On the Scientific Applications of IGS Products: An Assessment of the Reprocessed TIGA Solutions and Combined Products

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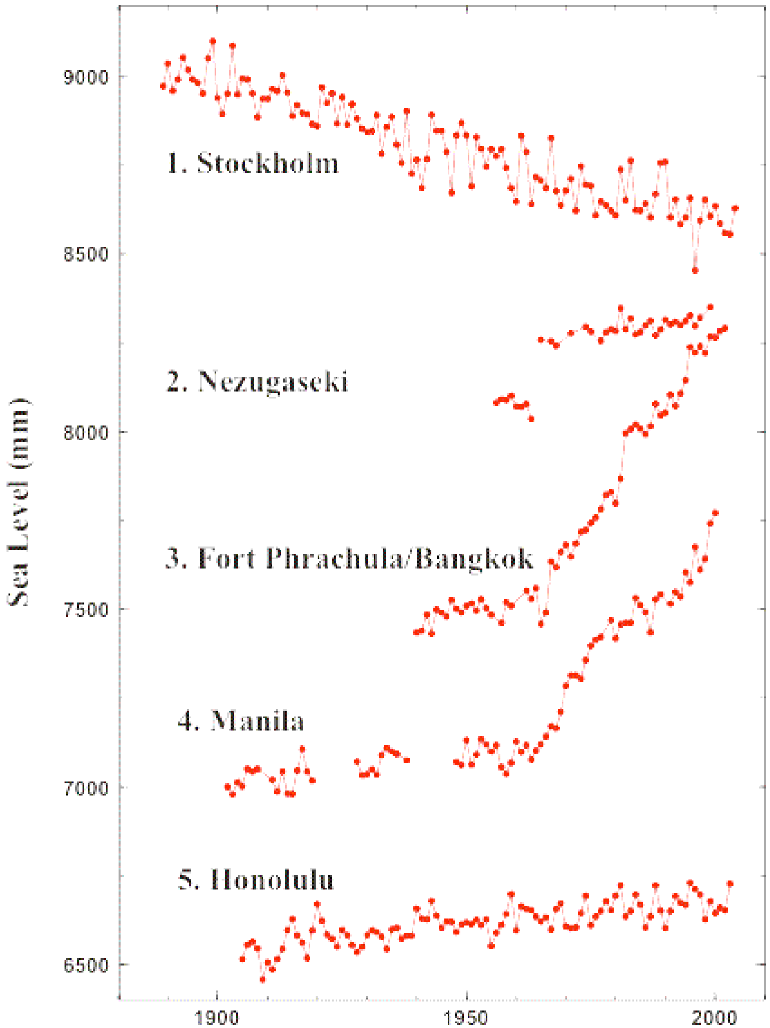
[4] British Isles continuous GNSS Facility, University of Nottingham, United Kingdom
[5] German Geodetic Research Institute, Technical University of Munich (DGFI), Germany
[6] Geoscience Australia, Australia

IGS Workshop 2017, July 02-07. 2017, Paris, France

Overview

- Some Background
- TIGA Combination
- Internal Evaluations
  - TAC Contributions
- External Evaluations
  - ITRF2014, JPL and NGL Solutions
  - Comparisons to Absolute Gravity
  - Impact on Sea Level Change Estimates
- Conclusions

Mean Sea Level (MSL) Records from PSMSL

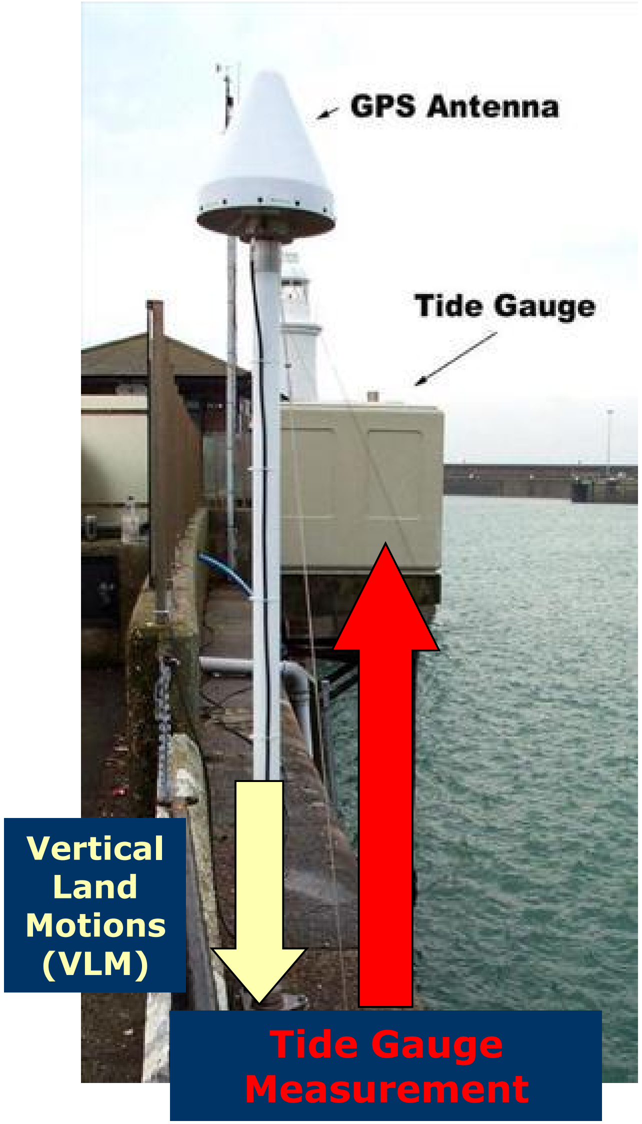


- **Stockholm - Glacial Isostatic Adjustment** (GIA; sometimes called Post Glacial Rebound or PGR): Site near Stockholm shows large negative trend due to crustal uplift.
- **Nezugaseki - Earthquakes**: This sea level record from Japan, demonstrates an abrupt jump following the 1964 earthquake.
- **Fort Phrachula/Bangkok - Ground water extraction**: Due to increased groundwater extraction since about 1960, the crust has subsided causing a sea level rise.
- **Manila - Sedimentation**: Deposits from river discharge and reclamation work load the crust and cause a sea level rise.
- **Honolulu - A 'typical' signal** that is in the 'far field' of GIA and without strong tectonic signals evident on timescales comparable to the length of the tide gauge record.

(PSMSL, 2015)

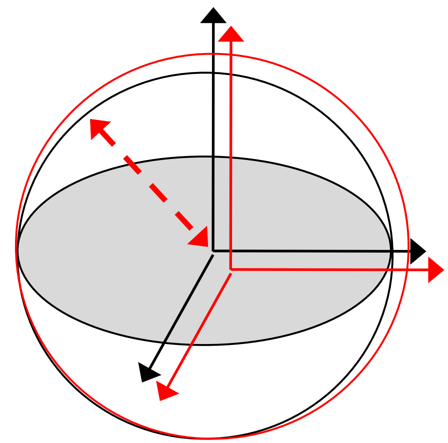
A Brief History of GNSS Tide Gauge Monitoring

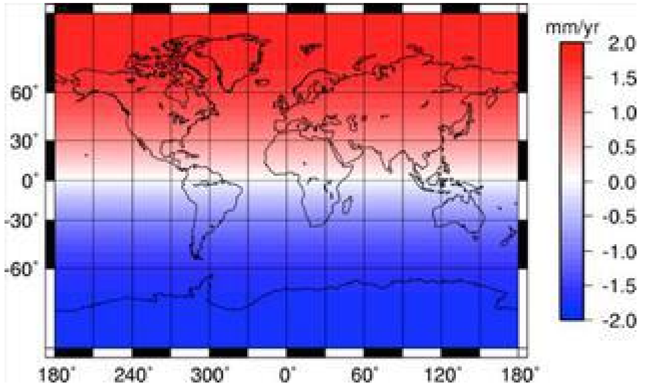
- IAPSO committee recommends GPS to monitor tide gauge benchmarks [Carter et al, 1989]
  - To determine vertical land movements (VLM)
- First attempts using episodic GPS in UK [Ashkenazi et al., 1993]
- IAPSO committee and IGS/PSMSL recommend continuous GPS [Carter, 1994; Neilan et al, 1997]
- IGS establishes TIGA PP (2001) which becomes TIGA WG after 2010
- Many projects to measure geocentric sea level [Sanli and Blewitt, 2001; Teferle et al., 2002, Snay et al., 2007; Wöppelmann et al., 2007; …]
- …but, it was not so straight forward as initially thought…



