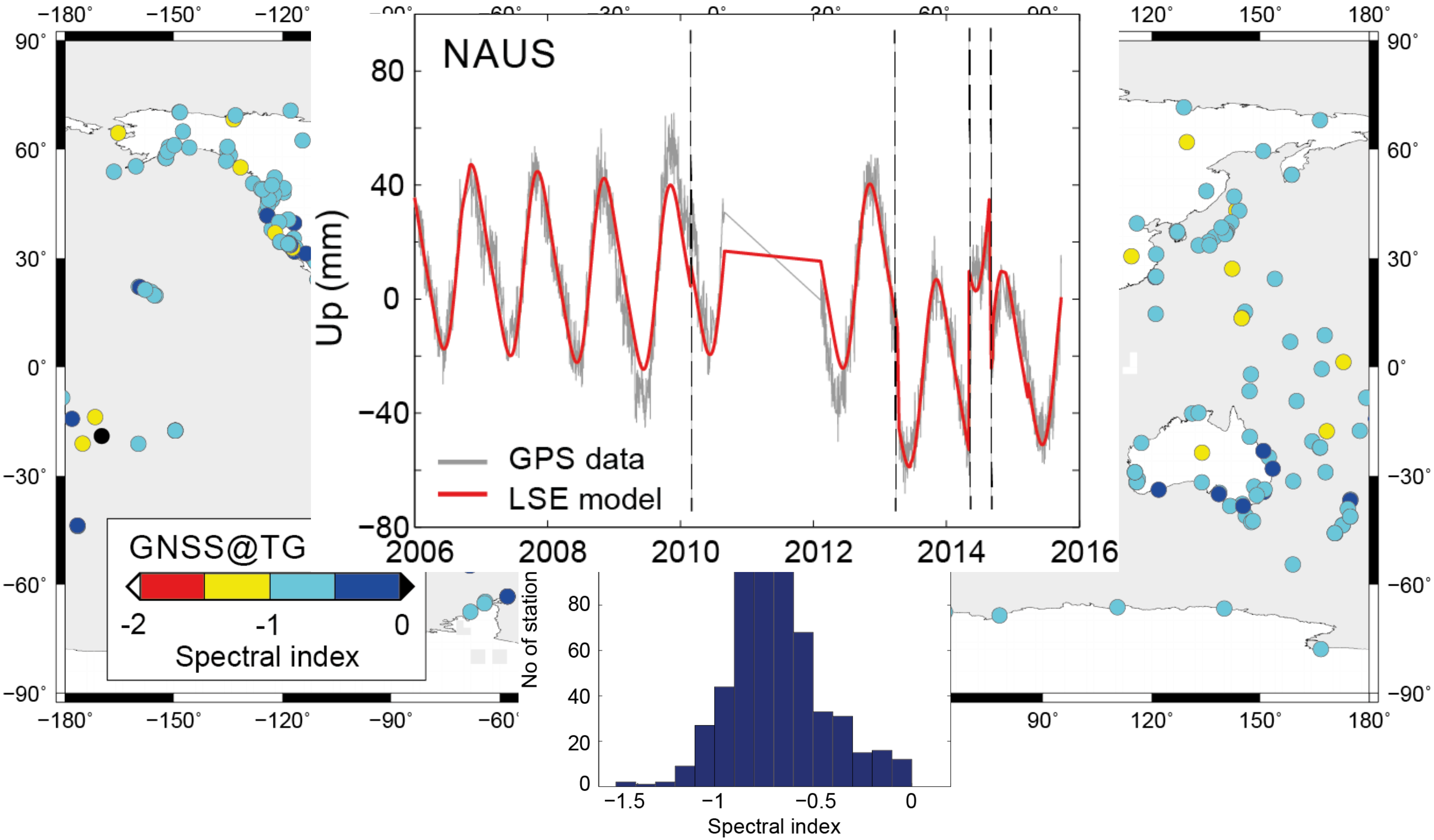
- **Outliers:** interquartile range (IQR)
- **Offsets:** epochs identified in the International Terrestrial Reference Frame 2008 solution and updated with our own solution-specific offset information and visual inspection



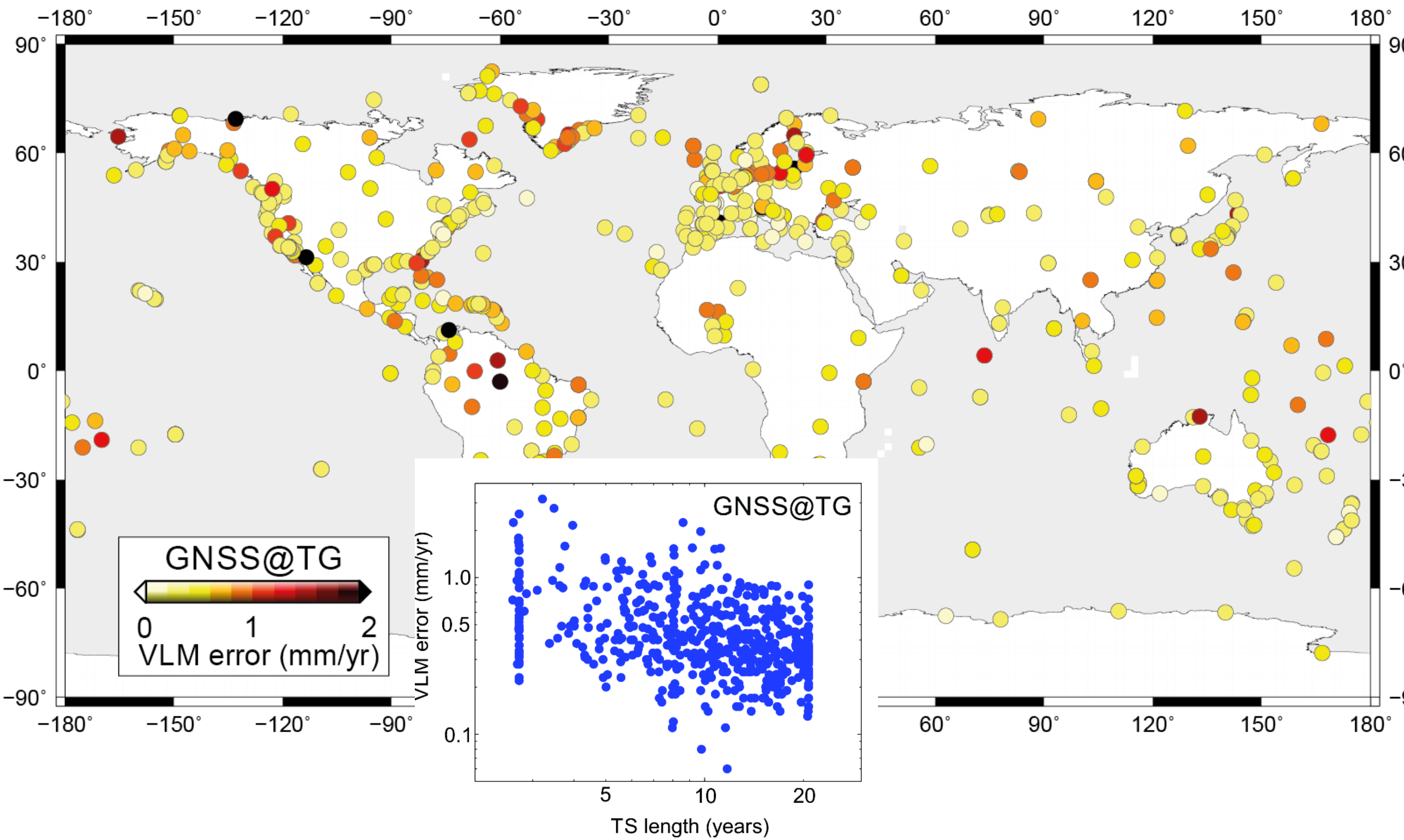
Noise	κ
White	-1
Flicker	-2
Random-Walk	-3

