Combination of Tide Gauge Benchmark Monitoring (TIGA) Analysis Center from repro2 solutions

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Abstract

Recently the International GNSS Service (IGS) Tide Gauge Benchmark Monitoring (TIGA) Working Group (WG) has completed their repro2 solutions by re-analyzing the full history of all relevant Global Positioning System (GPS) observations from 1995 to 2015. This re-processed data set will provide high-quality estimates of vertical land movements for more than 700 stations, enabling regional and global high-precision geophysical/geodetic studies. All the TIGA Analysis Centres (TACs) have processed the observations recorded by 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) besides those of the global IGS core network used for its reference frame implementations. Following the recent improvements in processing models, strategies (http://acc.igs.org/reprocess2.html), this is the first complete reprocessing attempt by the TIGA WG to provide homogeneous position time series relevant to sea level changes. In this study we report on a first multi-year daily combined solution from the TIGA Combination Centre (TCC) at the University of Luxembourg (UL) with respect to the latest International Terrestrial Reference Frame (ITRF2014). Using GLOBK combination software package, we have computed a first daily combined solution from TAC solutions already available to the TIGA WG. These combinations allow an evaluation any effects of the individual TAC parameters and their influences on the combined solution with respect to the latest ITRF2014. Some results of the UL TIGA multi-year combinations in terms of geocentric sea level changes will be presented and discussed

Introduction

Sea level change as a consequence of climate variations has a direct and significant impact in many coastal areas around the globe. Over the last one and a half centuries sea level changes have mainly 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 (see Wöppelmann and Marcos, 2016).

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 in doing so providing time series of vertical land movement in a well-defined global reference frame. To achieve this objective, four 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 (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 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 4 gives details of the TACs and of their contributed networks It is noteworthy that all four contributing TACs have analysed global networks with a consistent set of reference frame stations both in ITRF2008 (IGb08) and the newly released ITRF2014. The spatial distribution of the combined network is shown in Figure 1.

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.

Combined Solution Using IGS08

Our main goal within the TIGA working group is to combine all the TACs solution to form a combined solution using two independent software package 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 uncertainity 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).

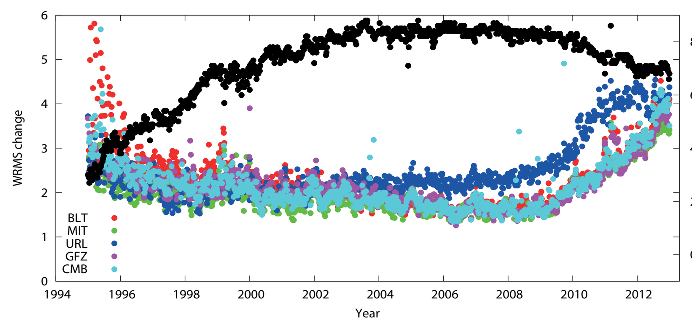

Figure 2. The cumulative weighted RMS (WRMS) of the weekly solutions of the stabilized sites. The black dots represent the number of core sites that are used to realize the frame w.r.t to IGb08 frame.

Preliminary Solution Using ITRF2014

Before the final TIGA ACs combined solution becomes available, we have made an assessment of the individual TACs including 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.

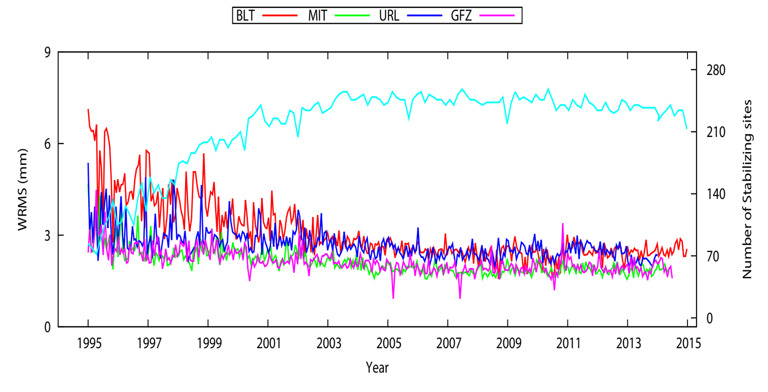

Figure 3. The cumulative weighted RMS (WRMS) of the daily solutions of the stabilized sites. The cyan solid line represent the number of stabilizing sites that are used to realize the TACs solution w.r.t to the ITRF2014.

GPS Re-processing at BLT

The IGS community has given high priority to the harmonization of processing standards since the homogenous reprocessing 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.

