Error analysis of Tide Gauge Benchmark Monitoring (TIGA) Analysis Center stacked solutions

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IGS

BIGF

Abstract

In 2013 the International GNSS Service (IGS) Tide Gauge Benchmark Monitoring (TIGA) Working Group (WG) started their reprocessing campaign, which proposes to re-analyze all relevant Global Positioning System (GPS) observations from 1995 to the end of 2013. This re-processed dataset will provide high quality estimates of land motions, enabling regional and global high-precision geophysical/geodetic studies. Several of the individual TIGA Analysis Centers (TACs) have completed processing the full history of GPS observations recorded by the IGS global network, as well as, many other GPS stations at or close to tide gauges, which are available from the TIGA data center at the University of La Rochelle (www.sonel.org). The TAC solutions contain a total of over 700 stations. This study focuses on the evaluations of any systematic error present in the three TIGA analysis center (TAC) SINEX solutions: the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle (ULR). We have analyzed the residual position time series of the individual TAC a combination of automatic and manual discontinuity identification, applying a post-seismic deformation model adopted from ITRF2014 for those stations that are affected by earthquakes, followed by the stacking of the daily solution of the individual TAC into a long term linear frame. We have carried out the error analysis using the Combination and Analysis of Terrestrial Reference Frame (CATREF) software package. The TIGA Combination Centre (TCC) at the University of Luxembourg (UL) is responsible for providing a combined solution with a global set of vertical land movement estimates.

Introduction

Sea level change as a consequence of climate variations has a direct and significant impact for coastal areas around the world. Over the last one and a half centuries sea level changes have been estimated from the analysis of tide gauge records. However, these instruments measure sea level relative to benchmarks on land. It is now well established that the derived mean sea level (MSL) records need to be de-coupled from any vertical land movements (VLM) at the tide gauge.

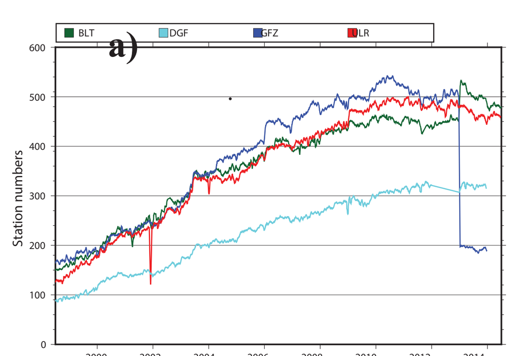
Global Navigation Satellite System (GNSS) technology, in particular the Global Positioning System (GPS), has made it possible to obtain highly accurate estimates of VLM in a geocentric reference frame from stations close to or at tide gauges. Under the umbrella of the International GNSS Service (IGS), the Tide Gauge Benchmark Monitoring (TIGA) Working Group has been established to apply the expertise of the GNSS community to solving issues related to the accuracy and reliability of the vertical component as measured by GPS and to provide time series of vertical land movement in a well-defined global reference frame, (Schöne and Thaller, 2009). To achieve this objective, a number of TIGA Analysis Centers (TACs) contribute re-processed global GPS network solutions to TIGA, employing the latest bias models and processing strategies in accordance with the second re-processing campaign (repro2) of the IGS.

One of the objectives of the TIGA Working Group is to produce consistent station coordinates on a daily basis in the form of SINEX files, which are useful for multi-solution combinations, i.e. following largely the example of the routine IGS combinations. In this study we aim to explore the potential in improving the precision and accuracy of the station coordinates and station velocities through network analysis. So far, only three of five TAC solutions have a complete time series and are now available for a preliminary multi-year combination. These include the solutions of the British Isles continuous GNSS Facility – University of Luxembourg consortium (BLT), the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle (Table 1). The fourth solution from Deutsches Geodätisches Forschungsinstitut (DGFI) is soon to be completed but we have identified an issue in their time series at the start of 2010, coincident with the inclusion of GLONASS observations in their daily SINEX files. Hence, we have not included the DGF solution in this study. The solution from the 5th TAC, Geoscience Australia (AUT) is still to be completed. It is noteworthy that all five contributing TACs have analyzed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations, which is different for earlier TIGA solutions (Schöne and Thaller, 2009).