- **Noise analysis:** Hector software (Bos et al., 2013):
  - White noise plus power-law process (WN+PLN(κ))
  - Method: Maximum Likelihood Estimation (MLE)
- **Vertical Land Movement (VLM) Estimates:**
  - Vertical Velocities with realistic uncertainties

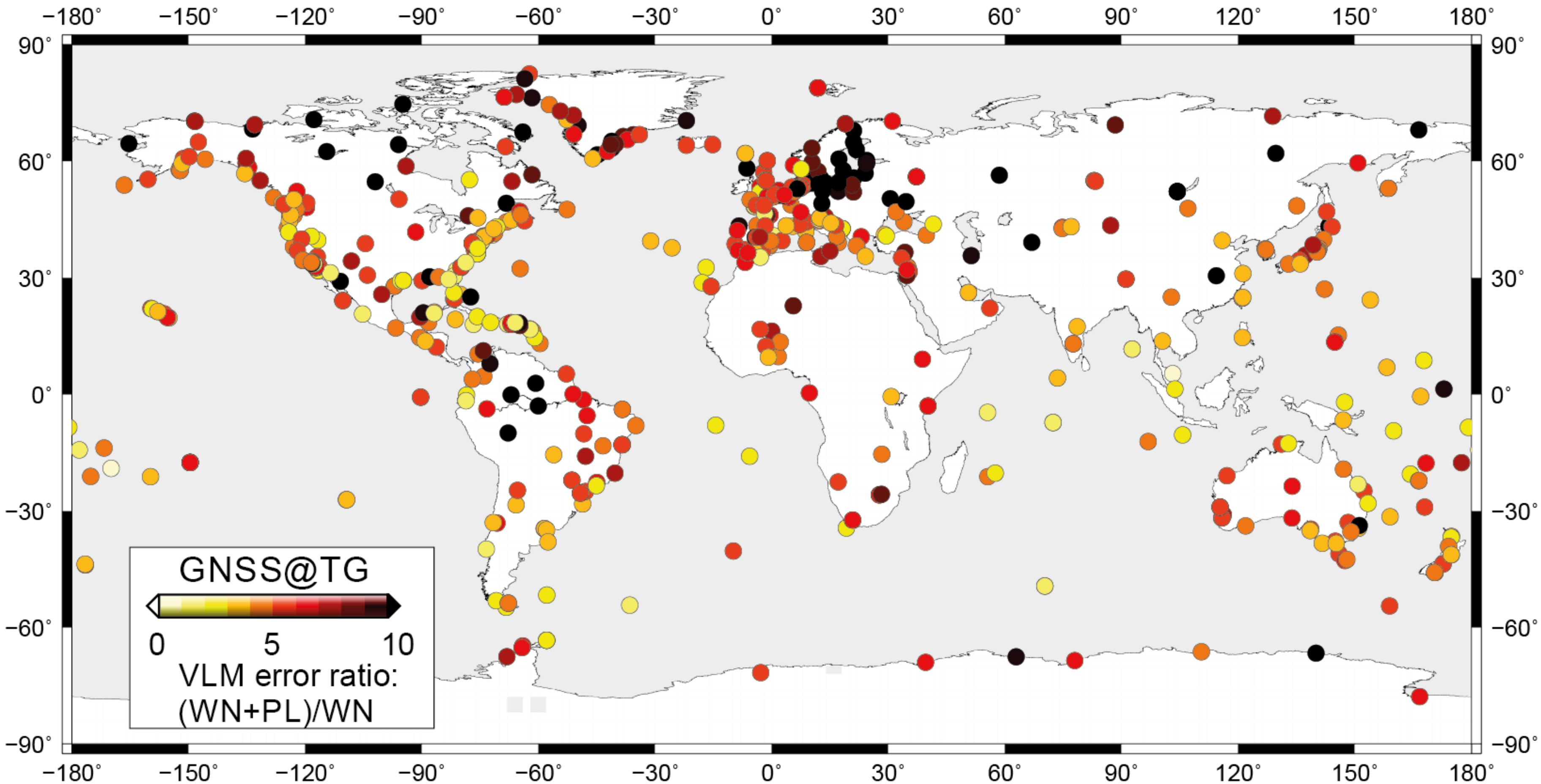
Spectral Index Estimates



Velocity Uncertainties (White+Power-Law Noise)

