Assessment of the BLT Tide Gauge Benchmark Monitoring (TIGA) repro2 Solution

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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 in solving issues related to the accuracy and reliability of the vertical component as measured by GPS and to provide estimates of VLM in a well-defined global reference frame. To achieve this objective, four TIGA Analysis Centers (TACs) contribute reprocessed 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 (See Table 1)

In preparation for the TIGA re-processing campaign, the consortium of the British Isles continuous GNSS Facility (BIGF) and the University of Luxembourg TIGA Analysis Centres (BLT) has produced a multi-year long time series solutions, based on the Bernese GNSS Software Version 5.2 (BSW5.2) (Dach et al. 2015) using a double difference (DD) network processing strategy as our reprocessing 2 (repro2) solution.

In this study, we aim to explore the potential in improving the precision and accuracy of the station coordinate and station velocity estimates based on the individual and combined solutions. Unfortunately, only three TAC solutions have been completed while the fourth one is to be completed soon. Table 1 and Figure 1 gives details of the TACs and of the combined network. It is noteworthy that all four contributing TACs have analysed global networks with a consistent set of reference frame stations, i.e. in ITRF2008 (IGb08).

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

TAC	Host Institution	Software package	Contributors
BLT	British Isles continuous GNSS Facility and the University of Luxembourg TAC (BLT), UK and Luxembourg	BSW5.2	FN Teferle, A Huneganw, RM Bingley, DN Hansen
DGF	Deutsches Geodätisches Forschungsinstitut, Germany	BSW5.2	L Sánchez
GFZ	GeoForschungsZentrum Potsdam (GFZ), Germany	EPOS P8	T Schöne Z Deng
ULR	Centre Littoral de Geophysique, University of La Rochelle (ULR), France	GAMIT/ GLOBK V10.5	G Wöppelmann,M Gravelle, A Santamaría-Gómez

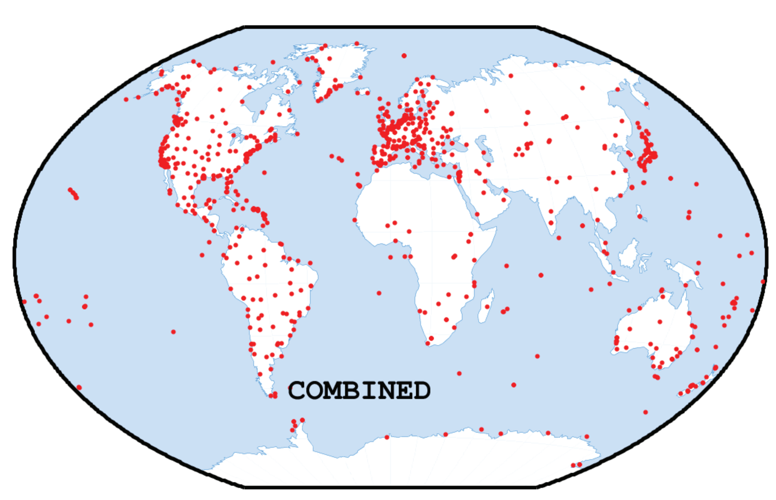

Figure 1. Spatial distibution of the stations for the combined network.

Quality Control of Reprocessed BLT Solution

In order to assess our repro2 daily solutions, we look into varieties of metrics of the post-fit residual position time series. We have used the CATS software to estimate the station velocities as a primary target to assess the VLM at or close to tide gauges. The model includes fitting a linear trend, annual and semi-annual terms, and offsets due to discontinuities in GPS time series. The metrics we are looking at include the power spectra, weighted root mean square and station velocities and the effect of discontinuities on the velocity estimates.

Spectral Analysis

We have estimated the power spectra of the post-fit residual position time series from our repro2 solutions. The stacked spectra are calculated from individual power spectrum for sites that have more than five years of data interval and are not affected by earthquakes. To discriminate dominant features in the power spectra, we have applied a moving average boxcar filter, following Ray et al. (2008). All the three spectra show the dominant seasonal peaks as well as peaks at harmonics of the GPS draconitic year (Figure 6). The Up component shows also a prominent peak at the fortnight but with less energy in the horizontal components. A closer look shows three power surges at the fortnight peak at periods of 13.7, 14.2 and 14.8 days.