In this study we present the quality of the TAC solution before the final combination by the TIGA working group at the TIGA Combination Centre (TCC) at the University of Luxembourg (UL). The will incorporate all the five TAC solutions using a combination software packages: Combination and Analysis of Terrestrial Reference Frame (CATREF) (Altamimi et al, 2002). Figure 1 shows the number of stations from the TAC and the distribution of the station

TAC	Host Institutions	Software package	Contributors
BLT	British Isles continuous GNSS Facility and University of Luxembourg TAC (BLT), UK and Luxembourg	BERNESE V.5.2	F. N. Teferle, A. Hunegnaw, R. M. Bingley, D. N. Hansen
DGF	The Deutsches Geodätisches, Forschungsinstitut, Germany	BERNESE V.5.2	
GFZ	GeoForschungsZentrum (GFZ), Potsdam, Germany	EPOS P8	T. Schöne, Z. Deng
ULR	Centre Littoral de Geophysique, University of La Rochelle (ULR), France	GAMIT V.10.5	G. Wöppelmann, A. Gómez-A. Santamaría, M. Gravelle

Table 1. Lists currently available TIGA Analysis Centres. BLT, GFZ, ULR and DGF currently contributing to the TIGA combination (TAC) solution. All the four TACs include a core global network list of sites from IGb08 reference stations.



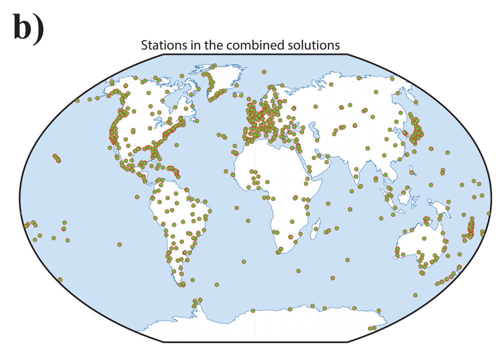


Figure 1: a) Number of stations from the Individual contributing TIGA AC's and b) the distributions of the stations in this study.

Time series of station positions

We have computed the residual station positions for each TAC solutions with respect to the IGb08 solution. This provides a first quality assessment of the individual TIGA contributions. Here we have chosen ONSA, Onsala, Sweden as an example and all the stacked station positions from the three TAC solutions are shown in Figure 2a. Due to the higher noise level we also show the filtered residuals (Figure 2b) obtained from boxcar filter with a 90 day window. Clearly the three TAC solutions show quite good agreement and a similar temporal evolution of the respective time series. As the initial observations are identical to all contributing TAC, but the differences stem from the different software packages and different processing strategies and settings (e.g. cut off angles).