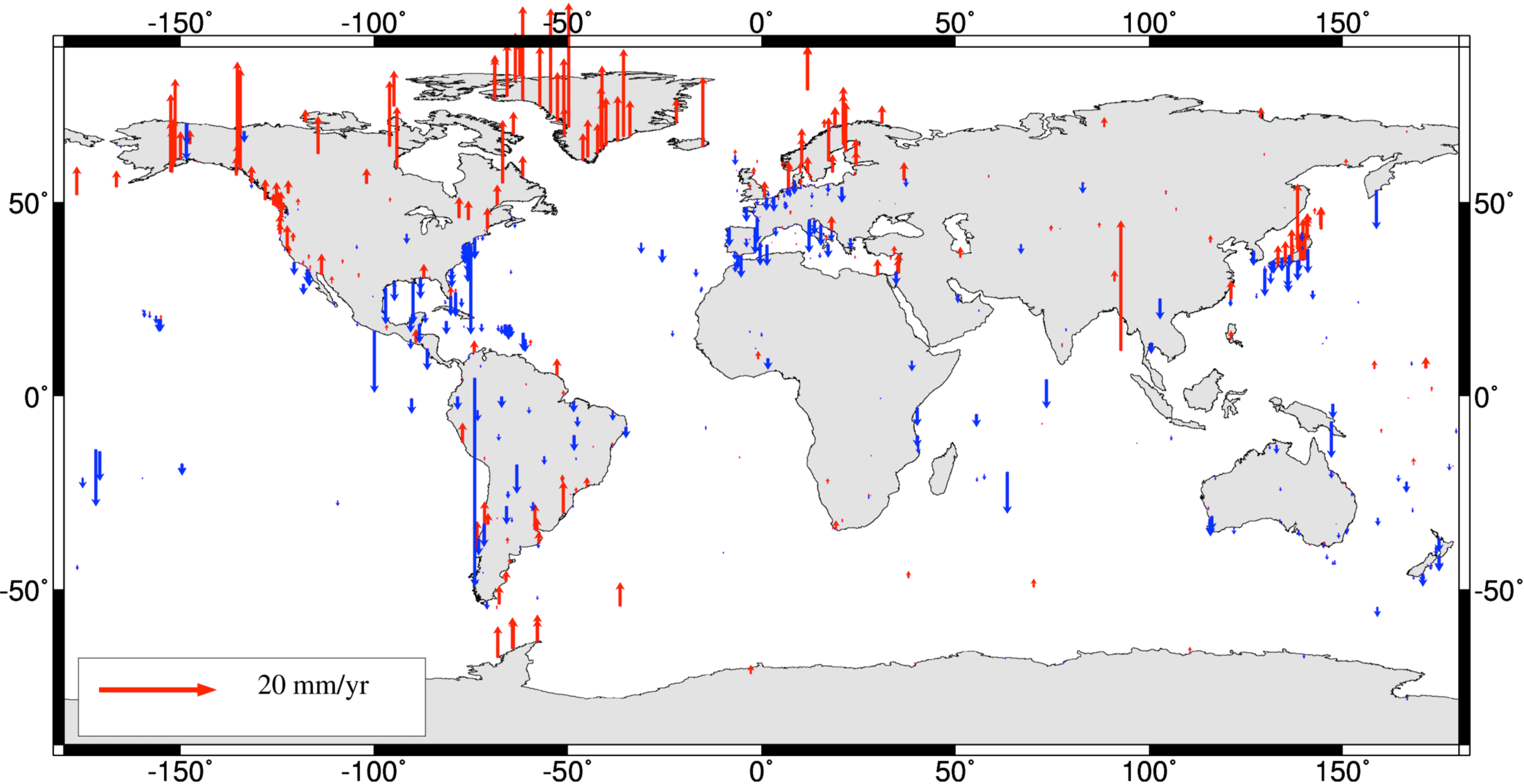


Ratio of Uncertainties (WN+PLN)/WN



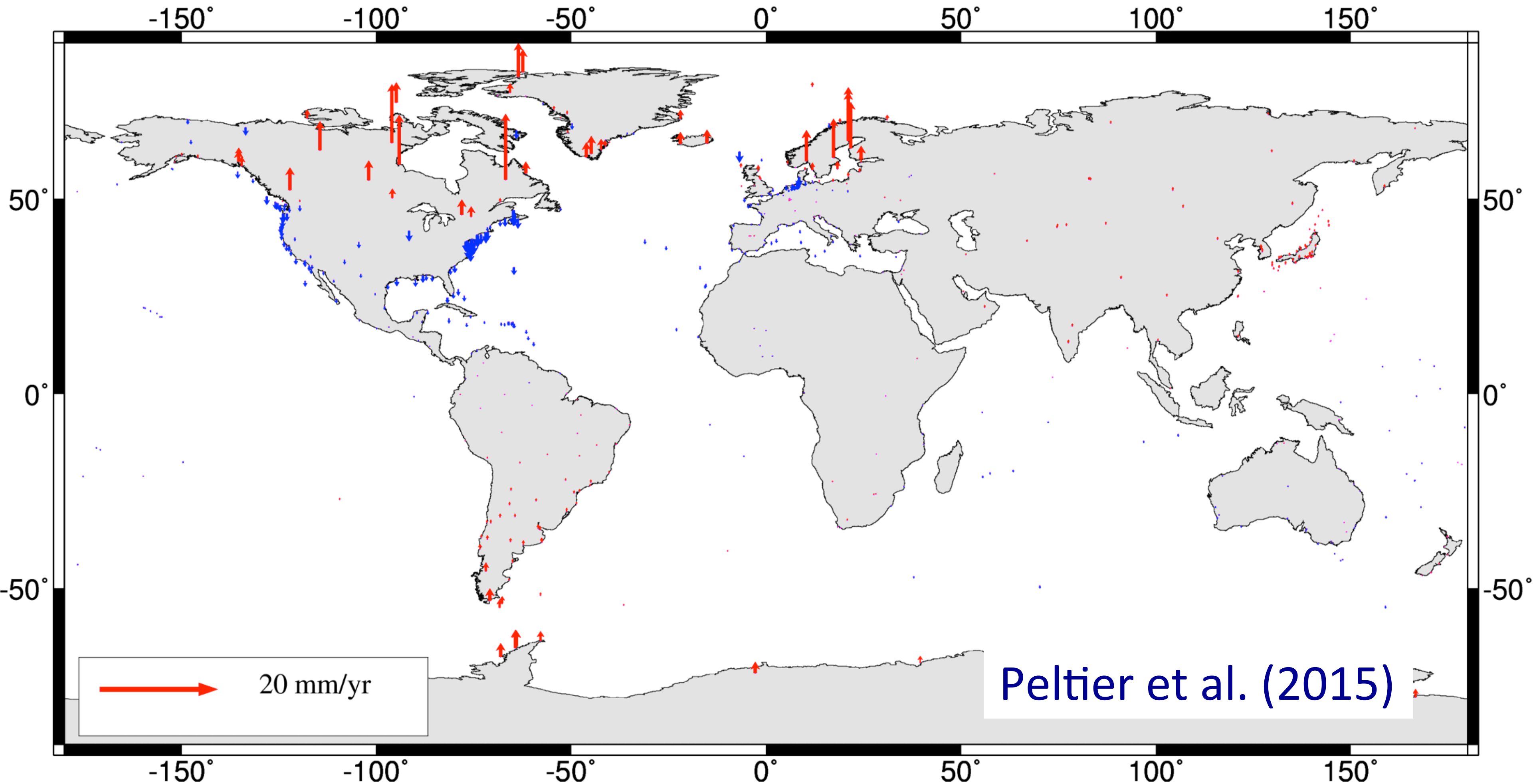
- WN-only uncertainties would be 5-10+ times underestimated
- For a significant number of stations the uncertainties would be too optimistic by more than an order of magnitude

BLT Vertical Velocities



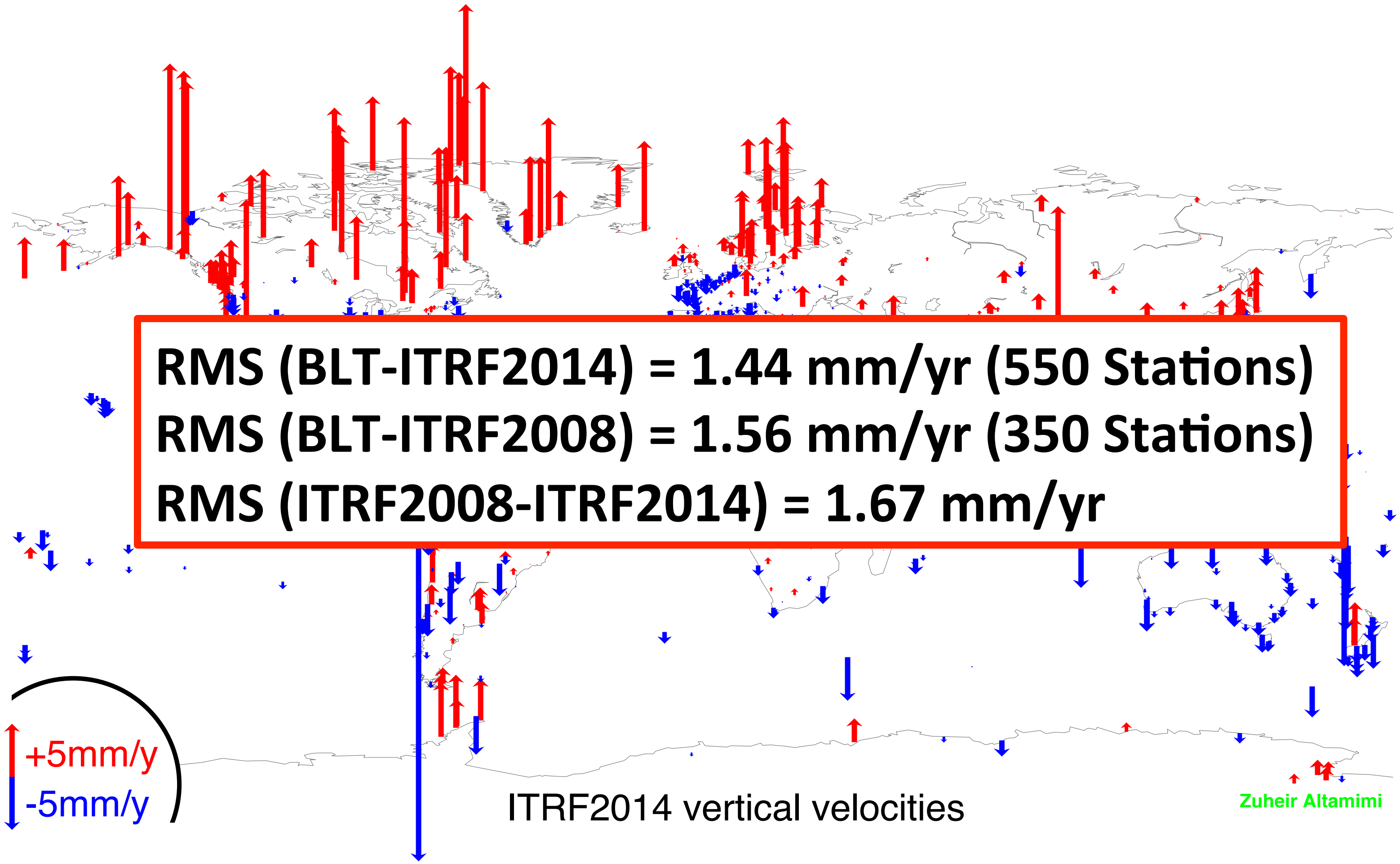
RMS Agreement for corresponding locations (BLT-ULR): 0.83 mm/yr
ULR, Wöppelmann et al. (2009)