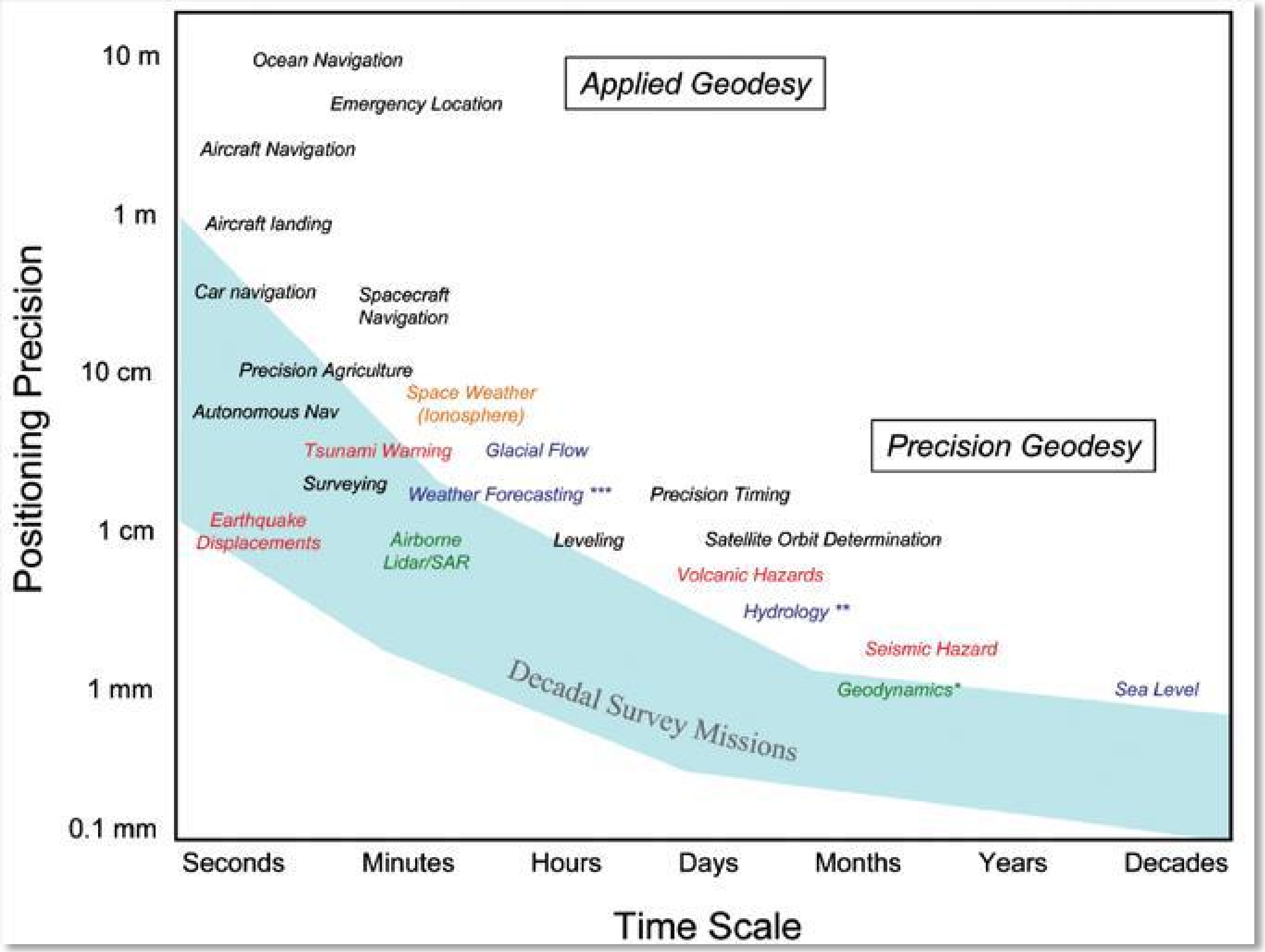
Reference Frames Requirements

- For sea level studies (e.g. tide gauge monitoring, satellite altimetry) the vertical component is of primary concern
- Vertical velocities are measured conceptually relative to the geocentre, but in reality are relative to a practical realization – a reference frame
- Accuracy of the vertical velocities depends on the **stability of the origin** and **scale** of this frame
- Sea level studies require a **frame stability of 0.1 mm/yr** and a **scale stability of 0.01 ppb/yr** (e.g. Blewitt et al., 2006; 2010)
- Then (2010) an improvement of an order of magnitude was required!





Geodesy Requirements for Earth Science

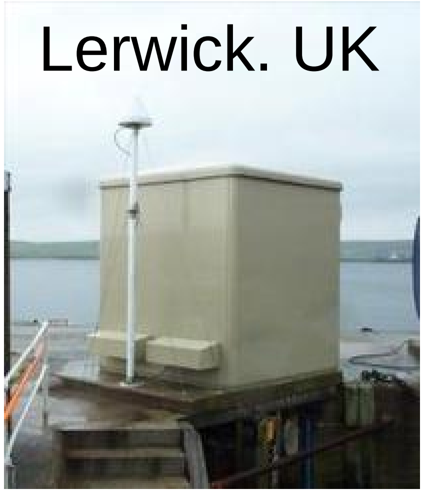


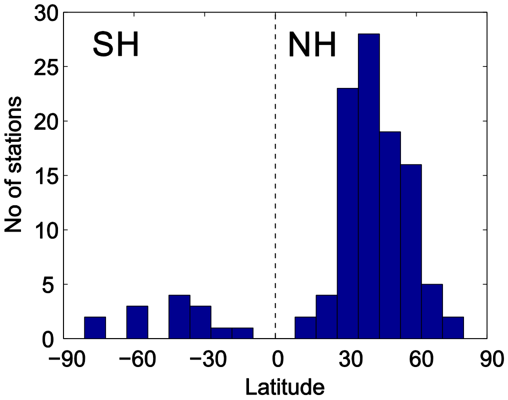
NRC Report [2010]

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)





TIGA WG links

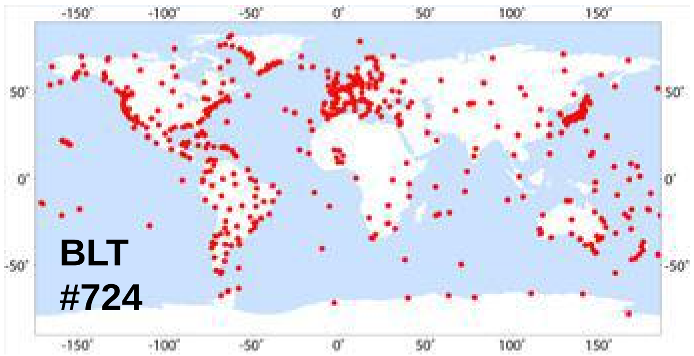
- GGOS Theme 3: Sea-Level Rise and Variability
- The goal of Theme 3 is the demonstration of the value of the GGOS Infrastructure for an integrated Sea Level Monitoring and Forecasting. This includes
  - identification of the requirements for a proper understanding of global and regional/local sea-level rise and variability especially in so far as they relate to geodetic monitoring provided by the GGOS infrastructure.
  - to establish links to external organizations (e.g. GEO) and advocate the GGOS contribution to sea level science.
  - identification of a preliminary set of practical projects, which will demonstrate the viability, and the importance of geodetic measurements to mitigation of sea-level rise at a local or regional level.

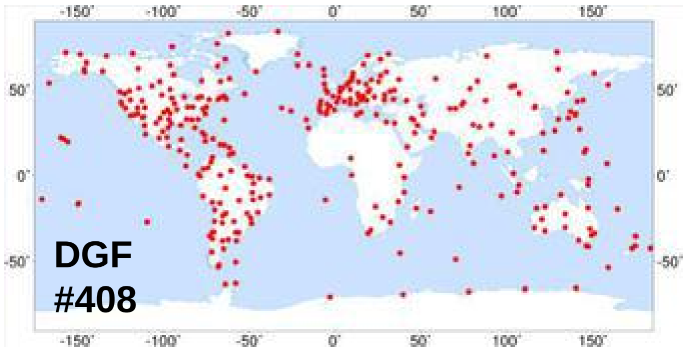
- Supported by UNESCO/IOC (GLOSS) and GCOS

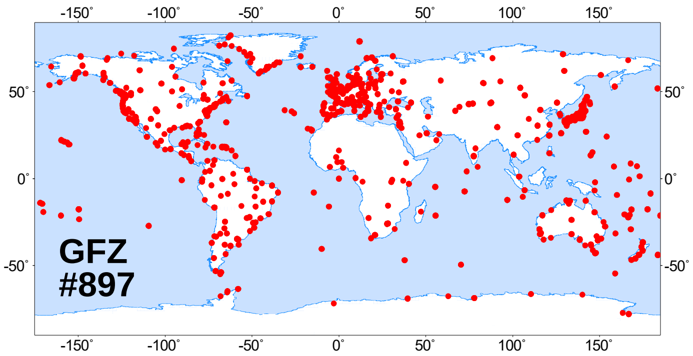
Current TIGA Analysis Centres (TAC)

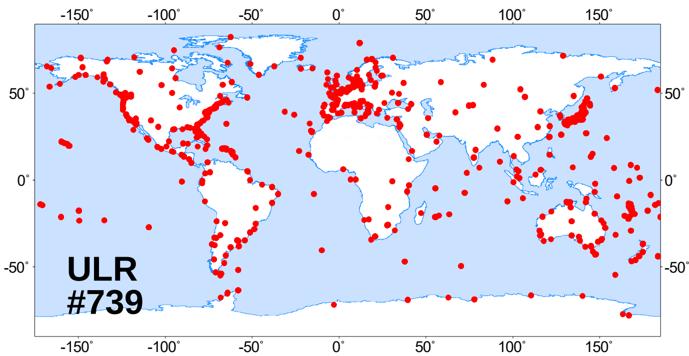
TAC	Host Institutions	Software package	Contributors
AUT	GeoScience Australia, Canberra, Australia	BERNESE V5.2	M. Moore, M. Jia
BLT	British Isles continuous GNSS Facility and University of Luxembourg TAC (BLT), UK and Luxembourg	BERNESE V5.2	F. N. Teferle A. Huneganw R. M. Bingley D. N. Hansen
DGF	The Deutsches Geodätisches, Forschungsinstitut, Germany	BERNESE V5.2	L. Sanchez
GFZ	GeoForschungsZentrum (GFZ), Potsdam, Germany	EPOS P8	T. Schöne Z. Deng
ULR	Centre Littoral de Geophysique, University of La Rochelle (ULR), France	GAMIT V10.5	G. Wöppelmann A. Gómez-A. Santamaría M. Gravelle

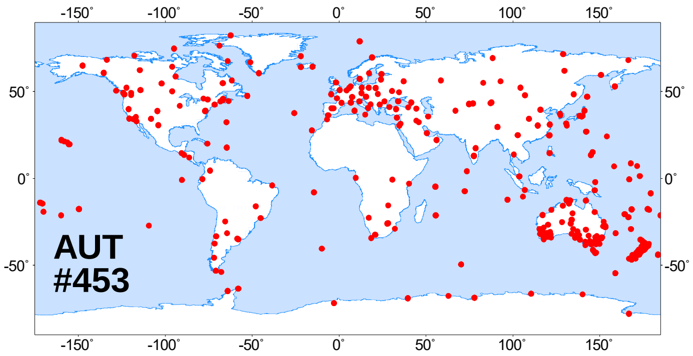
TAC Global Networks







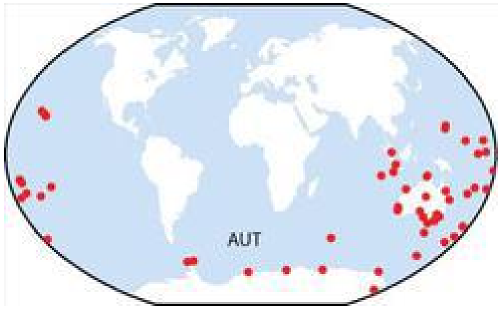


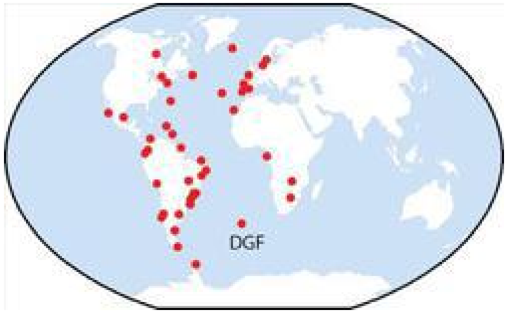


TIGA Data Centre:
University of La Rochelle (ULR):
www.sonel.org

TIGA Combination

- …a story of delays and patience!
- Initially combination was impossible due to largely heterogeneous networks and incompatible processing strategies [Schöne et al., 2009]
- Decision in 2011 for a TIGA repro in parallel to the IGS repro2
- Some TACs required repro products from IGS AC – delayed start
- A software bug required a second repro2 by two TACs in 2015
- Numerous issues and external factors caused further delays for some TACs
- After several cut-off dates - 3 contributing TACs for Release 1.0