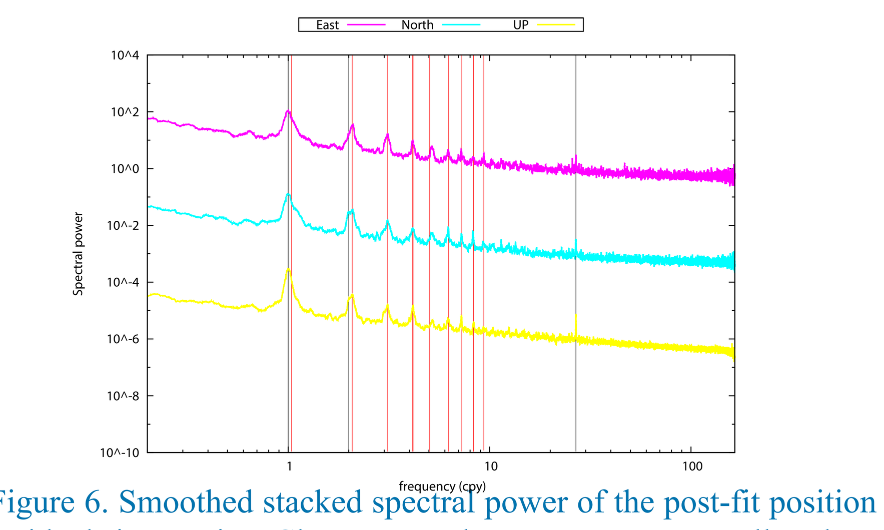

Figure 6. Smoothed stacked spectral power of the post-fit position residual time series. Clear seasonal power surges as well as harmonics of the GPS draconitic frequencies are identified in all components. There is also a sharp power surge in the fortnightly bands in all the three components, but much more pronounced in the up component. The black lines indicate the annual, semi-annual and fortnightly peaks. The red lines indicate draconitic harmonics

Weighted Root Mean Square

The weighted root mean square (WRMS) values of the residual is a key aspect of the metrics to assess the quality of the post-fit position residuals for all stations available to our repro2 solution. We have plotted the WRMS for each of the time series as a function of latitude for the components North, East and Up. There is no clear spatial correlation of the residual position time series. The north component WRMS shows a smaller scatter compared to the east component, an indication that some of the ambiguities may not have been resolved (see Figure 7).

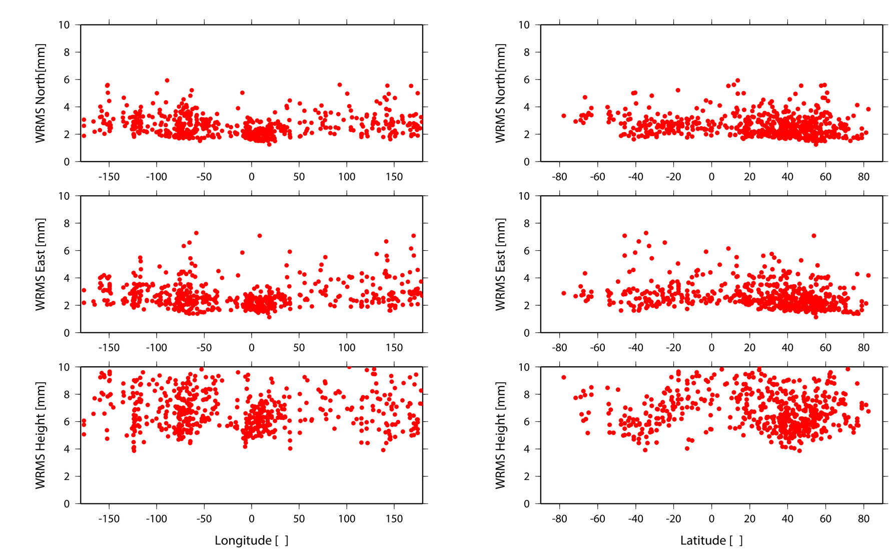

Figure 7. The WRMS variations for the position residuals. The WRMS residuals are arranged with respect to latitude to highlight any spatial patterns. No apparent feature that indicates such spatially correlated variations. However, there is only a small number if stations within -20 and +20 degrees latitude as well as an imbalance in the hemispherical distribution of stations.