ICE-6G(VM5a) Model Vertical Velocities at TGs



RMS Agreement for corresponding locations (BLT-GIA): 1.29 mm/yr

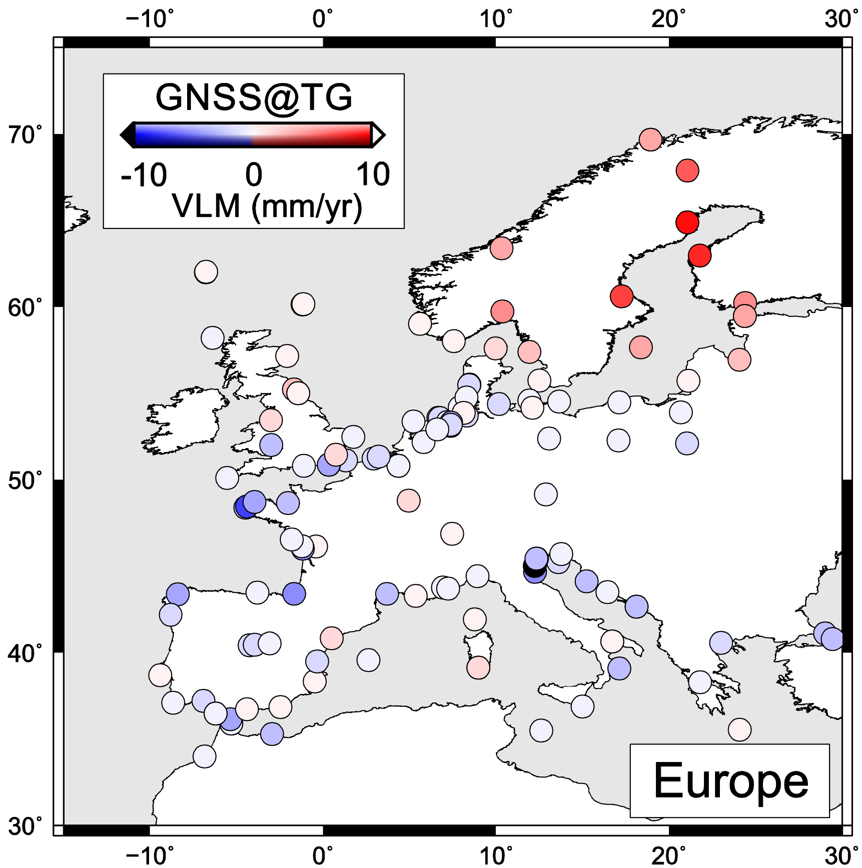
ITRF2014 Vertical Velocities (with formal error less than 0.2mm/yr)

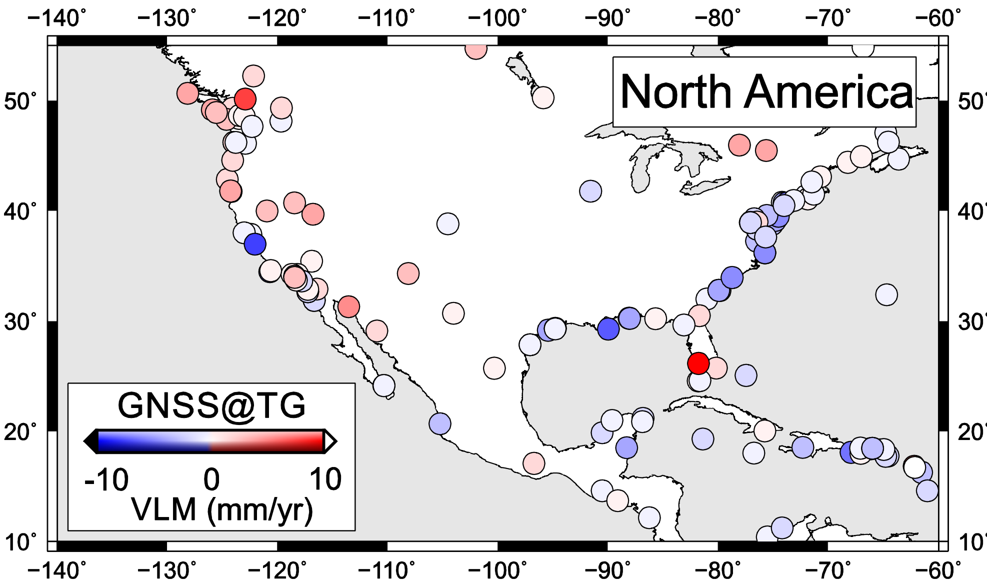


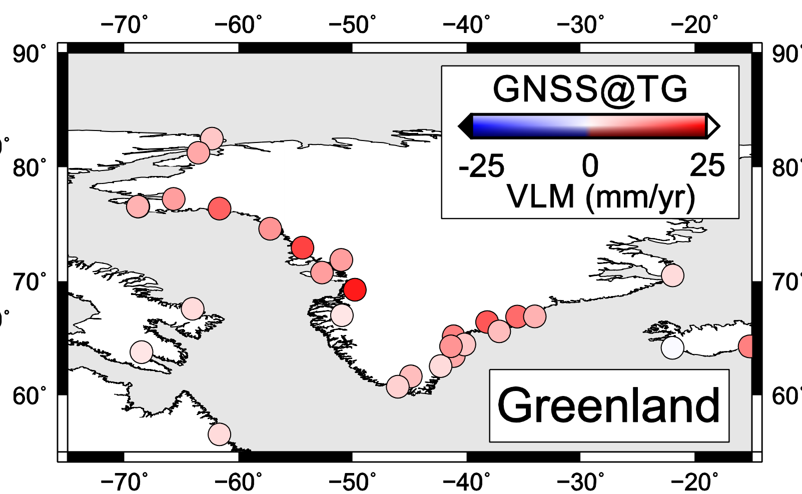
RMS (BLT-ITRF2014) = 1.44 mm/yr (550 Stations)
RMS (BLT-ITRF2008) = 1.56 mm/yr (350 Stations)
RMS (ITRF2008-ITRF2014) = 1.67 mm/yr

Altamimi et al. (2016)