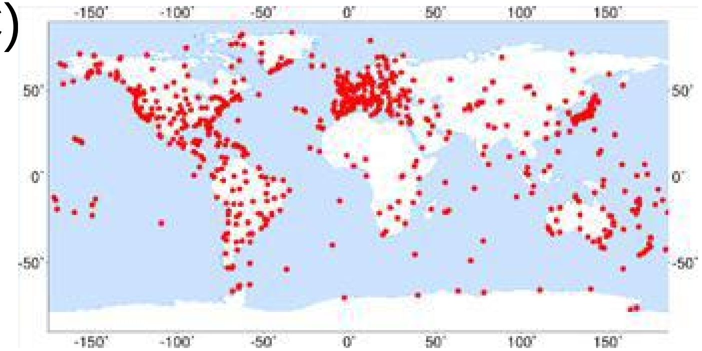




TIGA Combination (Release 1.0)

- Produced by TIGA combination center (TCC) at the University of Luxembourg

- The main TIGA product is an IGS-style combination of individual TAC solutions



All tracking stations in the combined solution

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

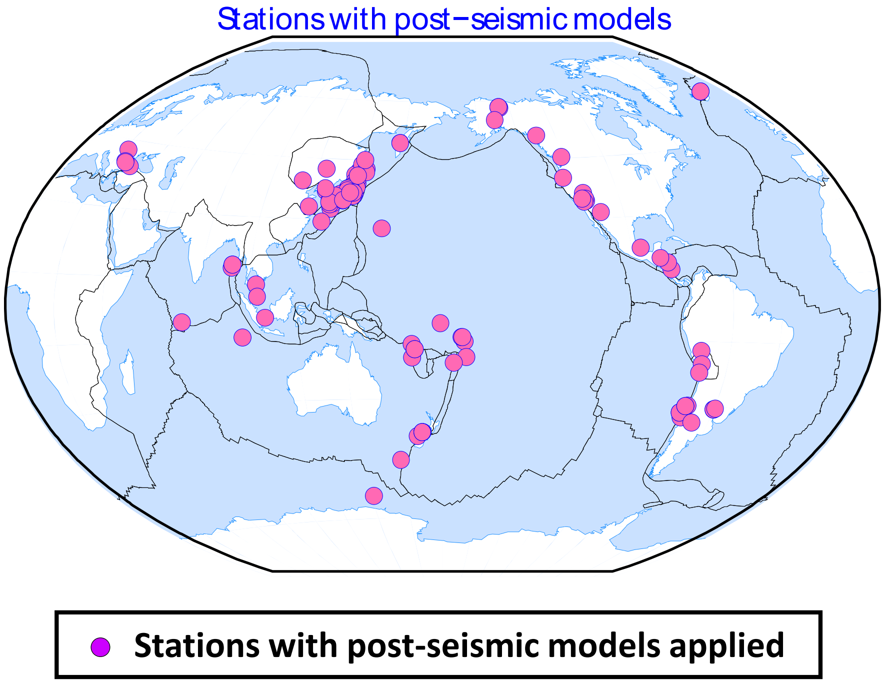
    - Offsets, depending on TAC solutions
    - Computationally intensive, depends on the use of UL HPC infrastructure

- Long-term stacking
- Software packages for combination: CATREF and Globk (during preliminary solutions)

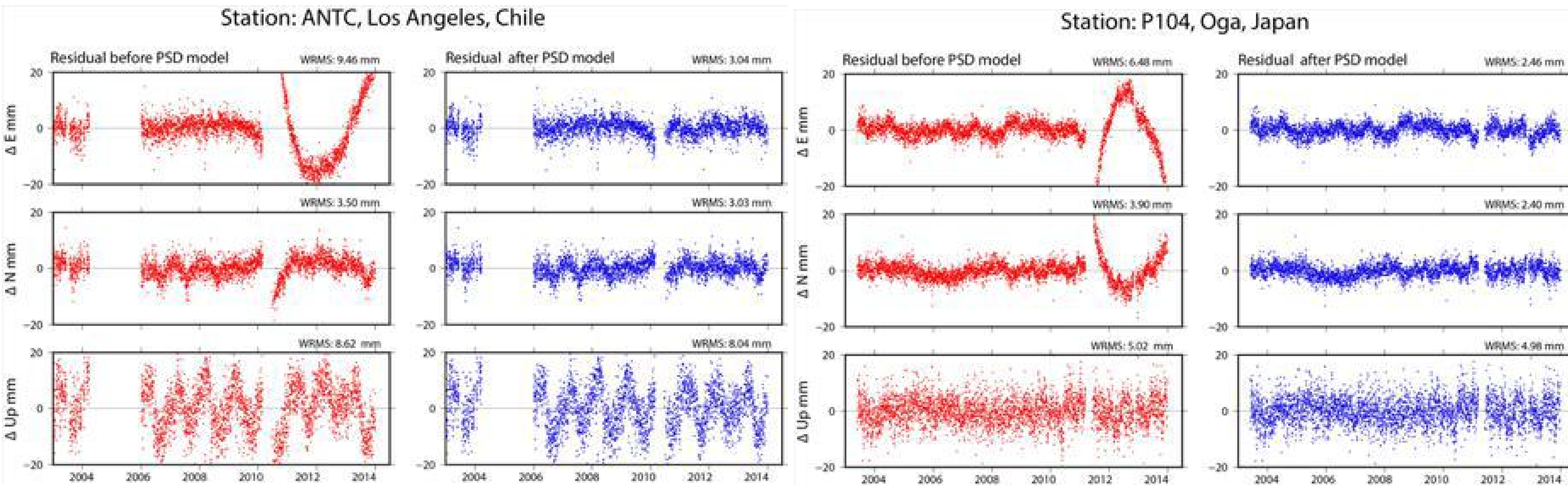
Post-seismic deformation modeling

- We correct post-seismic deformations before stacking
- For each E, N and U time series:
  - Used models: Exp, Log, Exp+Exp, Exp+Log

- **119 stations are affected**
- **11% of all stations**

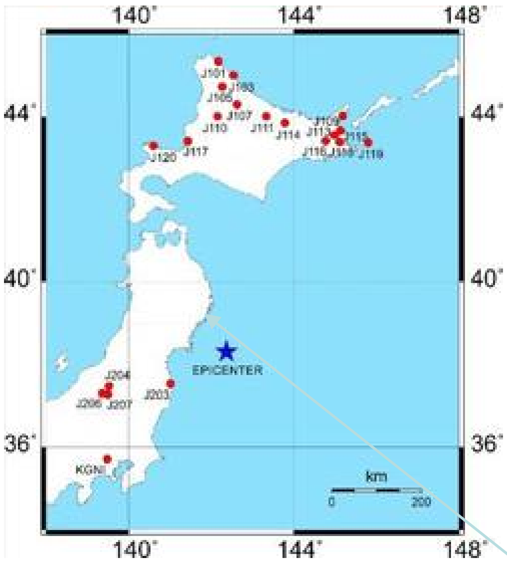


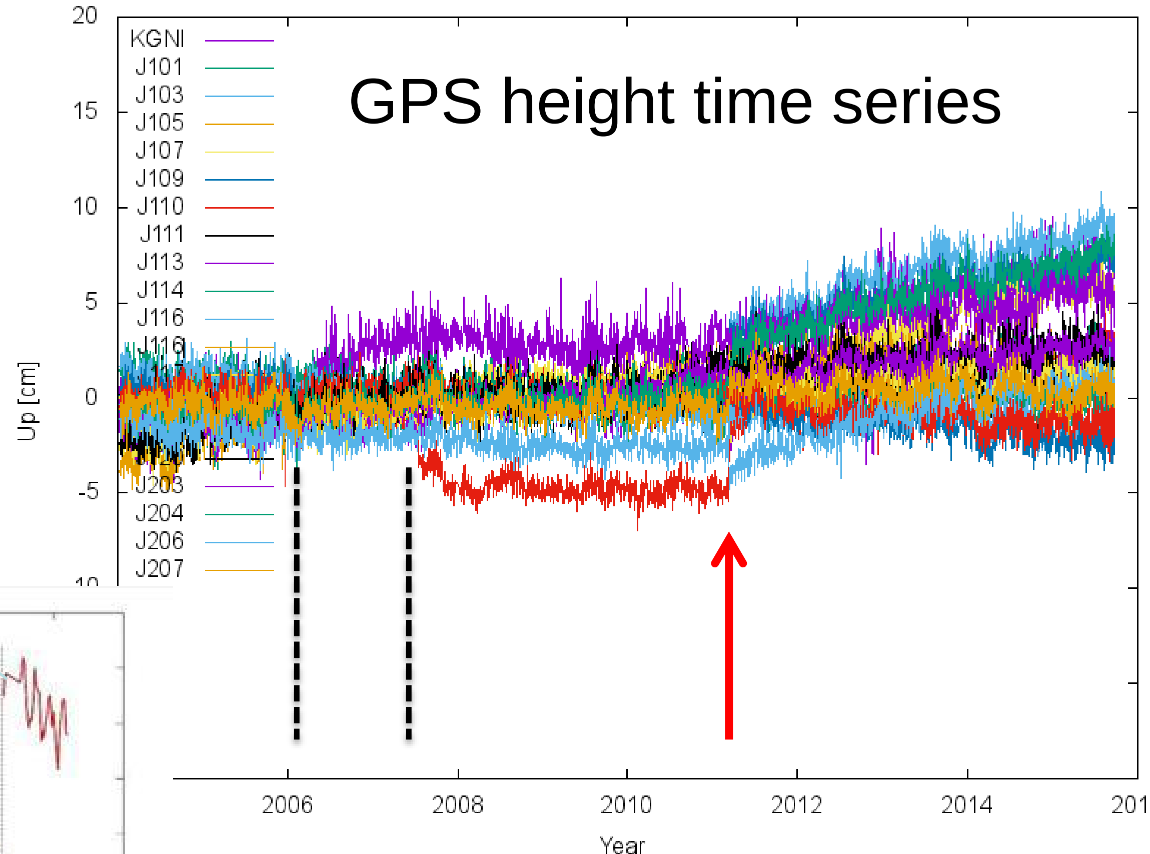
Post-seismic Deformation Modelling (following ITRF2014)