Combination

Our main goal within TIGA working group is to combine all TAC solutions to form a combined solution using two independent software packages: CATREF (Altamimi et al., 2002) and GLOBK (Herring et al.2006). This combined solution will be used to estimate the VLM for studying long-term sea level trends while minimizing the uncertainty level. A preliminary combined solution from our TIGA solution indicated that the error bound grows using the ITRF2008 or its derivative (IGb08) datum as the time series extend far from the reference frames epoch origin (See Figure 2).

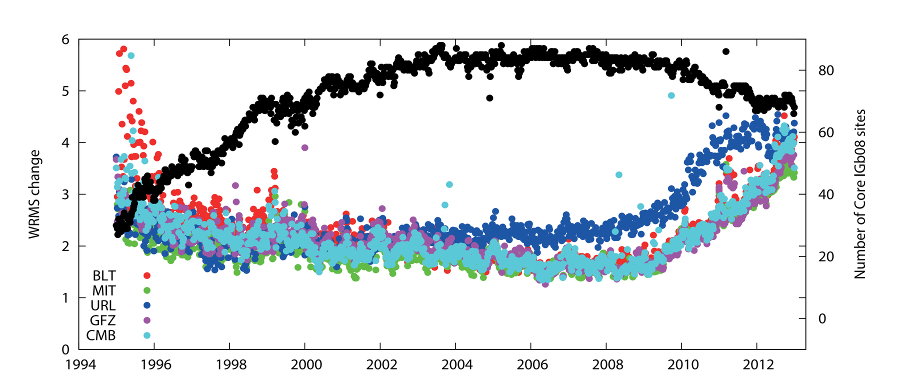

Figure 2. The cumulative weighted RMS (WRMS) of the weekly solutions of the stabilized sites. The black dots represent the number of core sites that are used to realize the frame w.r.t to the IGb08 frame.

Before the final TIGA ACs combined solution becomes available, we have made an assessment of the individual TAC solutions including the MIT solutions w.r.t the newly released ITRF2014. Figure 3 illustrates the cumulative WRMS for stabilizing sites using ITRF2014 frame. The solutions are now stabilized and improved compared to the old ITRF2008 (IGS08) reference frame.

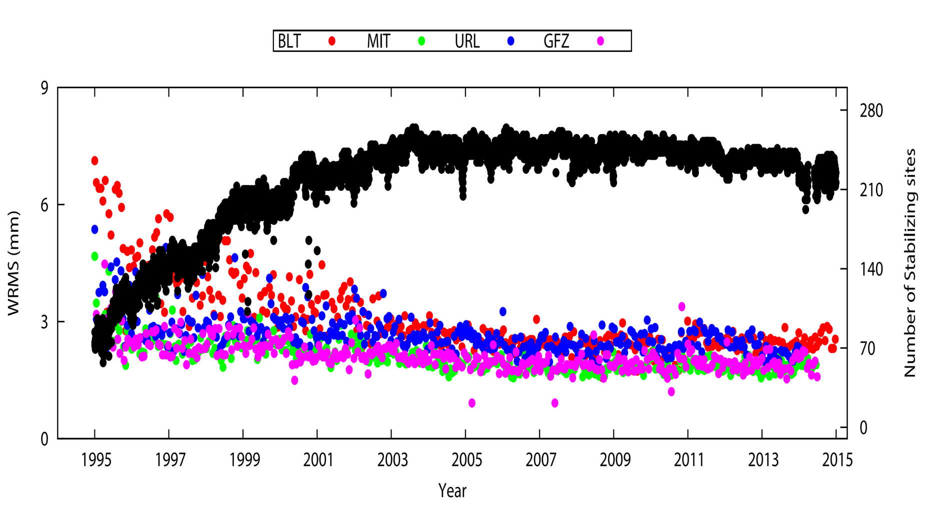

Figure 3. The cumulative weighted RMS (WRMS) of the daily solutions of the stabilized sites. The cyan solid line represent the number of stabilizing sites that are used to realize the TAC solutions w.r.t to ITRF2014.