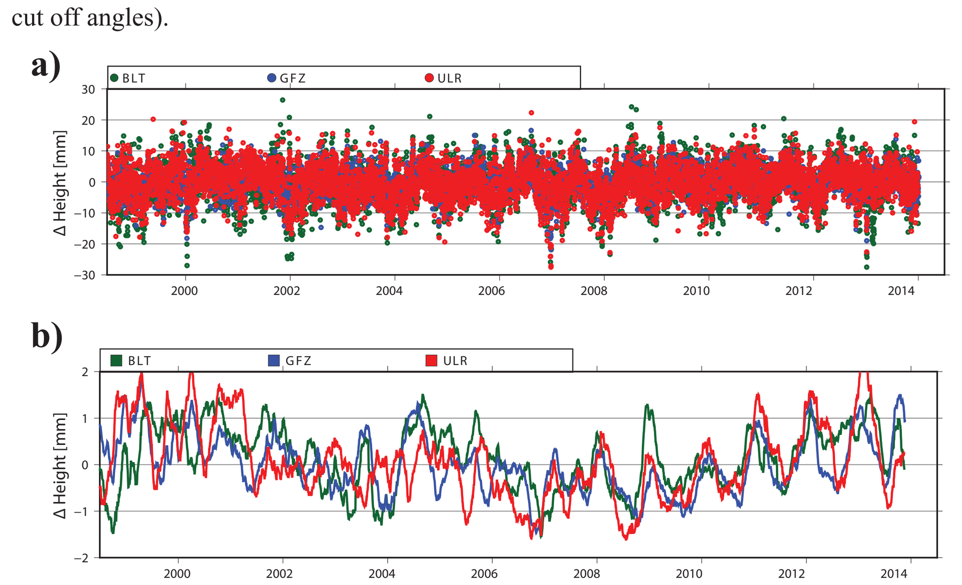


Figure 2. a) The residual time series for the height component for each contributing TAC for ONSA, Onsala, Sweden with respect to IGb08, b) the smoothed version of the same residual position time series.

Post-seismic deformation modelling

GPS residual position time series show non-linear trajectories during and after earthquakes. This post-seismic displacement (PSD) as experienced by GPS stations are usually located near major plate boundaries. Each of the TAC comprises a significant number of continuous GNSS stations located around these boundaries and their time series show coseismic as well as postseimic deformations. Figure 3 shows the distributions of the GNSS stations affected by earthquakes. Without modifying the trajectories of these affected stations, their velocity estimates are adversely affected. We adopted the model by ITRF2014 (Altamimi et al., 2016). The residual time series fitting is based on four parametric models: logarithmic, exponential, logarithmic + exponential, and exponential + exponential decays.

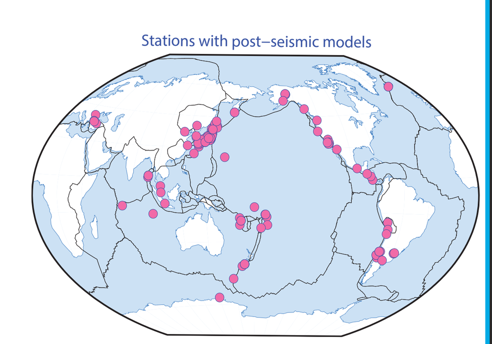


Figure 3. The distribution of 119 GPS stations that are affected by earthquakes which need a postseismic parametric models

We have implemented the PSD models in the CATREF software package before we perform stacking of the Individual TAC solution. Figure 4 shows the results of the PSD parametric modelling for selected stations in Japan and Chile. For P104, Oga, Japan, a combination of logarithmic + exponential is fitted for the horizontal components and while only one Exponential parameter is fitted for the Up component. For ANTC, Los Angeles, Chile, the fit is the same for the horizontal components as for P104 but for the up component the PSD uses two exponential decays parameters. After the fit, there is an almost 3 fold improvement in the east component and 60% improvement in the north component while the improvement in the Up component reaches up to 8%.