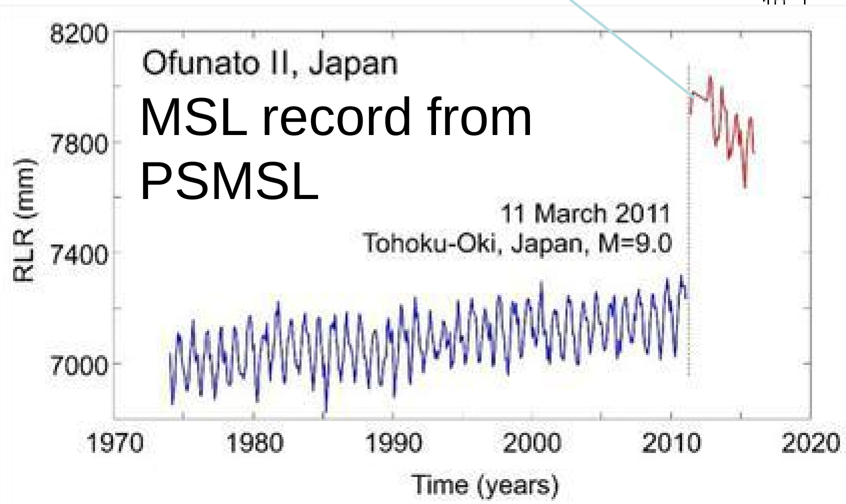


- RMS reduction in E and N components are substantial
- Significant improvements also in the Up component

Tōhoku 2011 Earthquake, Japan
Impacts of Post-seismic Deformation





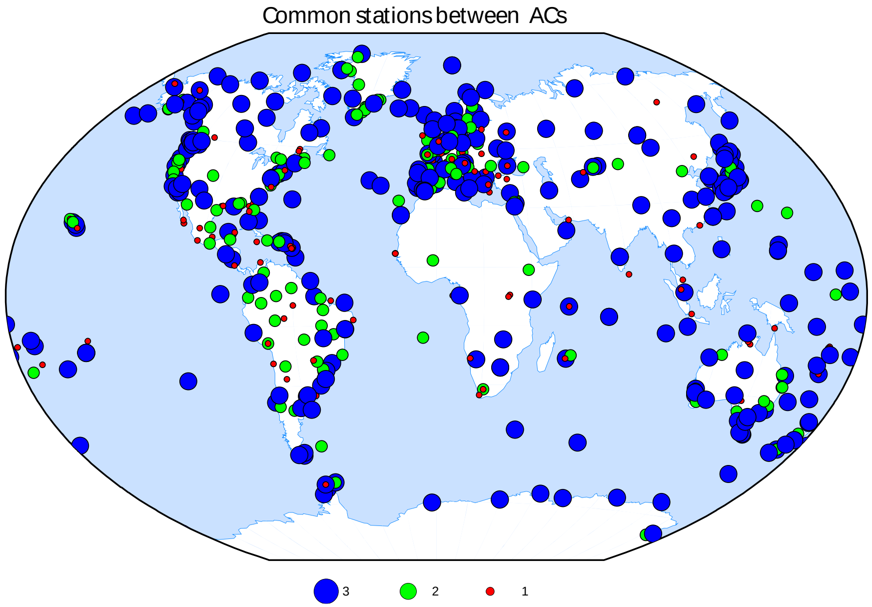


There are 34 pairs of GPS and TG for Japan. Each MSL records in the PSMSL RLR data base needs to be inspected for known earthquakes. See also Rudenko et al. (2013).

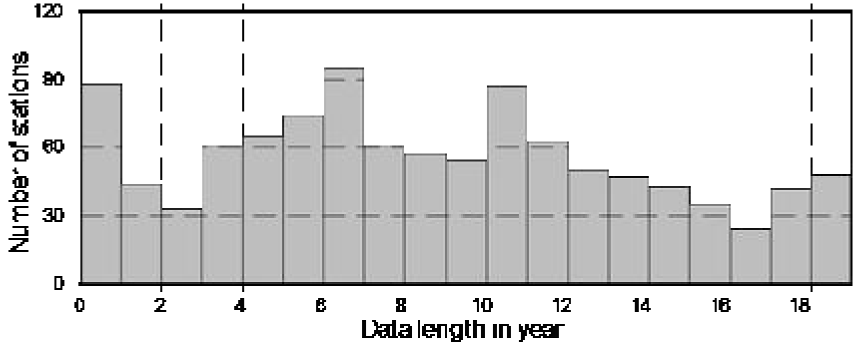
TIGA Combination Solution Information

- 6936 SINEX solutions

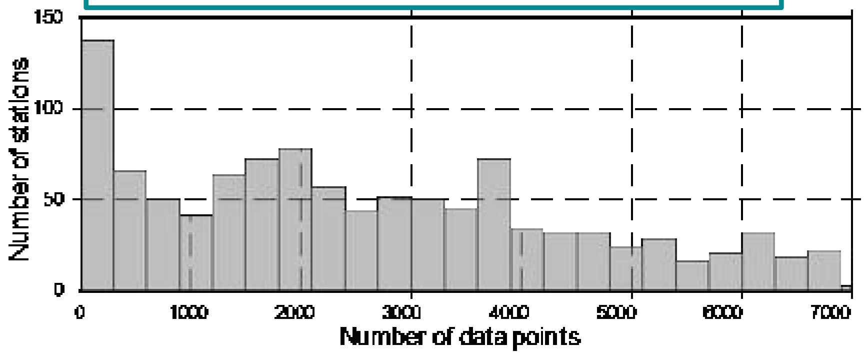
- Daily station positions
- January 1, 1995 → January 1, 2014
- 1087 stations



Histogram of data length of TIGA combination time series



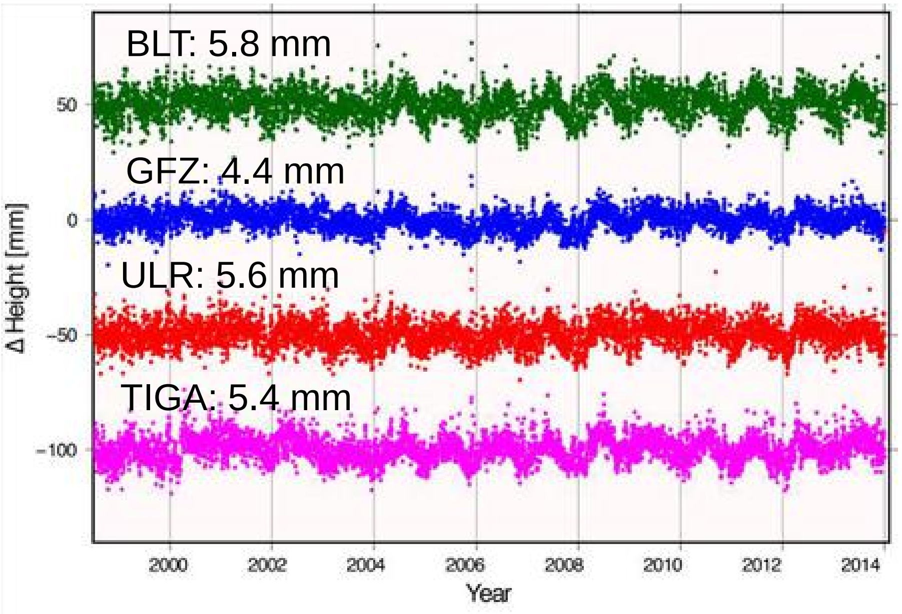
Histogram of data points in TIGA combination time series