GPS Re-processing at BLT

The IGS community has given high priority to the harmonization of processing standards since the homogenous re-processing of all past available GPS data up to the present is key to estimating meaningful geophysical parameters from the derived long time series. This is crucial to this study in order to obtain highly accurate estimates of VLM through a full re-processing of all observations from continuous GPS stations at or close to tide gauges. The reprocessing strategy and models used at BLT are shown in Table 2.

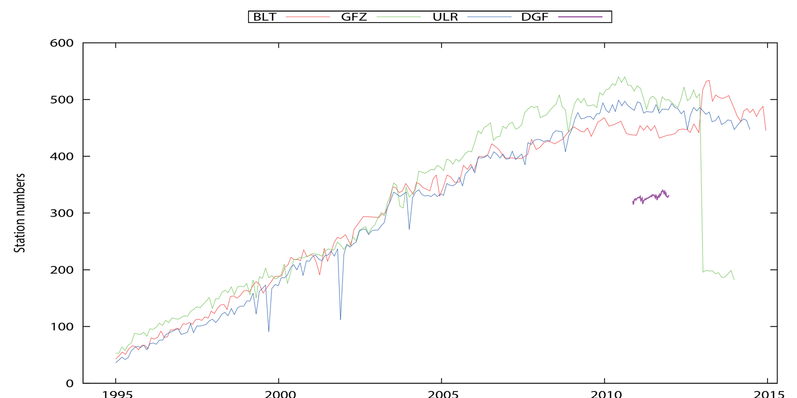

Figure 4: The number of sites available in TIGA and IGS AC SINEX files. Three TACs process well over 400 stations since 2005 onwards.

Table 2: Reprocessing strategy and model applied for BLT repro2 solution

Software	Bernese BSW5.2
Satellite/ARC	GPS, 72 hours
Elevation cutoff Angle	3 degrees and the cosine(Elevation) quartic dependent weighting
Ionosphere	Ionosphere free linear combination (L3) including second order corrections
Antenna PCV (Receiver and satellite)	IGS absolute elevation and azimuth dependent PCV igs08.atx file
Troposphere	VMF Mapping function and Dry a priori and Wet troposphere model from VMF
Troposphere gradients	Chen and Herring tilt estimation for N-S and W-E directions
Conventions	IERS2010
Ocean tides	FES2004
Static Gravity field	EGM2008 (12X12, C20, C21, S21 as per IERS2010 convention)
Ambiguity resolution	Resolved integers up to 6000km using double different techniques depending on the baseline length
Datum	No-Net Rotation (NNR) with respect to the IGb08 GPS only frame
Network size	Upwards 400 stations
Time period	1995 -2015 (October)
Data	Double difference phase and code observations

Besides BLT the three other TACs, DGF, GFZ and URL, also provide reprocessed GPS solutions following the IGS repro2 standards and bias models using BSW5.2, EPOS P8 and GAMIT/GLOBK V10.5 software packages, respectively, i.e. the three currently available TAC solutions use different software packages. The solutions include SINEX files from GPS week 0782 (Jan. 1995) to GPS week 1825 (Dec. 31, 2014). Figure 4 provides evidence of increasing number of stations used by the individual TAC solutions for this period. While Figure 5 shows the station distributions for the individual TACs network distributions.