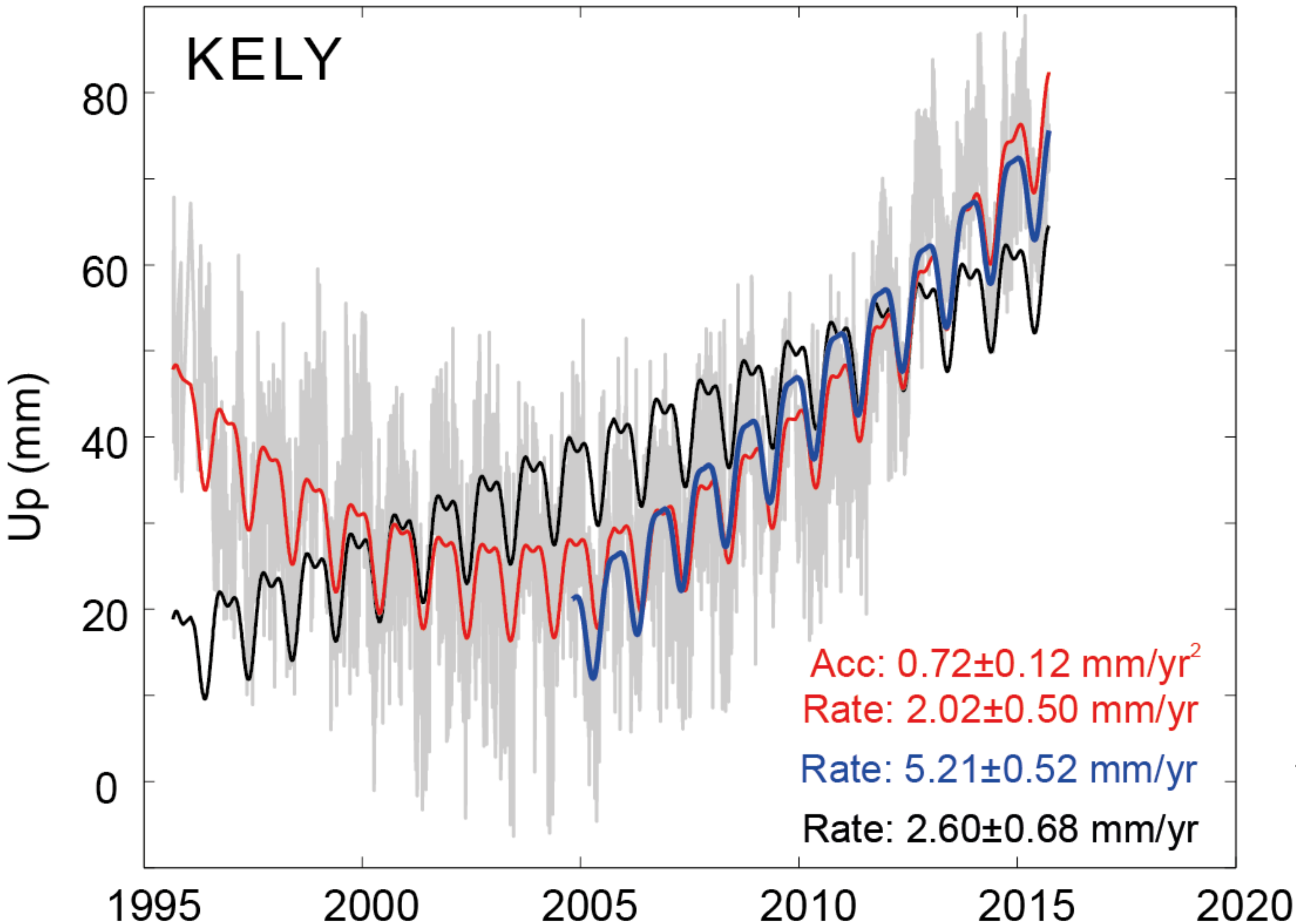
BLT Vertical Velocities Regions (1)





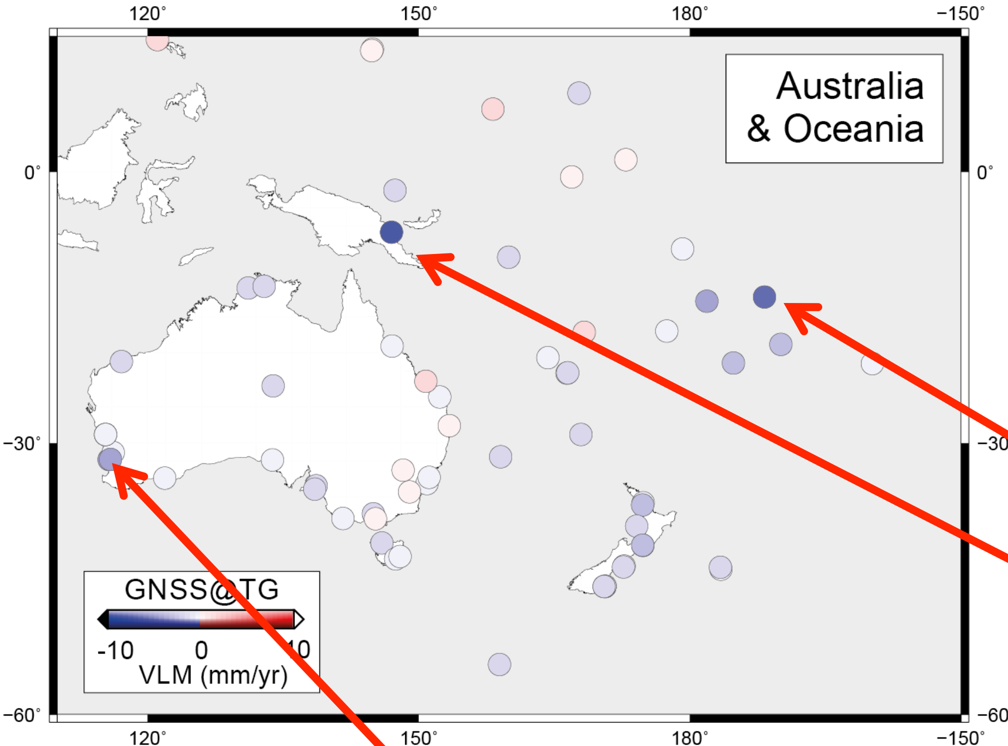


Non-Linear Motions in Greenland



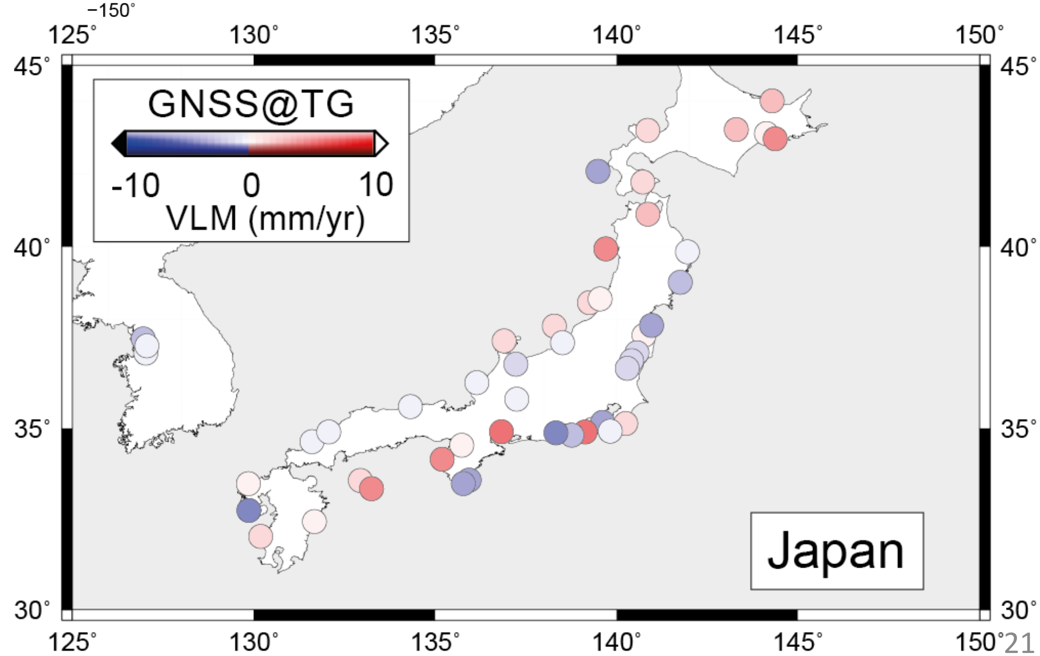
Bevis and Brown (2014) have used the time series for KELY up to 2010.4 and found the UP acceleration to be 0.49 ± 0.02 mm/year^2.