The effect of post-seismic deformation modelling on selected time series

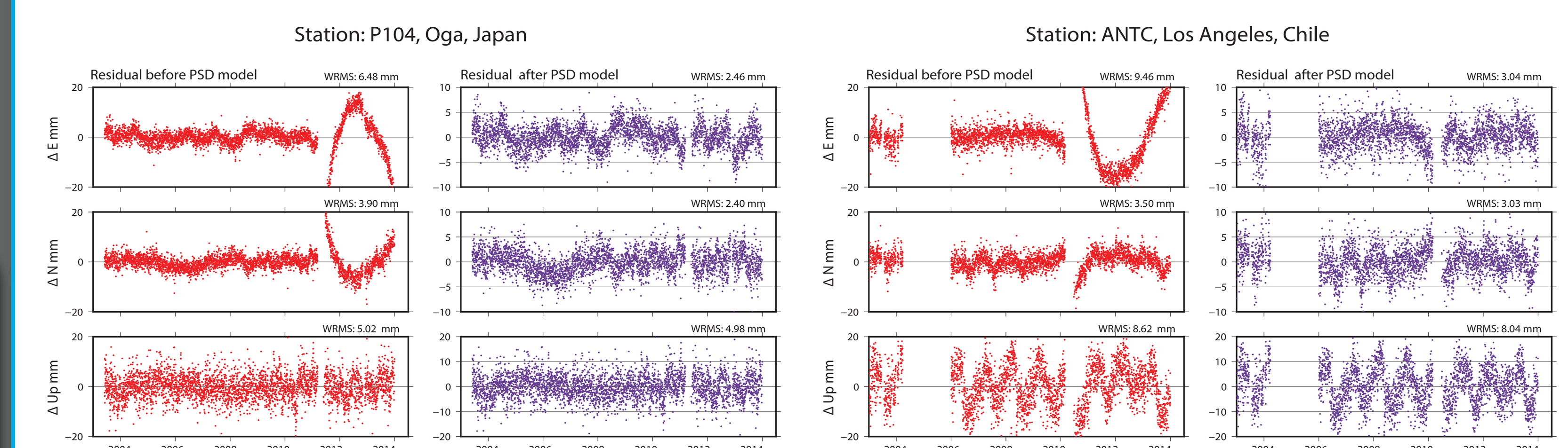


Figure 4. The residual time series for P104, Oga, Japan (left) and ANTC, Los Angeles, Chile (right). Red dots depict the residual times series before fitting a PSD model and dark blue dots depict after fitting the ITRF2014 PSD model. Note, the different scales of the vertical axes. Clearly the PSD parametric modelling has substantially improved the residual time series with a significant decrease in WRMS, especially for the horizontal components – a reduction of the noise level up to 200 % for some stations and a minor, but still discernible improvement for the Up component – a reduction of the noise level up to 8%.

Daily stacked residual position time series

The daily repeatability of the stacked residual position time series. Figure 5 shows the weighted RMS (WRMS) of the individual stacked solutions. For the early years, there is a higher noise level in general but more so from the BLT solution. There is also a slightly higher noise level in the Up component for the BLT stacked solution. On the other hand, the horizontal components' noise levels are low. There is however, a slight increase in the East component WRMS for the GFZ solution in 2011. This effect is under investigation.

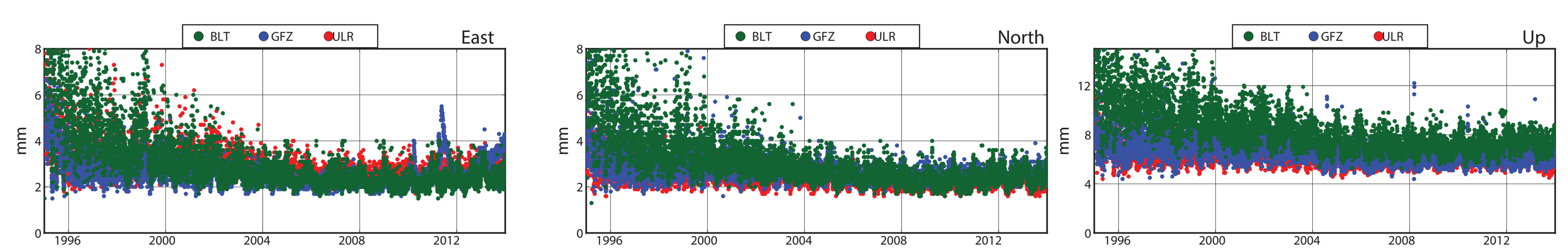


Figure 5. Daily repeatability (WRMS) of the individual TAC residual station positions from the stacked solutions. The green dots depicts the BLT, blue dots depicts GFZ and red dots depicts ULR solutions for the East, North and Up components.

Spectral Analysis

We have estimated the power spectra of the stacked residual position time series from BLT, GFZ and ULR solutions. The normalized Lomb-Scargle periodogram is computed for all residual position time series. The individual power spectra were stacked after we have calculated each individual spectra including now even for those stations that are affected by earthquakes since we have now applied the PSD model. To discriminate dominant features in the power spectra, we have applied a smoothing using a moving average boxcar filter (filter1d), following Ray et al. (2008). Figure 6 shows the stacked normalized periodograms from BLT, GFZ and ULR solutions. All the three spectra show the dominant seasonal peaks as well as peaks at harmonics of the GPS dracontic year. The Up component shows also a prominent peak with fortnightly period even though it is also visible in the horizontal components.