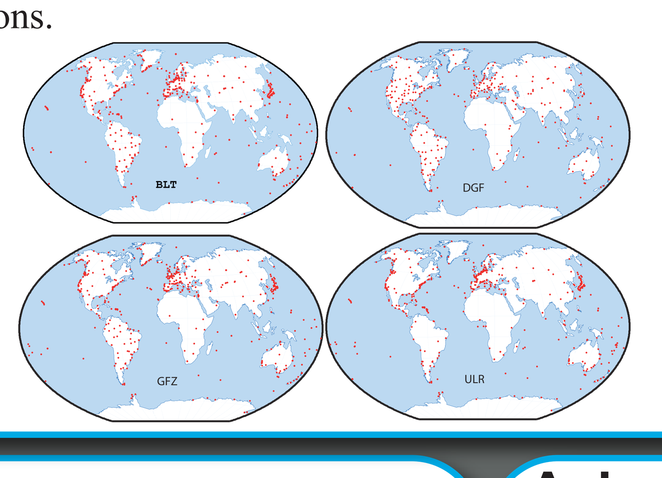

Figure 5. Spatial distribution of the stations for individual TACs and the combined network.

Preliminary Vertical Velocity

The BLT multi-year repro2 solution contains station coordinates and vertical velocity for over 600 sites. Figure 8 illustrates the vertical velocity field w.r.t the IGS08. The BLT vertical velocity in North America, Greenland and North Europe are dominated by strong uplift due to Post Galacial Rebound (PGR).

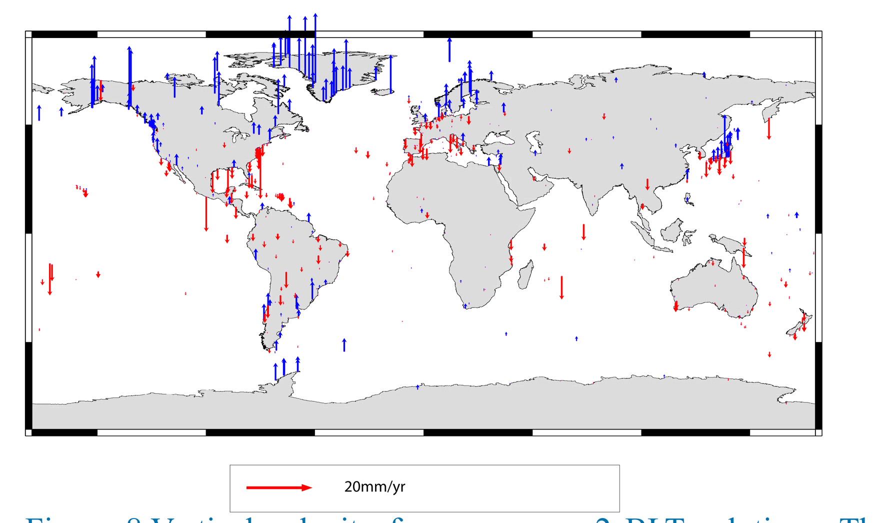

Figure 8.Vertical velocity from our repro2 BLT solutions. The vertical velocities are expressed in the IGb08 frame.

ULR and BLT repro2 Solutions

We have computed the vertical velocity estimated between the latest ULR TIGA solution (ULR5) with our repro2 solution from BLT for stations longer than 3 years of data and with data gaps not exceeding 30%. Figure 9 shows the vertical velocity difference between the two repro2 solutions. The difference in RMS is sub millimetre with almost no bias between them. RMS statistics is shown in Table 3

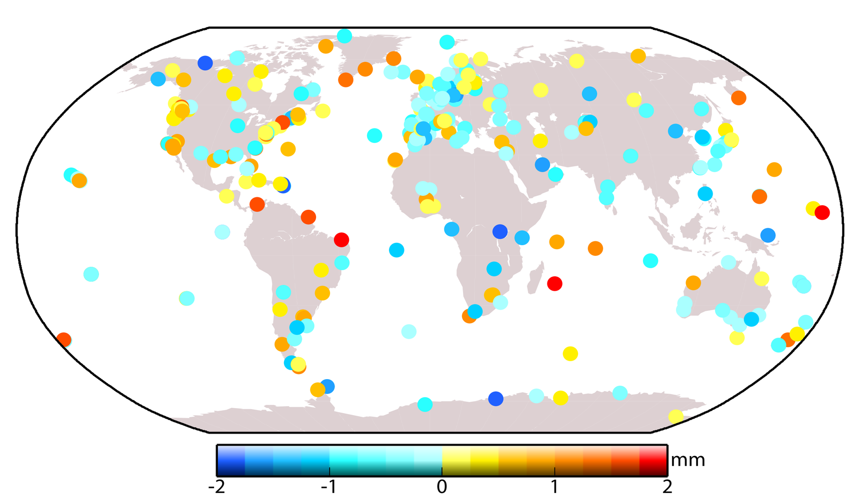

Figure 9. The vertical velocity differences between the two repro2 TIGA solutions (BLT- ULR)