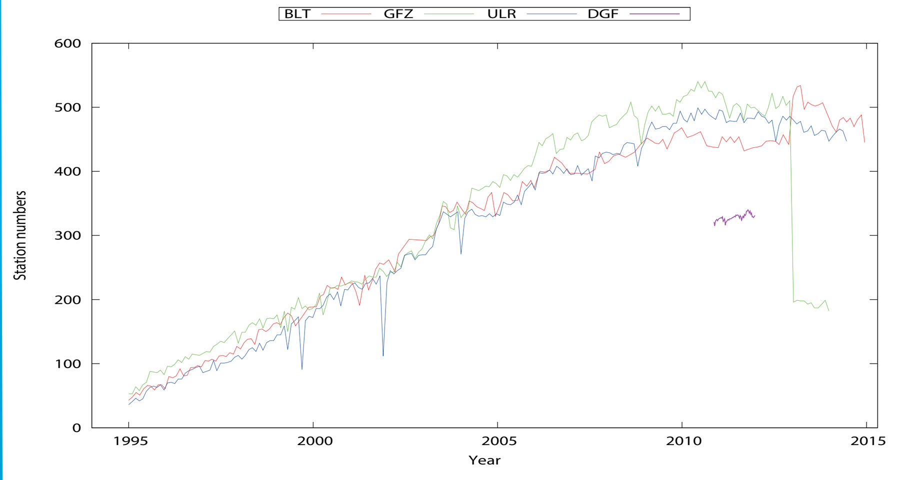

Figure 4: The number of sites available in TIGA and IGS AC SINEX files. Three TACs process well over 400 stations since 2005 onwards.

Table 2: Reprocessing strategy and model applied forBLT 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.

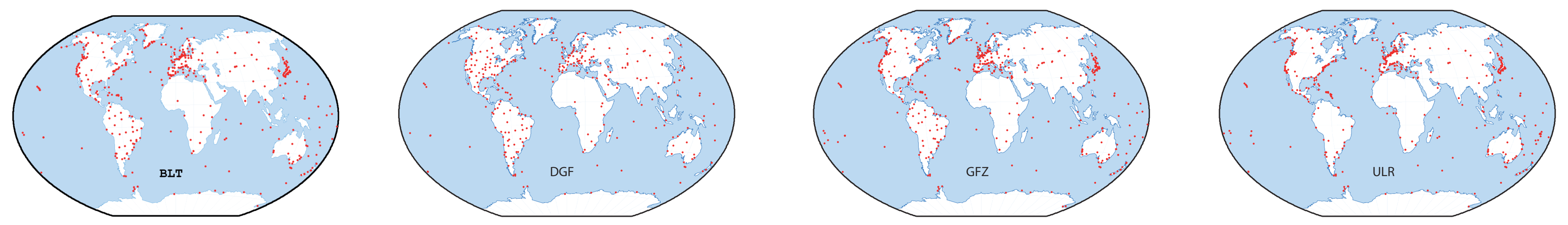

Figure 5. Spatial distibution of the stations for individual TACs and the combined network.

Quality Control of Reprocessing at BLT

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 model implemented in the CATS software package in estimating the station velocities as a primary target to assess the vertical land motion near or close to tide gauge stations. 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 dracontic 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.

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 the stations available to our repro2 solution. We have plotted the WRMS for each of the time series as a function of latitudes and longitudes 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).

Acknowledgement:

The computational resources used in this study were provided by the High Performance Computing Facility at the University of Luxembourg, Luxembourg. The IGS and its ACs are highly appreciated for their data, products and solutions. We are especially thankful to the TIGA data providers and to SONEL.org at the ULR.

Spectral and WRMS vartations plots

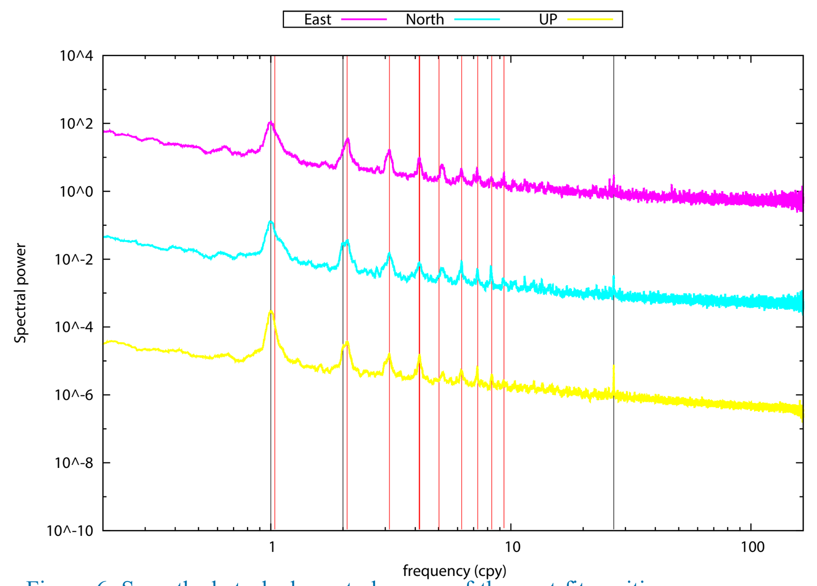

Figure 6. Smoothed stacked spectral power of the post-fit position residual time series. Clear seasonal power surges as well as harmonics of the GPS dracontic frequencies are identified in all components. There is also a sharp power surge in the fortnightly bands in all the three components, but much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