A closer look shows three power surges at the fortnightly peak at periods of 13.7, 14.2 and 14.8 days. There is a power at an 8 day period only particular to the BLT solution which is related to the inclusion of GLONASS data during the CODE product generation (see also POSTER G11B-1075). There is also a slight power around a 5 day period in the GFZ solution.

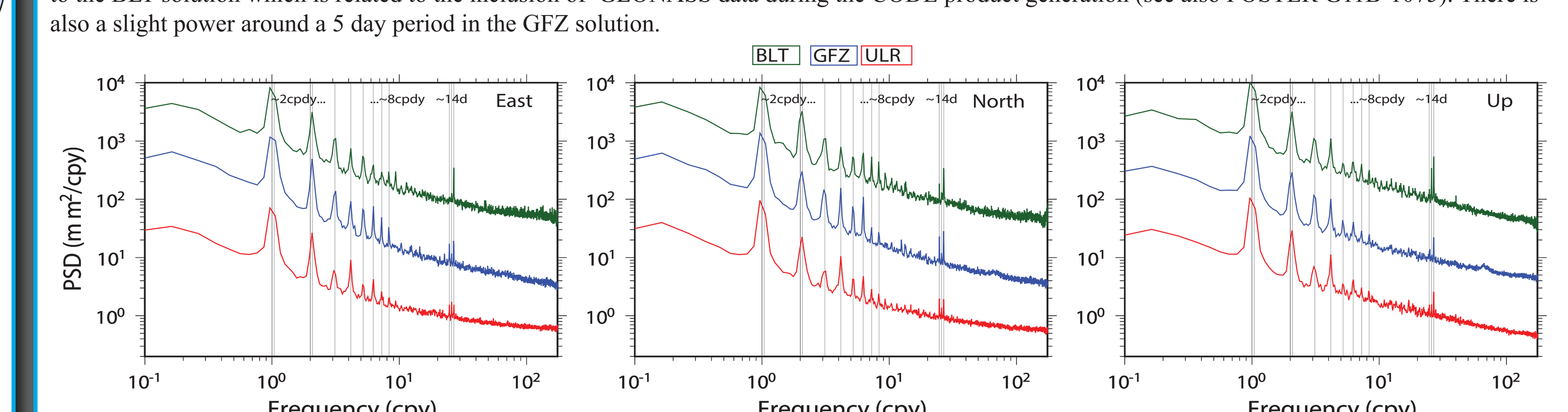


Figure 6. Smoothed stacked power spectra of the residual position time series. A small part of the spectrum that is affected by edge effects is removed from all the three components. Clear seasonal power peaks as well as harmonics of the GPS dracontic frequencies are identified in all components. There is also a sharp power peaks in the fortnightly band in all the three components, but much more pronounced in the Up component. The vertical black lines indicate the annual, semi-annual and fortnightly periods. The gray lines indicate 10 of the harmonics of the GPS draconitic periods. [**cpdy**= *cycle per draconitic year*]

Scale

As the terrestrial scale directly maps into the up component and it is important to investigate the scale time series. Figure 7 shows terrestrial scale parameters for the TAC solutions in parts per billion [ppb] and in millimeters. We have also plotted the corresponding power spectra. All three TAC scales show clear annual and semi-annual signals. Compared to the power spectra of the residual positon time series, the power spectra of the terrestrial scale time series show fewer GPS draconitic harmonics. The BLT and GFZ scale time series agree well but the ULR solution shows a larger scale variations. Table 2 shows the trends in the scales of TAC solution in part per billion.