RMS	Mean
0.8	0.1

Table 3. RMS and mean differences in mm/yr of GPS vertical velocity estimates between BLT and ULR solutions

Effect of Discontinuity on velocity Estimate

On average GPS station time series are affected by at least two discontinuities per decade. The impact of these offsets is especially severe for the Up component and, hence, for the estimated vertical velocities. Figure 10 shows how the vertical velocities can be adversely affected if one or more discontinuities are not accounted for.

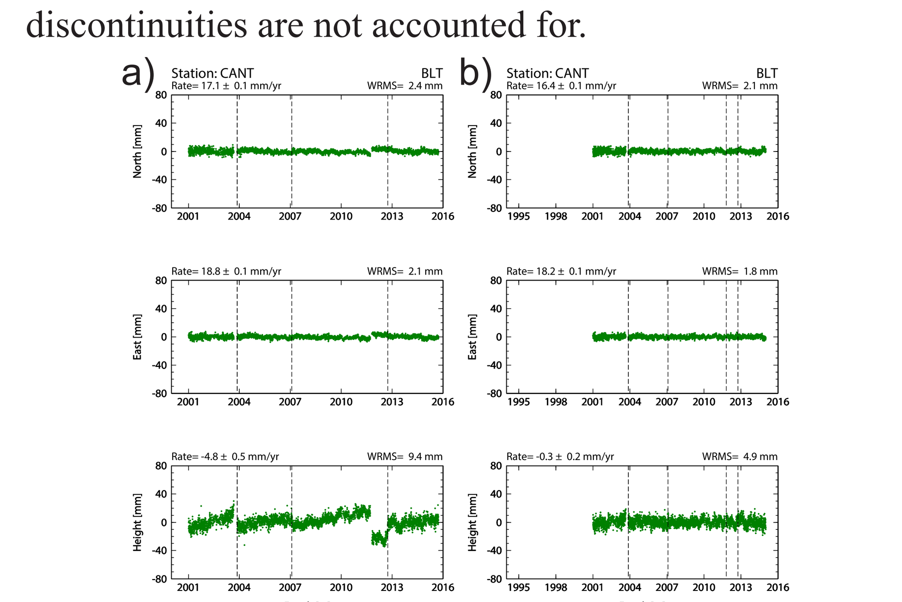

Figure 10. The daily residual position time series (green dots) at continuous GPS station CANT in Santander, Spain for the North, East, and Up components. The station is affected by many discontinuities. a) Shows the station has a vertical rate of -4.8 mm/yr if only three of the discontinuities were accounted. b) The same station, but now all possible discontinuities have been included in the model. The vertical rate for the Up component changes by almost an order of magnitude. The WRMS misfit of the residual position times series is given in the top right.

Conclusions

1.BLT has completed its repro2 solution of the TIGA network for the period 1995 to 2015. Discontinuities adversely affect station velocity estimates, which is of particular interest for vertical velocities to be used as vertical land movements estimates at tide gauges and more than 700 stations have been manually checked and validated.

2. There are subtle velocity differences between each of the individual TIGA solutions as shown for BLT and ULR. This demonstrates the need for an optimally combined solution from all TACs to be used as a VLM product for sea level studies.

3. An initial assessments attests that the new ITRF2014 provides a stable solution for the period 1995 to 2015 unlike the previous ITRF as we move away from the ITRF epoch origin. The TIGA combination center at the University of Luxembourg will compute such a combination with respect to the new ITRF2014 frame.

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