BLT Vertical Velocities Regions (2)

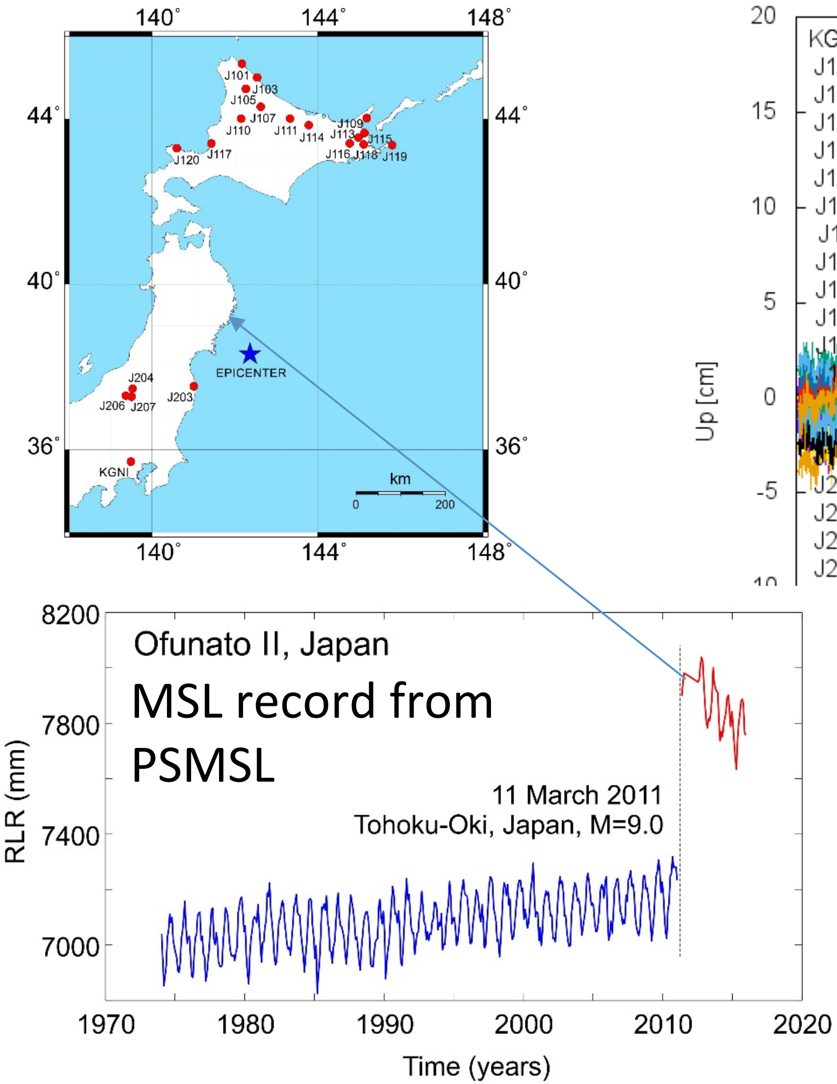


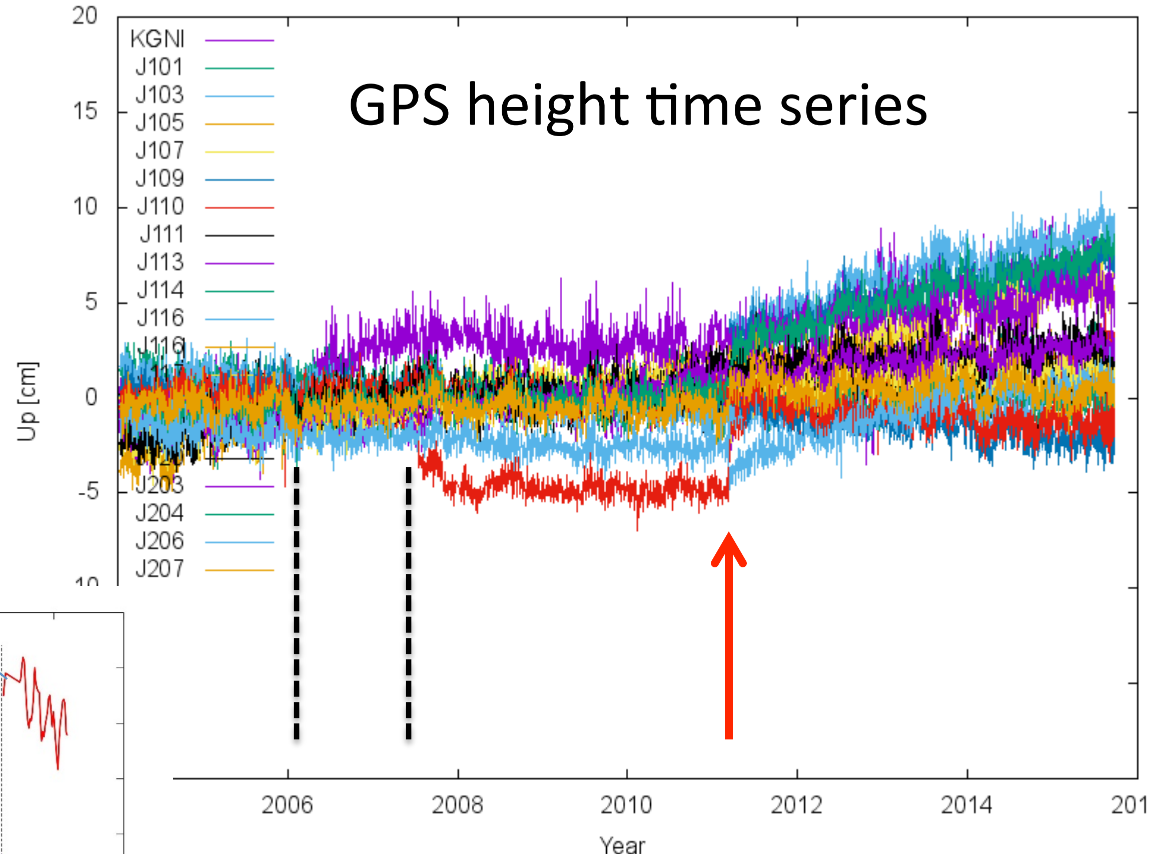
Samoa (SAMO)
Rate= -5.19 ± 0.76 mm/yr
Lae, Papa New Gunea (LAE1)
Rate= -6.26 ± 0.41 mm/yr

Featherstone et al. (2015) reported of non-linear subsidence at the TG in Fremantle near the GNSS stations PERT and HIL1. due to ground water extraction. This subsidence is different from that observed by the GNSS stations. Only evidence from various geodetic observations can provide the detailed understanding of the local issues.