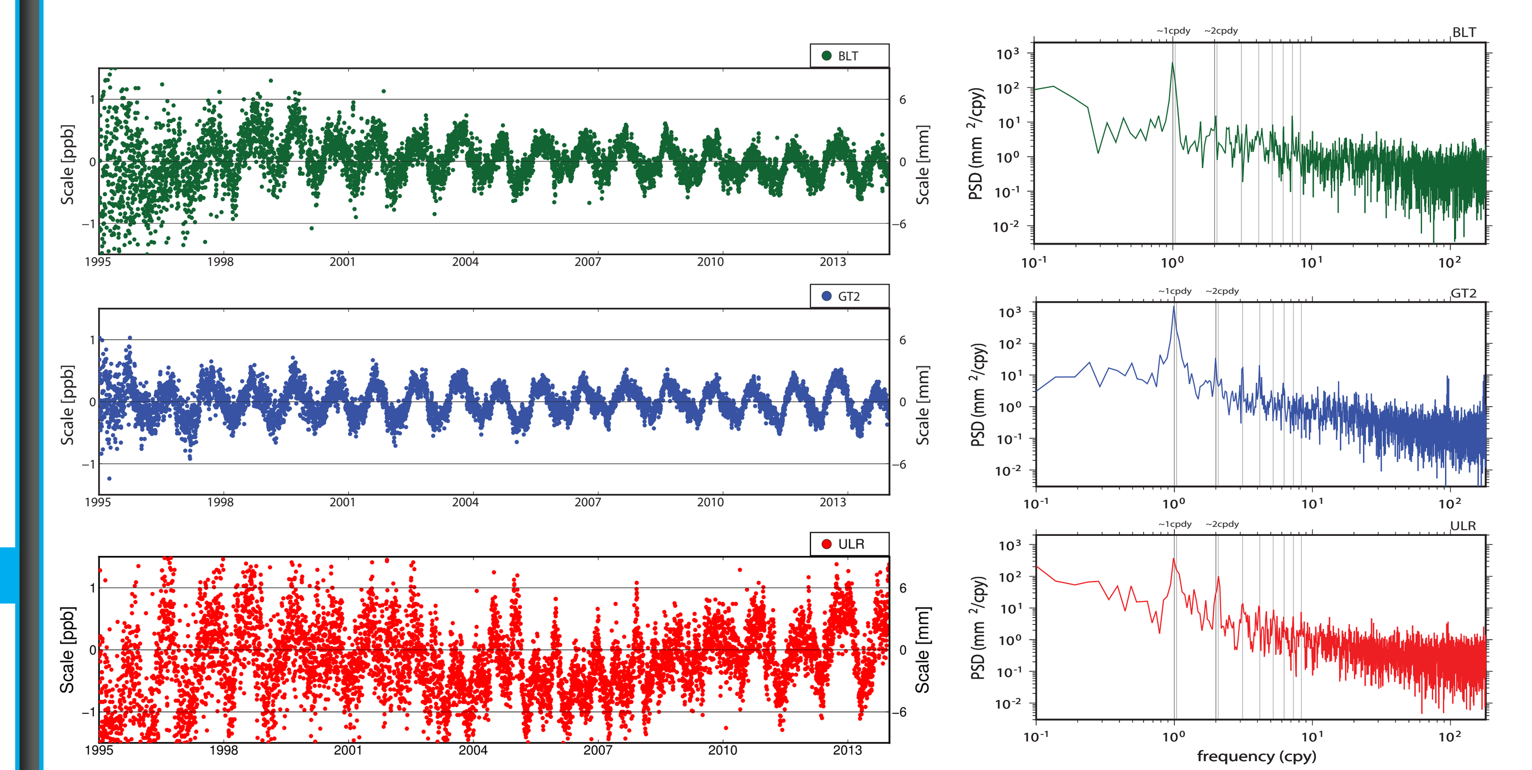


Figure 7. The time series of the terrestrial scales variations for the TAC solutions on the left and the corresponding power spectra on the right. The power spectra for all TAC show a dominant power on annual and semi-annual signals. The vertical gray lines indicate the harmonics of the GPS draconitic periods. The vertical black lines indicate the annual and semi-annual periods. [cpdy= cycle per draconitic year]

TAC	Trend	Bias
BLT	0.002 ± 0.009	-0.040 ± 0.083
GFZ	0.006 ± 0.007	+0.006 ± 0.071
ULR	0.052 ± 0.050	-0.195 ± 0.530

Table 2. The trend and bias of the terrestrial scales of the TAC solution. The unit is ppb.