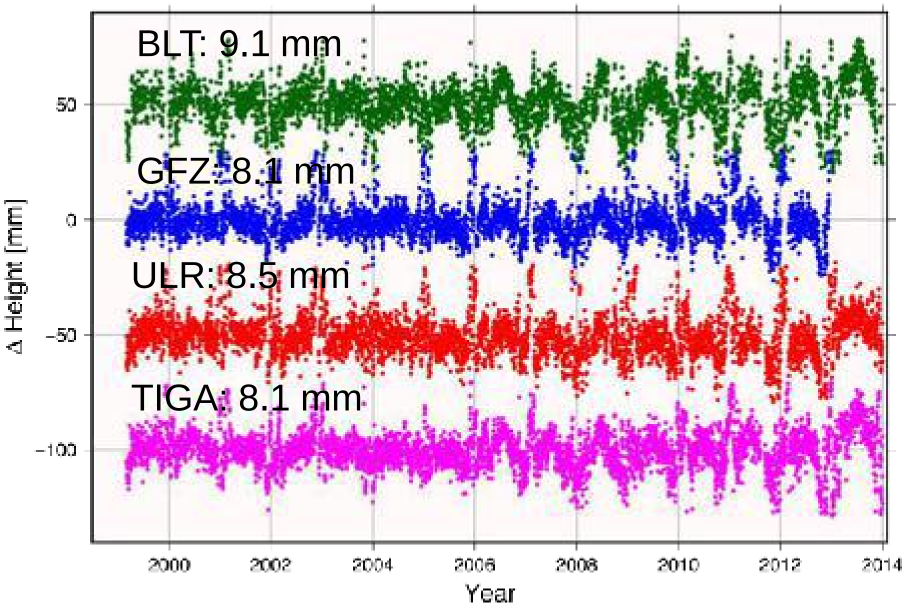


Residual Coordinate Time Series from TAC and Combined Solutions

GPS station, WSRT

GPS station, VAAS





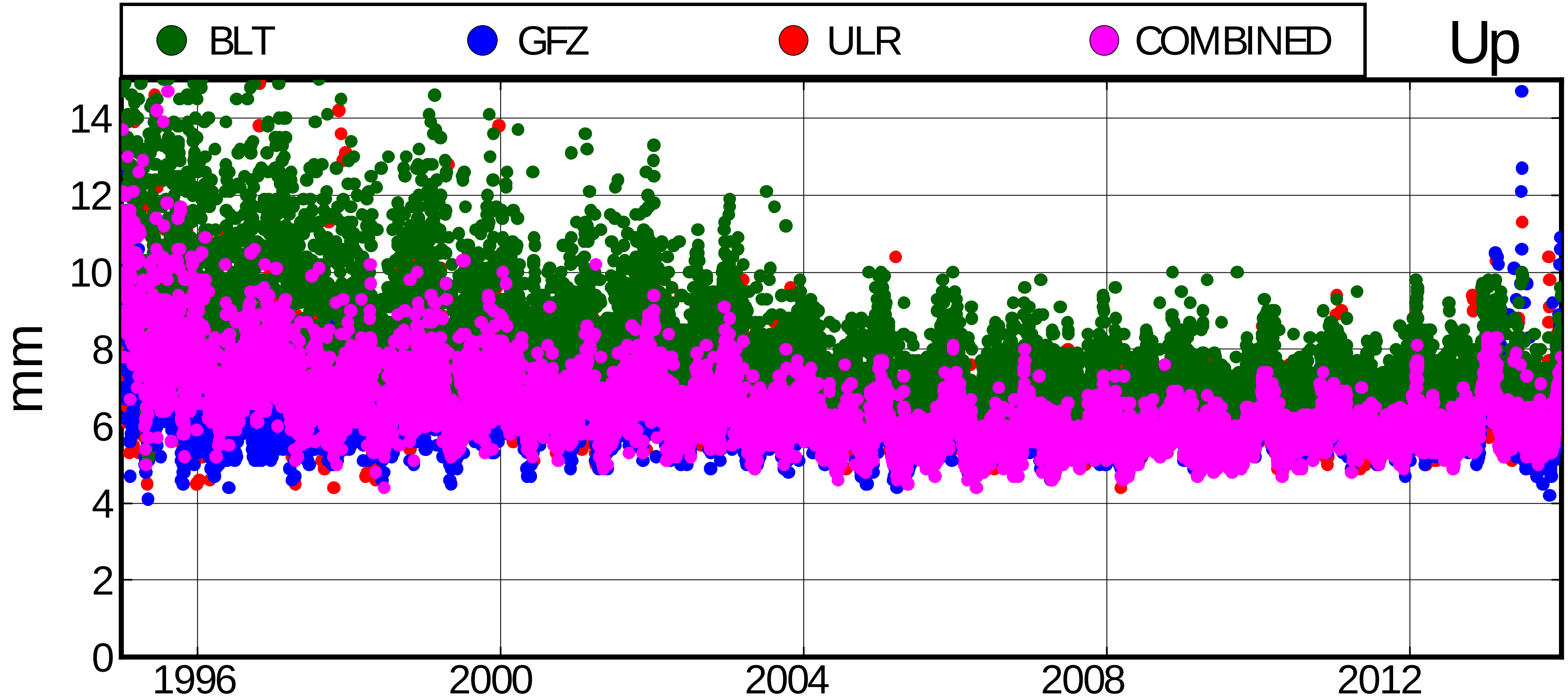
BLT

GFZ

ULR

COMBINED

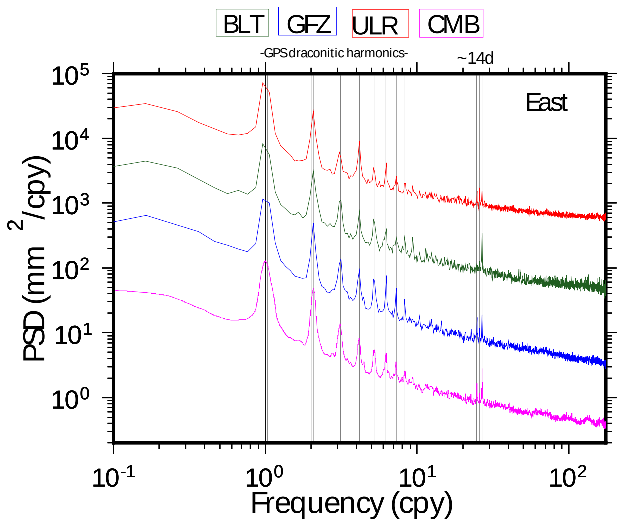
Daily WRMS for TAC and Combined Solutions

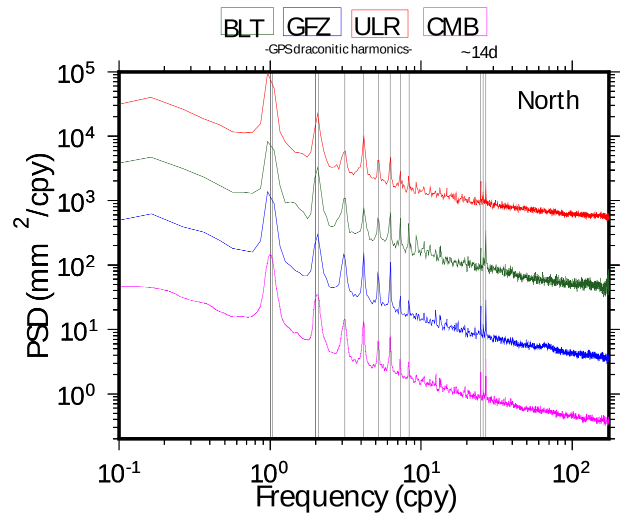


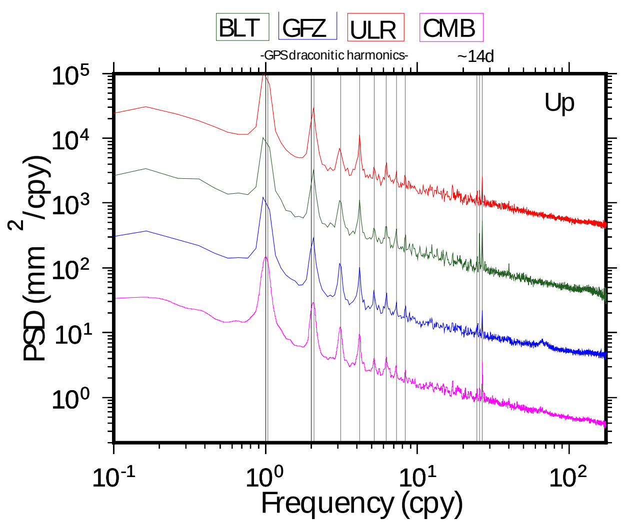
Daily WRMS of TAC and combined station position residuals

- **Inter-agreement from 2004 …**

Stacked Power Spectra for TAC and Combined Solutions



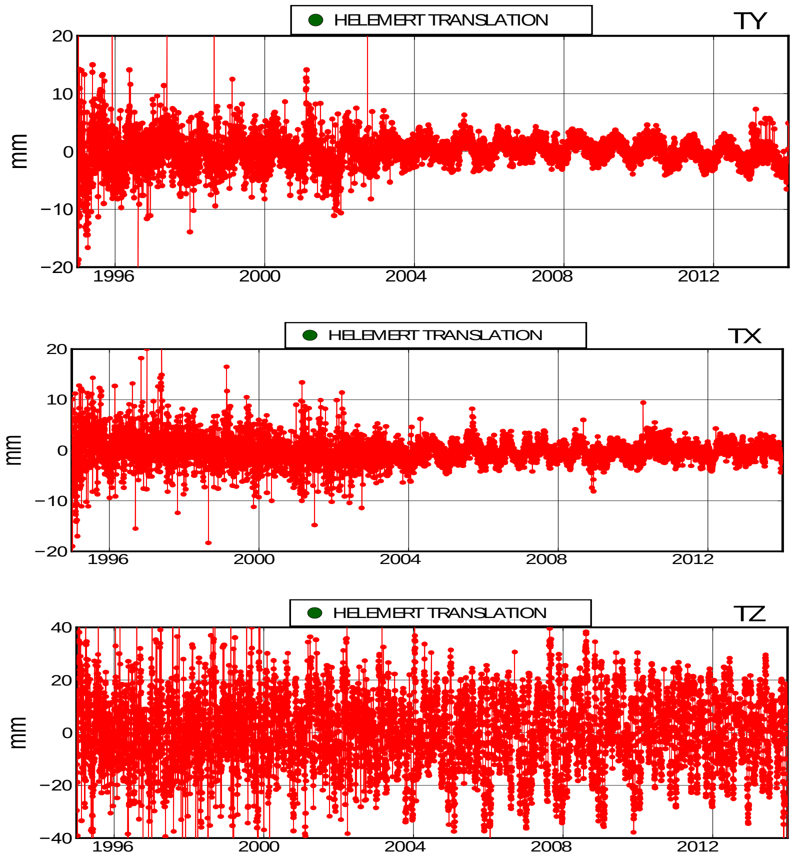




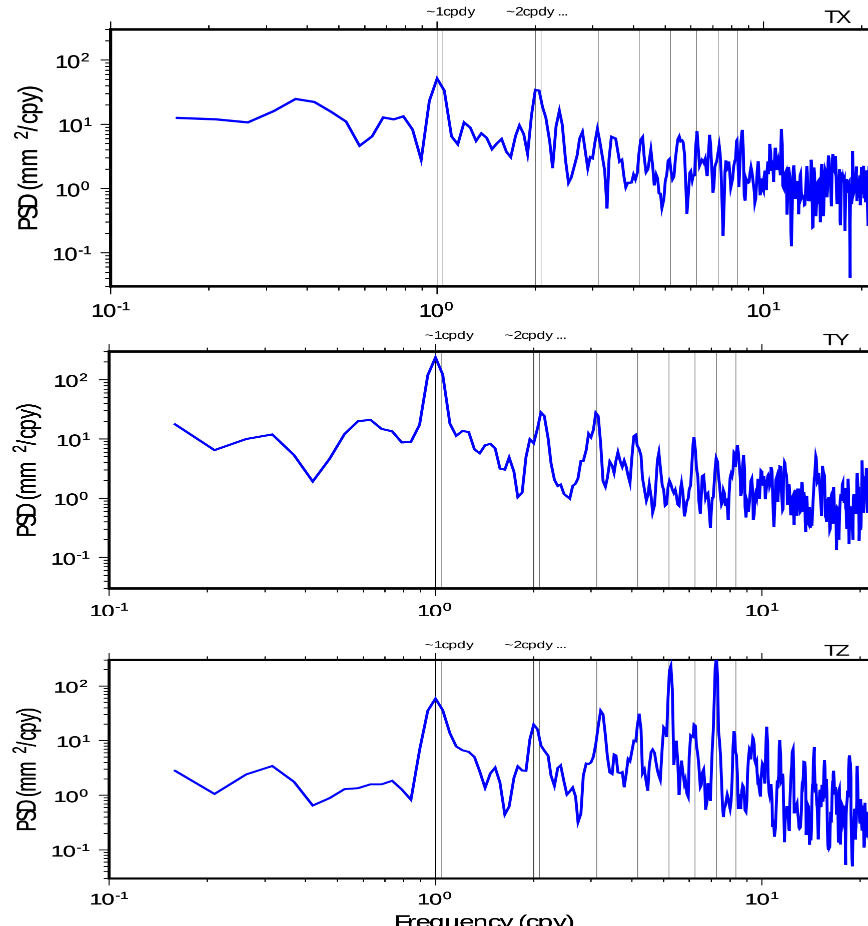
- **GPS draconitic harmonics are evident**
- **Fortnightly tidal peaks at 13.6d, 14.2d and 14.8d**

See also Abraha et al. [2016]