Tōhoku 2011 Earthquake, Japan
Impacts of Post-seismic Deformation

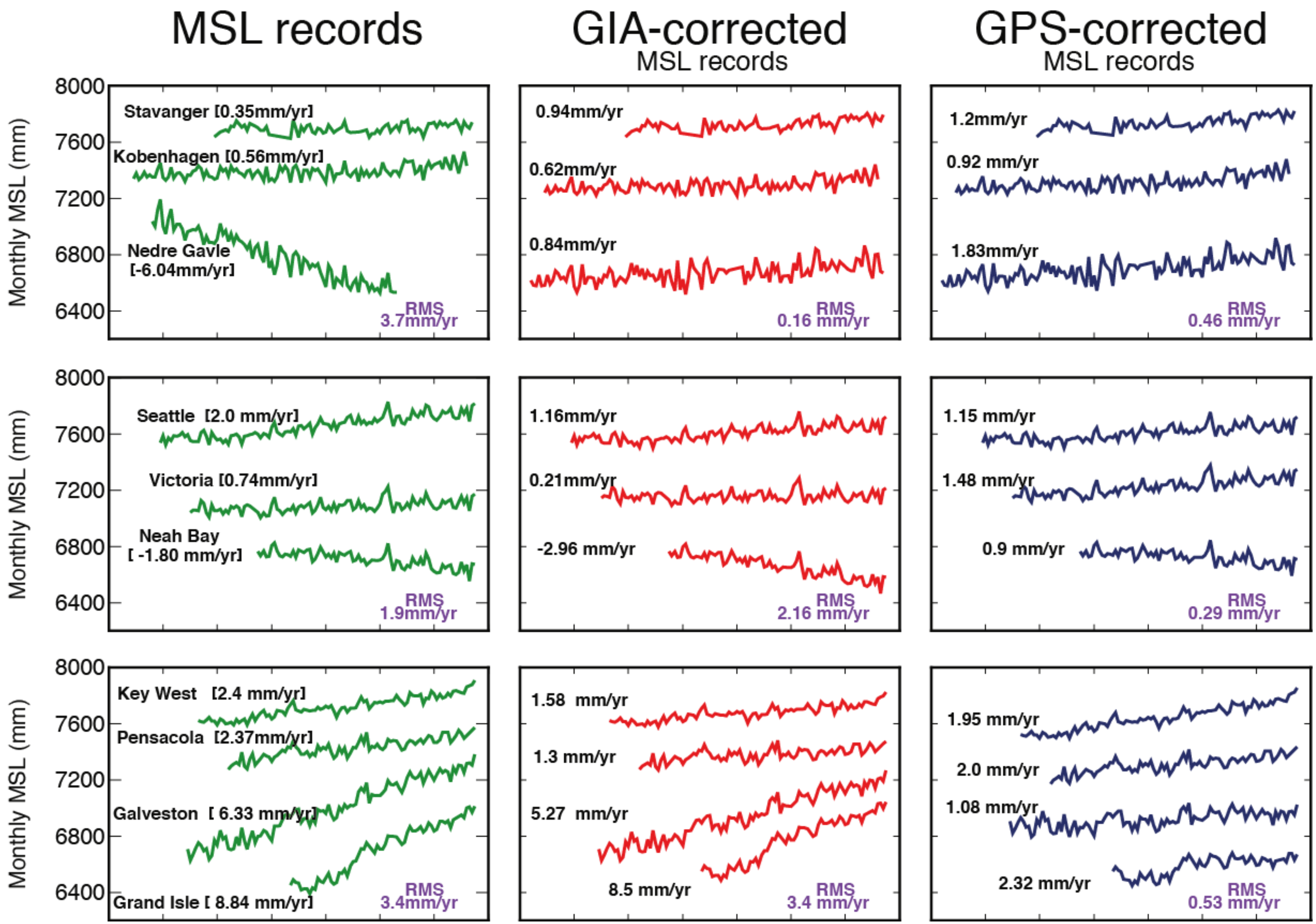




There are 34 pairs of GPS and TG for Japan. Each MSL records in the PSMSL RLR data base needs to be inspected for known earthquakes. See also Rudenko et al. (2013).

RLR MSL Records from PSMSL

(VLM-Corrected with GIA (ICE-6G(VM5a)) and GPS (BLT solution))



VLM-Corrected MSL Records

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	ULR Trend	BLT Trend	TG+GIA Trend	TG+ULR Trend	TG+BLT Trend
North Europe										
STAVANGER	63	16000	47	0.35 ±0.18	0,59	2.68 ±0.82	0.82 ±0.40	0,94	3,03	1,17
KOBENHAVN	101	7300	82	0.56 ±0.12	0,06	0.97 ±0.35	0.37 ±0.85	0,62	1,53	0,93
NEDRE GAVLE	90	11000	99	-6.04 ±0.22	6,87	7.12 ±0.19	7.87 ±0.88	0,83	1,08	1,83
North Sea and English Channel										
ABERDEEN	103	2	361	0.97 ±0.25	1,01	0.67 ±0.22	0.77 ±0.21	1,98	1,64	1,74
NEWLYN	87	10	202	1.81 ±0.12	-0,72	-0.21 ±0.27	-0.26 ±0.17	1,09	1,60	1,55
BREST	83	350	1	0.97 ±0.12	-0,61	-0.54 ±0.77	-1.84 ±0.28	0,36	0,43	-0,87
East Atlantic										
CASCAIS	97	84	52	1.29 ±0.18	-0,34	0.12 ±0.19	0.16 ±0.24	0,95	1,41	1,45
LAGOS	61	138	162	1.56 ±0.25	-0,41	-0.1 ±0.29	-0.97 ±0.22	1,15	1,46	0,59
Mediterranean										
MARSEILLE	105	5	61	1.33 ±0.12	-0,32	0.04 ±0.25	0.13 ±0.30	1,01	1,37	1,46
GENOVA	78	1000	59	1.17 ±0.08	-0,16	-0.16 ±0.85	-0.39 ±0.18	1,01	1,01	0,78

TG stations are selected and grouped according to Douglas (2001)
ULR Trends (Wöppelmann et al., 2009; GRL)

VLM-Corrected MSL Records (2)

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	ULR Trend	BLT Trend	TG+GIA Trend	TG+ULR Trend	TG+BLT Trend
NE North America										
EASTPORT	63	800	332	2.21 ±0.3	-1,34	2.07 ±0.87	0.04 ±0.37	0,87	4,28	2,25
NEWPORT	70	500	351	2.48 ±0.14	-1,42	0.42 ±0.37	-0.22 ±0.21	1,06	2,90	2,26
HALIFAX	77	3100	96	3.06 ±0.19	-1,54	-0.72 ±0.31	-1.00 ±0.15	1,52	2,34	2,06
ANNAPOLIS	70	11577	311	3.5 ±0.14	-1,84	0.69 ±0.94	-3.15 ±0.11	1,66	4,19	0,35
SOLOMON ISL	62	200	412	3.69 ±0.18	-1,71	-2.43 ±0.69	-1.54 ±0.33	1,98	1,26	2,15
NW North America										
VICTORIA	86	12000	166	0.74 ± 0.05	-0,53	1.2 ±0.23	0.74 ±0.20	0,21	1,94	1,48
NEAH BAY	65	7800	385	-1.8 ±0.09	-1,16	3.82 ±0.69	2.67 ±0.28	-2,96	2,02	0,87
SEATTLE	104	5900	127	1.99 ± 0.14	-0,84	0.14 ±0.31	-0.85 ±0.22	1,15	2,13	1,14
SE North America										
CHARLESTON I	82	8200	234	3.31 ±0.28	-1,13	-1.31 ±0.44	-0.41 ±0.73	2,18	2,00	2,90
GALVESTON II	94	4200	161	6.33 ±0.31	-1,06	-5.89 ±0.61	-5.25 ±0.55	5,27	0,44	1,08
MIAMI BEACH	45	4800	363	2.29 ±0.26	-0,83	0.46 ±0.61	1.38 ±0.72	1,46	2,75	3,67
KEY WEST	90	16000	188	2.40 ±0.16	-0,82	-0.59 ±0.38	-0.84 ±0.37	1,58	1,81	1,56
SW North America										
LA JOLLA	72	700	256	2.21 ±0.12	-0,72	-0.38 ±0.62	0.54 ±0.58	1,49	1,83	2,75
LOS ANGELES	78	2200	245	0.94 ±0.14	-0,74	-0.3 ±0.48	0.11 ±0.28	0,20	0,64	1,05
New Zealand										
AUCKLAND II	85	5	150	1.32 ±0.11	0,08	-0.87 ±0.48	-0.72 ±0.25	1,40	0,45	0,60
PORT LYTTELTON	101	2	247	2.18 ±0.27	0,14	-0.59 ±0.35	0.17 ±0.25	2,32	1,59	2,35
Pacific										
HONOLULU	99	5	155	1.43 ±0.3	-0,23	-0.15 ±0.36	-0.78 ±0.19	1,20	1,28	0,65