VLM estimates from TAC stacked solutions and ITRF2014

Figure 8 shows the vertical land movement estimates from all the TAC and from the recently released ITRF2014 reference frame solutions. Clear vertical land movements emerge with similar magnitudes between TAC and ITRF2014 solutions with a regional footprints. In the regions such as Greenland, North America, and Fennoscandia, the VLM reflect uplift mainly caused by past and present ice load responses. Table 3 shows the standard deviations of TAC solution with respect to the recently released ITRF2014 solution.

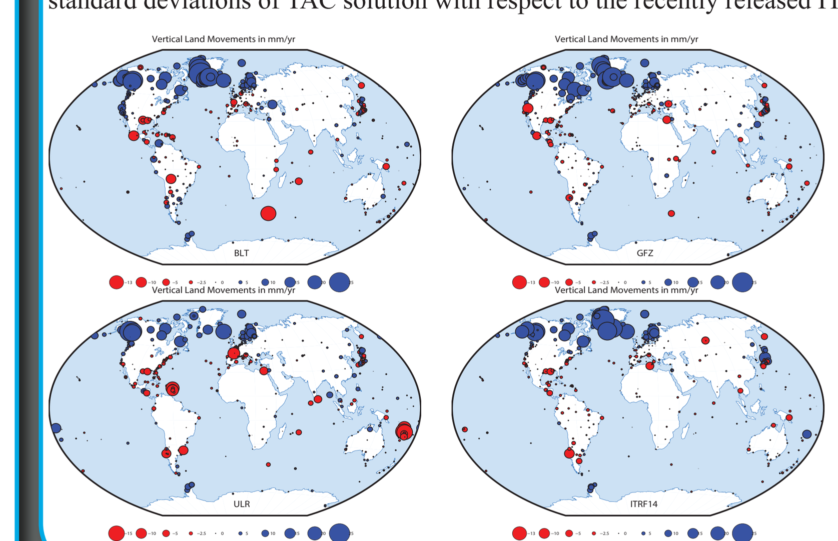


Figure 8. Vertical rate from stacked TAC solution: BLT, GFZ, ULR, and ITRF2014. The rates are expressed in the International Terrestrial Reference Frame (ITRF2008) for the TAC stacked solution.

Table 3. Bias and standard deviations of the TAC solution vertical land movement estimates with respect to the ITRF2014 estimates. Values are in mm/yr. More than 400 stations are used for the comparison

	BLT	GFZ	ULR
Scatter of Trends w.r.t ITRF2014	1.61	1.60	1.60
Bias w.r.t ITRF2014	0.2	0.2	0.2

Conclusions

We have presented an evaluation of the three individual TAC long-term (1995-2013), linear stacked solutions from the 2nd reprocessing campaign, which will form the first TIGA combined solution release. Similar to IGS combinations the individual solutions show good agreement with each other with variations being attributed to the different software packages and processing strategies used by the TAC. However, compared to the IGS solutions the TIGA solutions include many stations at or near tide gauges, which are deemed useful for sea level studies. While the reference frame is still aligned to IGb08, the TAC stacked solutions have benefited from our implementation of the seismic deformation models recently adopted by ITRF2014.

Further points are noteworthy:
- All TAC solution stacked spectra show prominent peaks at periods of seasonal and GPS draconitic harmonics.
- The scale time series of the TAC stacked solutions have no significant trends with respect to IGb08.
- The VLM estimates from all solutions show a remarkably good agreement in Greenland, Europe and Japan, and agree well with the ITRF2014 VLM estimates (based on 400+ common stations). Some outlying VLM estimates will be further investigated.

The TIGA combined solution and the stacked TAC solutions, as well as the VLM estimates will be available at the TIGA website as release 1.0 from early 2017. These VLM estimates should be considered as the primary TIGA product to correct tide gauge records for land level changes.

Acknowledgements

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