Helmert Translation Parameters

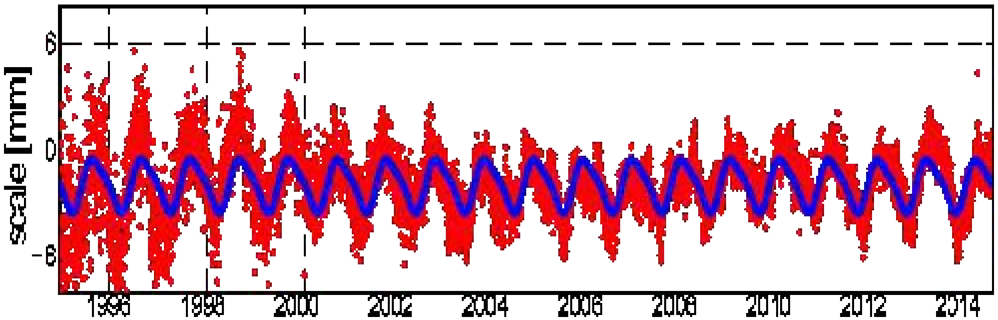


Daily translation parameters from TAC combined solution

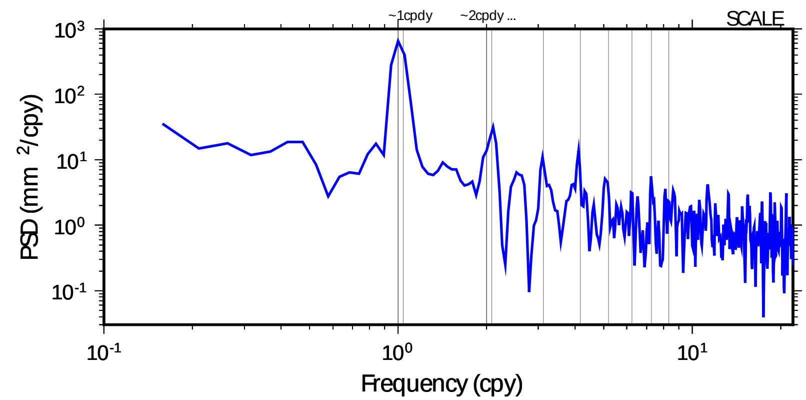


- Power spectra of the translation parameters
- High power at the sub-seasonal for the TZ translation

Terresterial Scale

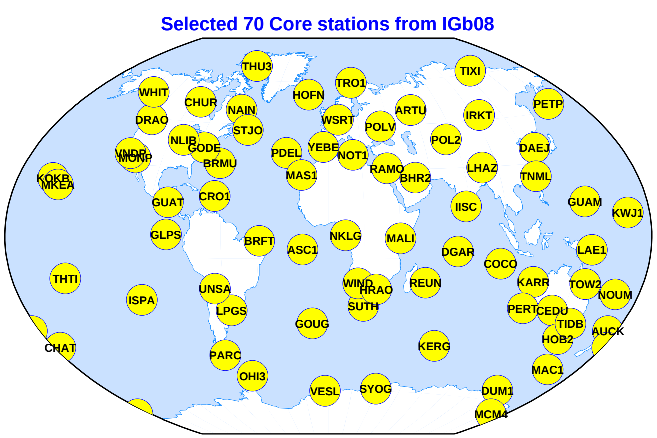


Periodogram for the scale parameter. with diminished draconitic harmonics present in the spectral plot. Annual signal is prominent and also semi-annual represent.



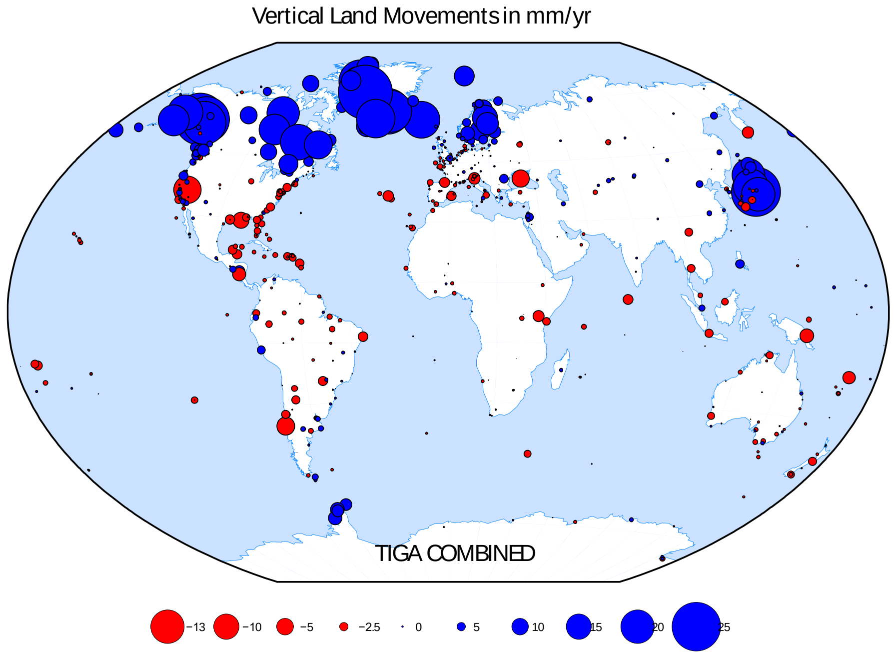
Fitting Trend and Annual, Semi-annual to the combined scale with respect to IGb08 (with selected sites of 70)

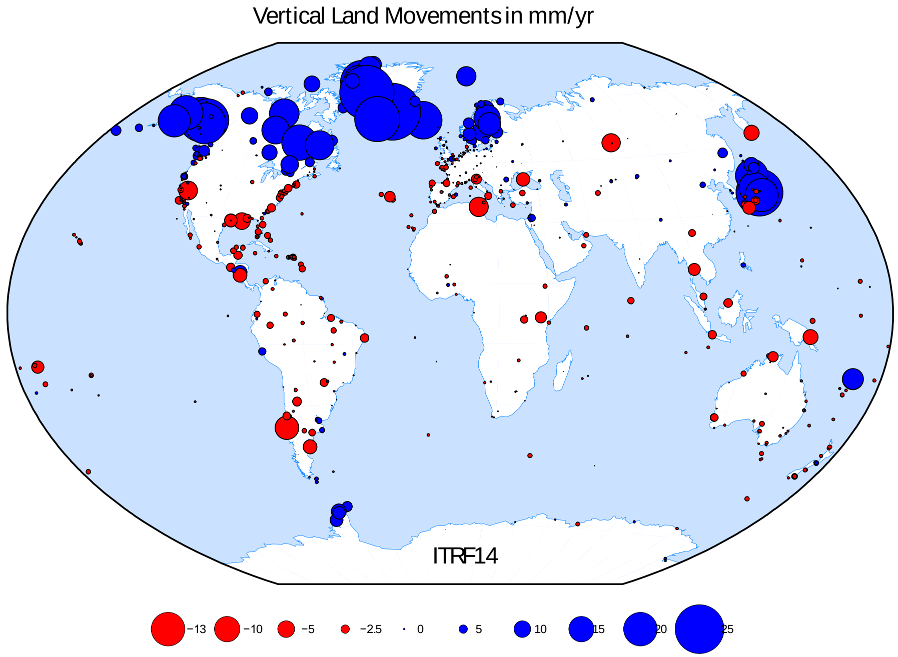
Bias [mm]	Trend [mm/yr]	Annual amp [mm]	Annual phi [deg]	Semi-ann amp [mm]	Semi-ann phi [deg]
-1.8	**0.02**	**1.6/1.4**	**-106/-103**	**0.2/0.1**	**50/138**



Scale factors derived from a loading model (ECMWF+GLDAS+ECCO2; http://loading.u-strasbg.fr). Values adapted from IGS repro2 solutions by P. Rebischung

VLM from TIGA Combination and ITRF2014 Solutions

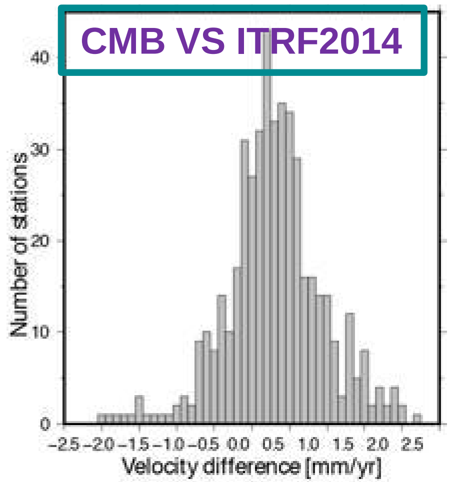


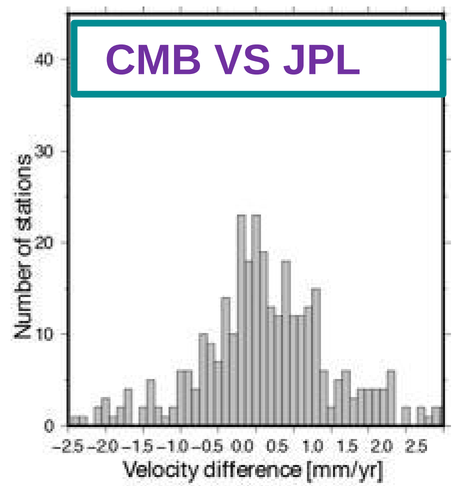


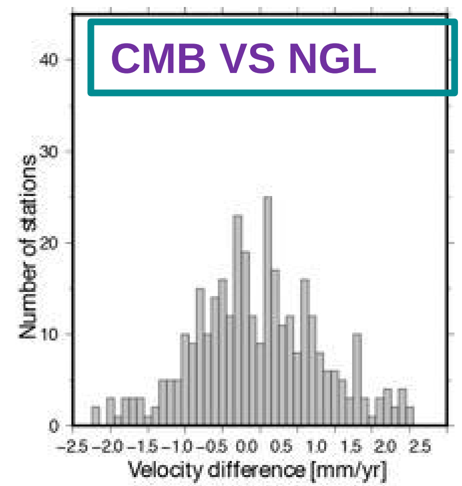
Overall the picture of VLM agrees with some larger differences at individual stations.