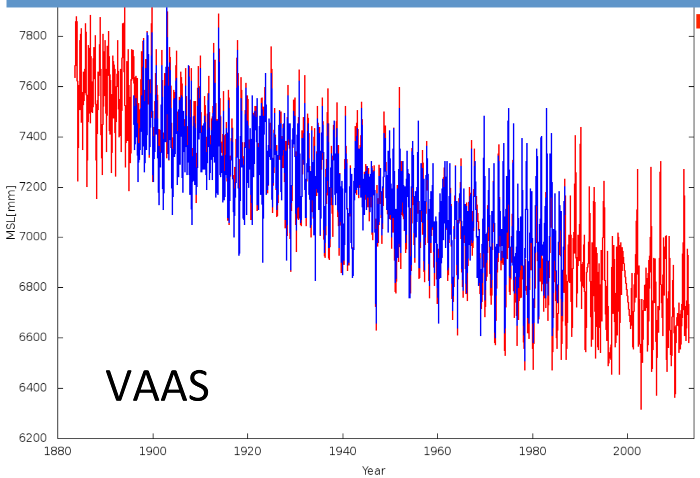
Standard deviations of Individual Sea Level Change Estimates using GIA, ULR and BLT VLM estimates

	No corrections to TG	GIA-corrected ICE6G (VLM5C)	GPS-corrected ULR	GPS-corrected BLT
Scatter of MSL Trends	**2.08**	**1.26**	**0.99**	**0.92**

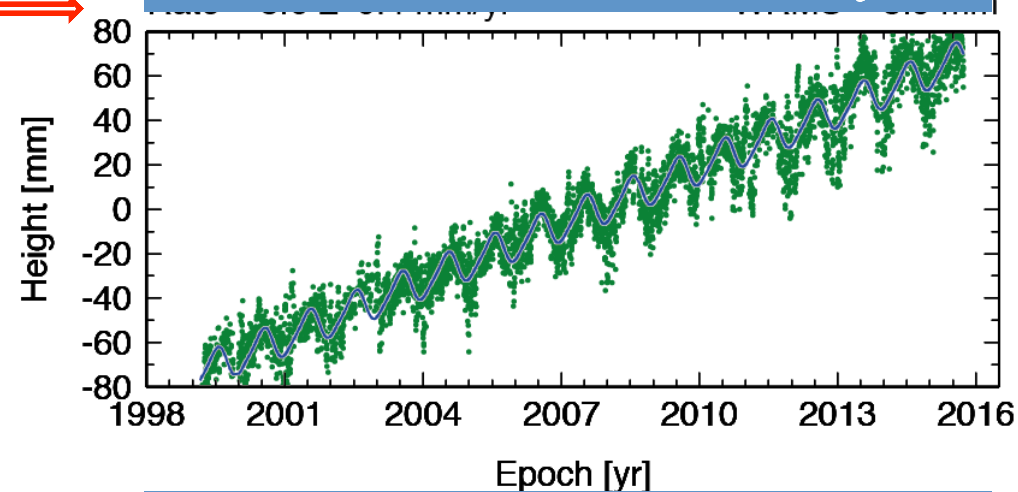
Values in mm/yr; 27 TGs were used.

Example of sea level applications

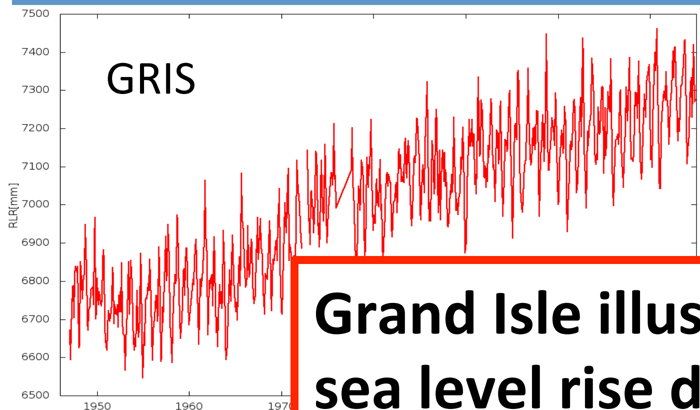
TG: -7.2 +/- 0.2 mm/yr



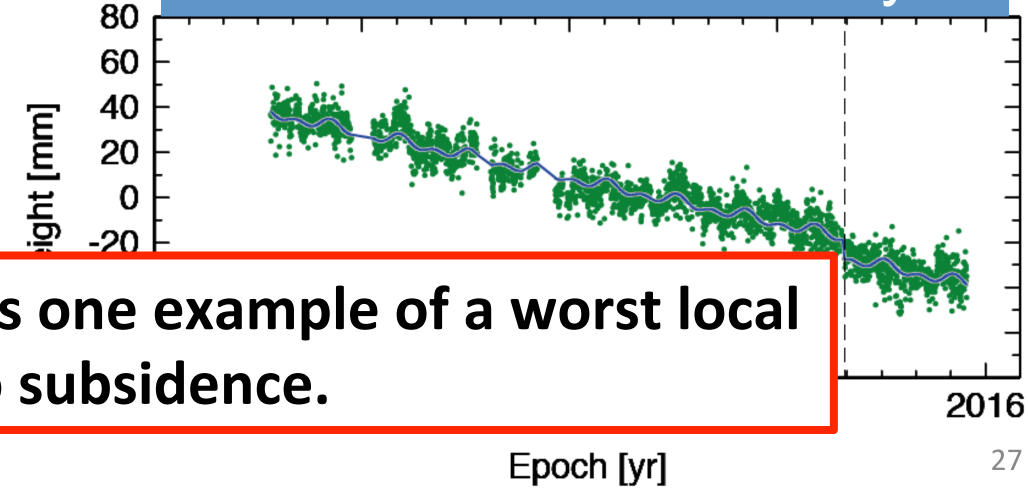
GPS: 8.6 +/- 0.4 mm/yr



TG: 9.0 +/- 0.2 mm/yr



GPS: -6.7 +/- 0.3 mm/yr



Grand Isle illustrates one example of a worst local sea level rise due to subsidence.

Conclusions

- The TIGA combination will be *the* solution for the sea level community
  - Now that TAC submissions are nearly complete the first release is foreseen for the AGU FM 2016
- Based on our BLT solution the analysis of the time series has started and takes into account all effects
  - offsets, accelerations, non-linear motions and multi-trend approaches and time-variable seasonal amplitudes
- Evaluations of the VLM estimates and interpretations in terms of sea level changes have been started based on the BLT solution

Thank you for your attention!

Acknowledgments

- Addisu Hunegnaw is funded by the University of Luxembourg IPRs GSCG and SGSL
- Anna Klos' visits to the University of Luxembourg were funded through the Polish Science Foundation and the COST Action ES1206
- Kibrom Ebuy Abraha is funded by the Fonds National de la Recherche, Luxembourg (Reference No. 6835562)
- Janusz Bogusz is supported by the Faculty of Civil Engineering and Geodesy of the MUT statutory research funds.
- The computational resources used in this study were partly provided by the High Performance Computing Facility at the University of Luxembourg (ULHPC)
- We acknowledge IGS/TIGA for providing the GNSS data and CODE for their products