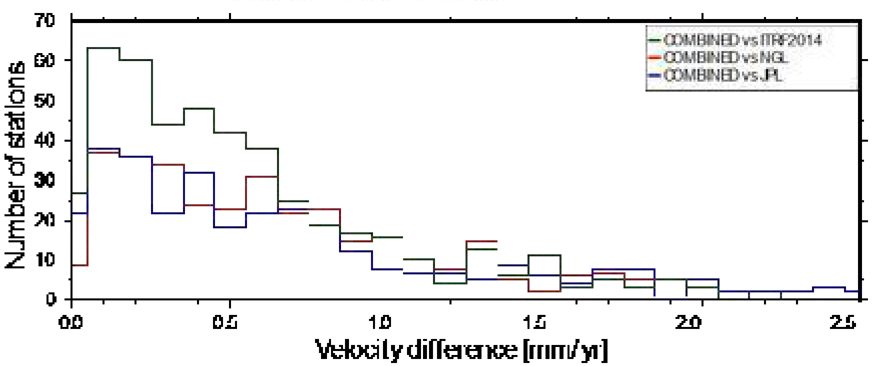
External Evaluations of TIGA Combination

Velocity difference between TIGA Combination and ITRF2014, JPL[1] and NGL[1] solutions





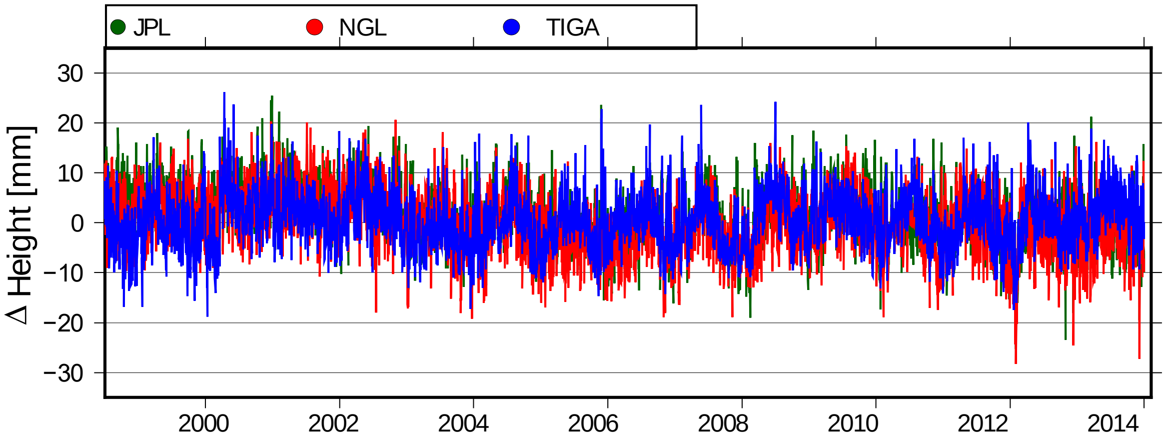


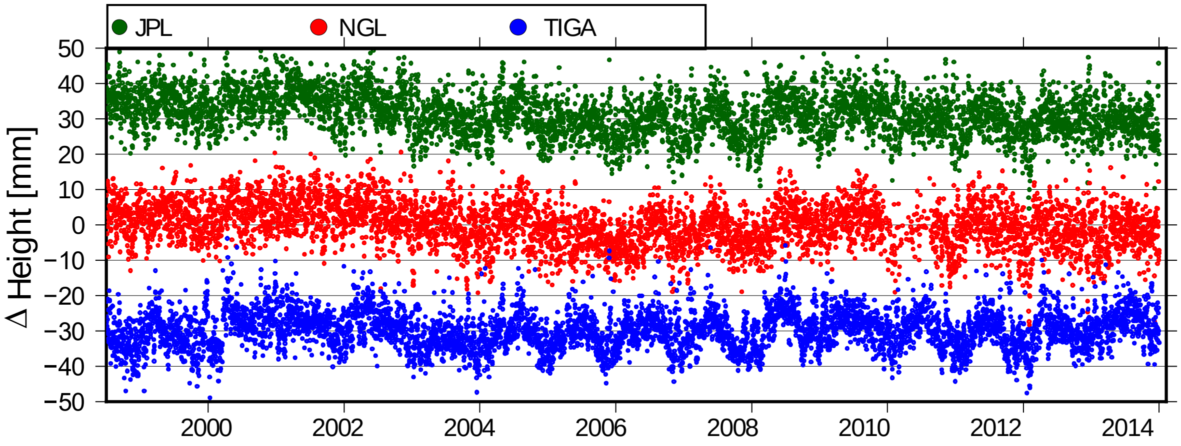


SOL.	RMS	Bias	Stn. #	% <0.5mm/yr
ITRF 2014	0.65	0.29	465	57.0
JPL	0.95	0.12	326	48.6
NGL	1.1	0.05	460	45.8

[1] NGL. JPL velocities are in different realization of IGS08. with insignificant differences

Height Differences for WSRT



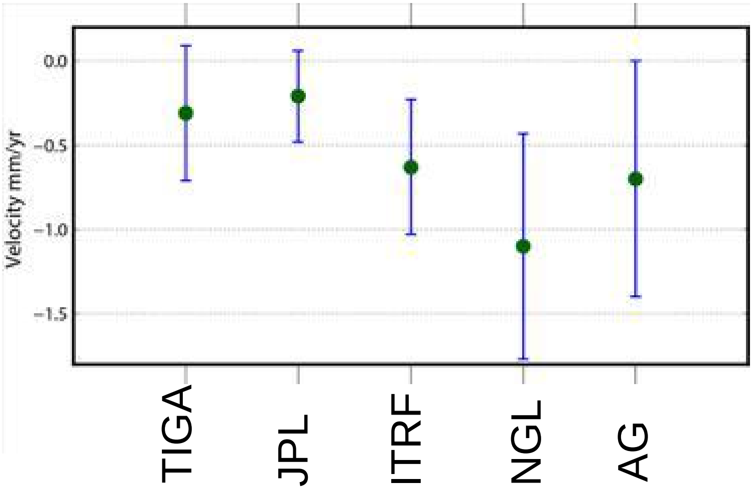


WSRT: RMS [mm]

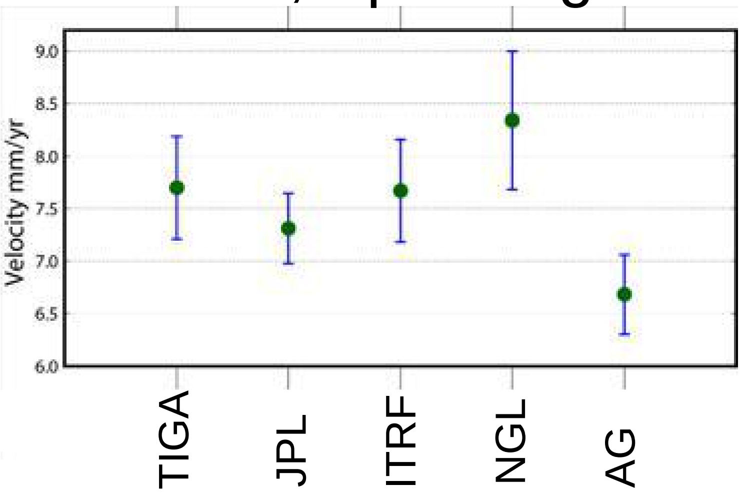
TIGA	JPL	NGL
5.4	6.0	6.2

Velocity Comparison with Absolute Gravity

NEWL, UK

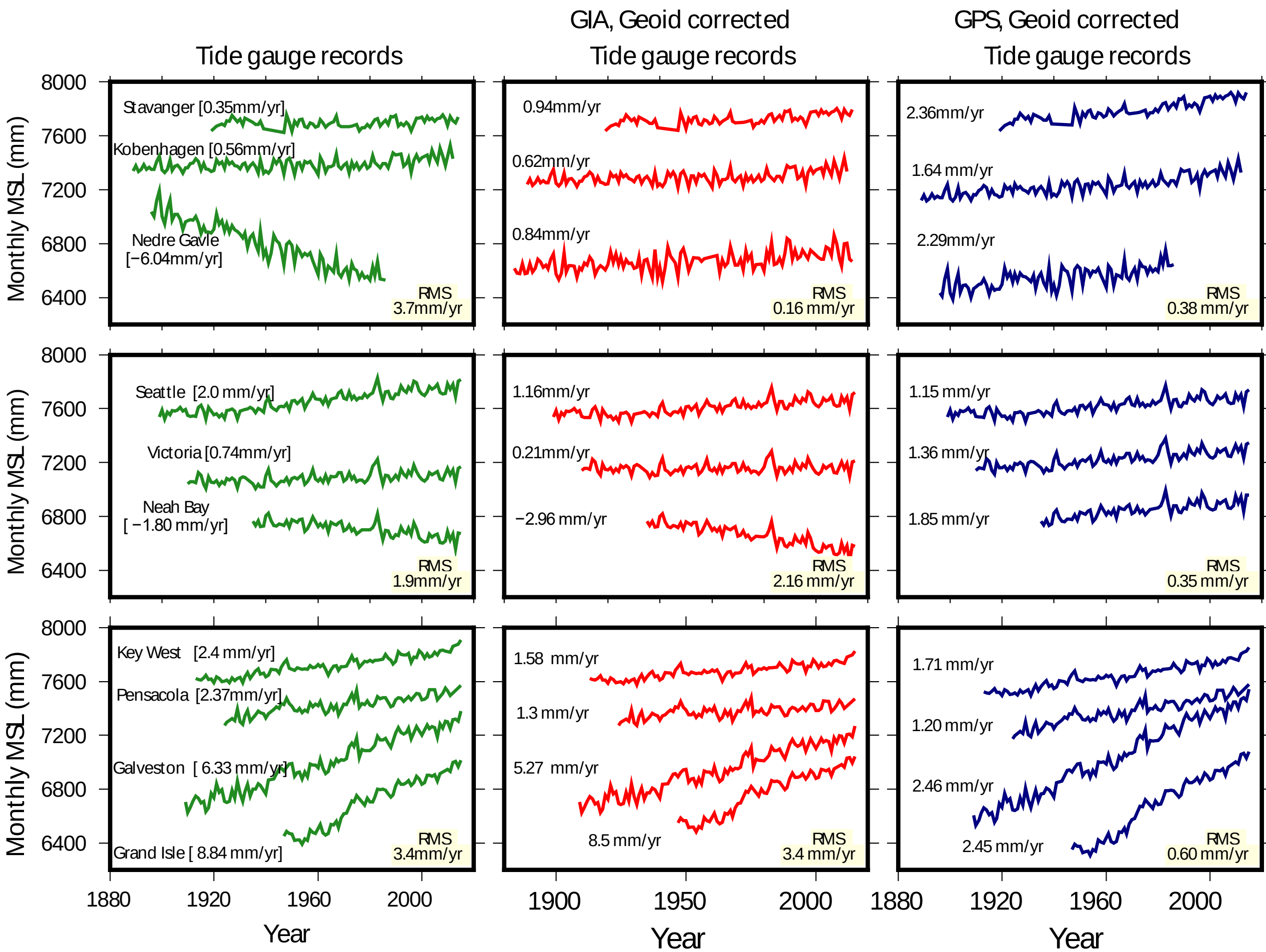


NYAL, Spitzbergen



MSL Records from PSMSL

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



North Europe

NW N. America

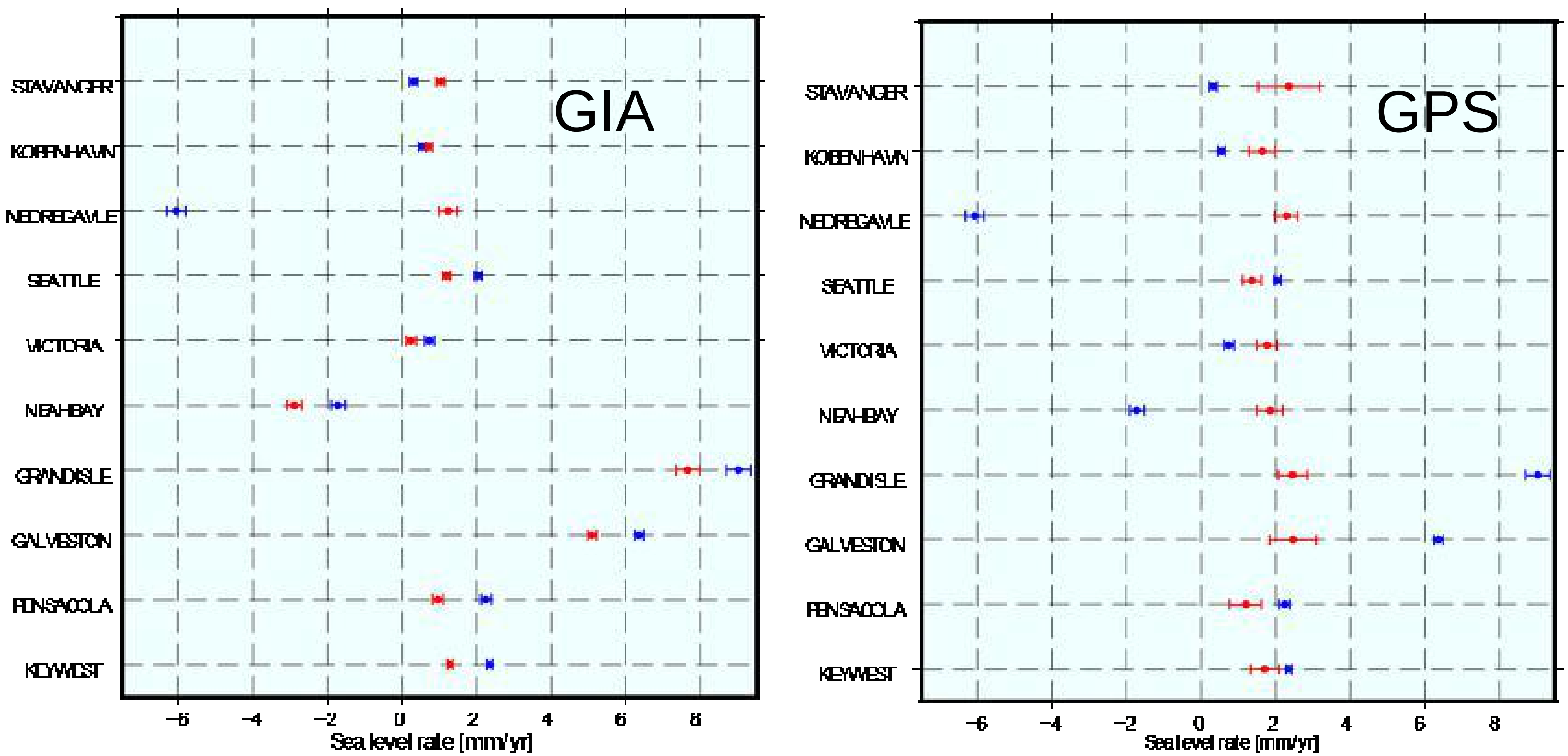
Gulf of Mexico Grand Isle. less dominated by GIA processes

- **GPS velocity corrections show a reduction in scatter**
- **GIA alone is not enough to correct local processes as shown in N. A & Gulf of Mexico**

[following Wöppelmann et al., 2006]

MSL Records from PSMSL Corrected for VLM

(GIA-ICE-6G(VM5a) and GPS-TIGA Combination)



● MSL Trends

● VLM-corrected MSL Trends

VLM-Corrected MSL Trends

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	TIGA Trend	TG+GIA Trend	TG+TIGA Trend
North Europe								
STAVANGER	63	16000	47	0.35 ±0.18	0.59	**1.91 ±0.40**	0.94	2.26
KOBENHAVN	101	7300	82	0.56 ±0.12	0.06	**1.30 ±0.85**	0.62	2.09
NEDRE GAVLE	90	11000	99	-6.04 ±0.22	6.87	**7.92 ±0.88**	0.83	1.88
North Sea and English Channel								
ABERDEEN	103	2	361	0.97 ±0.25	1.01	**0.75 ±0.21**	1.98	1.72
NEWLYN	87	10	202	1.81 ±0.12	-0.72	**-0.31±0.17**	1.09	1.50
BREST	83	350	1	0.97 ±0.12	-0.61	**-0.10±0.28**	0.36	0.87
East Atlantic								
CASCAIS	97	84	52	1.29 ±0.18	-0.34	**-0.07±0.24**	0.95	1.22
LAGOS	61	138	162	1.56 ±0.25	-0.41	**-0.34±0.22**	1.15	1.22
Mediterranean								
MARSEILLE	105	5	61	1.33 ±0.12	-0.32	**0.93 ±0.30**	1.01	2.26
GENOVA	78	1000	59	1.17 ±0.08	-0.16	**-0.34±0.18**	1.01	0.83

TG stations are selected and grouped according to Douglas (2001)

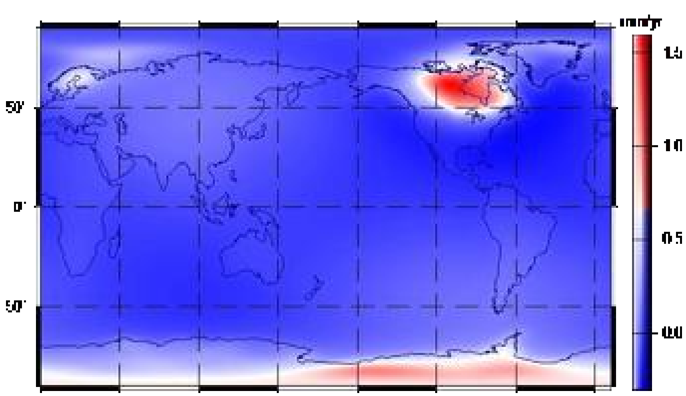
VLM-Corrected MSL Trends (2)

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	TIGA Trend	TG+GIA Trend	TG+TIGA Trend
NE North America								
EASTPORT	63	800	332	**2.21 ±0.3**	-1.34	**-0.38±0.37**	0.87	1.83
NEWPORT	70	500	351	**2.48 ±0.14**	-1.42	**-0.27±0.21**	1.06	2.21
HALIFAX	77	3100	96	**3.06 ±0.19**	-1.54	**-0.91±0.15**	1.52	2.15
ANNAPOLIS	70	11577	311	**3.5 ±0.14**	-1.84	**-2.09±0.11**	1.66	1.41
SOLOMON ISL	62	200	412	**3.69 ±0.18**	-1.71	**-1.54± 0.33**	1.98	2.15
NW North America								
VICTORIA	86	12000	166	**0.74 ± 0.05**	-0.53	**1.01 ±0.20**	0.21	1.75
NEAH BAY	65	7800	385	**-1.80 ±0.09**	-1.16	**3.58 ±0.28**	-2.96	1.78
SEATTLE	104	5900	127	**1.99 ± .14**	-0.84	**-1.00±0.22**	1.15	0.99
SE North America								
CHARLESTON I	82	8200	234	**3.31 ±0.28**	-1.13	**-1.65±0.73**	2.18	1.66
GALVESTON II	94	4200	161	**6.33 ±0.31**	-1.06	**-3.65± 0.55**	5.27	2.68
MIAMI BEACH	45	4800	363	**2.29 ±0.26**	-0.83	**0.25±0.72**	1.46	2.54
KEY WEST	90	16000	188	**2.40 ±0.16**	-0.82	**-0.29±0.37**	1.58	2.11
SW North America								
LA JOLLA	72	700	256	**2.21 ±0.12**	-0.72	**-0.72±0.58**	1.49	1.49
LOS ANGELES	78	2200	245	**0.94 ±0.14**	-0.74	**-0.19±0.28**	0.20	0.75
New Zealand								
AUCKLAND II	85	5	150	**1.32 ±0.11**	0.08	**-0.43±0.25**	1.40	0.89
PORT LYTTELTON	101	2	247	**2.18 ±0.27**	0.14	**-0.69±0.25**	2.32	1.49
Pacific								
HONOLULU	99	5	155	**1.43 ±0.3**	-0.23	**-0.68±0.19**	1.20	0.75

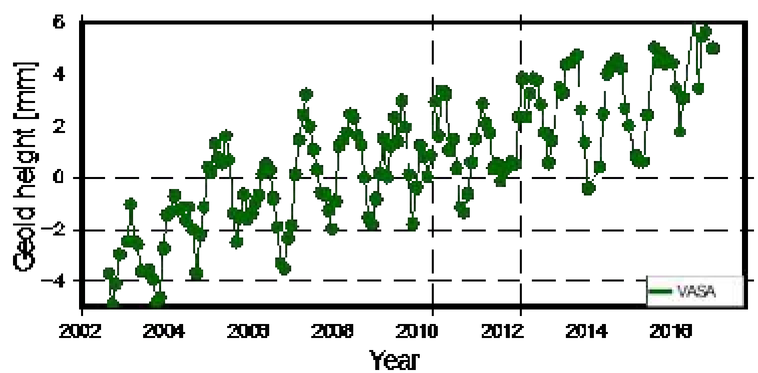
Standard deviations of Individual Sea Level Change Estimates using GIA, and TIGA combined VLM estimates

	No corrections TG records rate	GIA-corrected rate ICE6G (VLM5C)	GPS-corrected rate TIGA combined	GPS-geoid-corrected rate TIGA combined
Scatter of MSL Trends	2.08	1.26	0.57	0.59

- **Units in mm/yr; 27 TGs were used**



Global geoid changes associated with GIA



Geoid height changes associated with GIA, for station VAAS, Vaasa, Finland

Conclusions

- The TIGA Combination has been presented (Release 1.0)
  - Currently includes BLT, GFZ and ULR solutions
  - Awaiting DGF and AUT contributions
- High consistency between the individual TAC solutions, which perform fairly equivalent, maybe with the one from GFZ being the least noisy
- External evaluations of coordinates and velocities show good agreements to ITRF2014, other GPS solutions and absolute gravity. The latter needs to be further expanded due to its independence of the TRF. Other global evaluations need to be carried out [Collilieux et al., 2016]
- The TIGA Combination should become the VLM product of choice for the sea level community,…

…, next week at the WCRP/IOC Sea Level Workshop 2017 – www.sealevel2017.org .

Thank you for your attention!

The TIGA WG also promotes the installation of GNSS @ TG stations, especially in the Southern Hemisphere: Lüderitz, Namibia