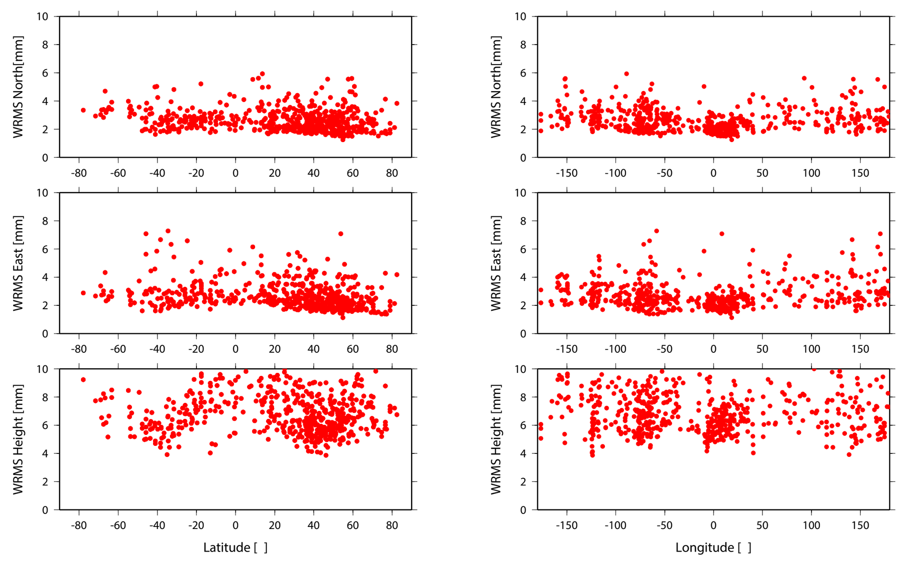

Figure 7. The WRMS variations for the position residuals. The WRMS residuals are arranged with respect to latitudes to highlight any spatial patterns. No apparent feature that indicates such spatially correlated variations. However, there is only a small number if stations within -20 and +20 degrees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

Amplitudes of annual and semi-annual signals

To accurately measure secular station velocity from GPS, the GPS time series has to be corrected by fitting a seasonally varying model with a certain amplitude and phase. Figure 8 shows the amplitudes of the annul and semi-annual signals of the model fit. Here we do not see any clear spatial correlation for the amplitudes of both dominant seasonal signals. However, the semi-annual signal has higher error bars. The majority of the amplitudes is below 2mm and 1mm, for the annual and semi-annual signals, respectively. The scale of the semi-annual is half the annual amplitudes

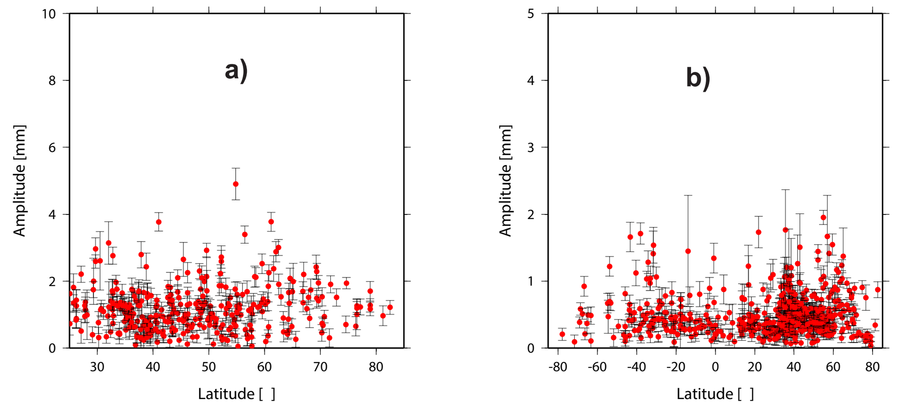

Figure 8. The amplitudes in units of mm for the model fit for the two prominent seasonal signals (annual (a) & (b) semi-annual). The amplitudes are below 2mm and 1mm, for the annual and semi-annual signals, respectively with no apparent spatial correlation. The scale of the semi-annual is half the annual. The error bar represents formal 1 standard deviations.

Preliminary Vertical Velocity

The multi-year repro2 from BLT consists of solutions for both station coordinates and vertical rates for over 700 sites. Figure 9 illustrates the vertical rate field for the Up component with respect to the International Terrestrial Reference Frame (ITRF2008). The BLT vertical rates in North America, Greenland and Fennoscandia regions are dominated by strong Post Galacial Rebound (PGR).

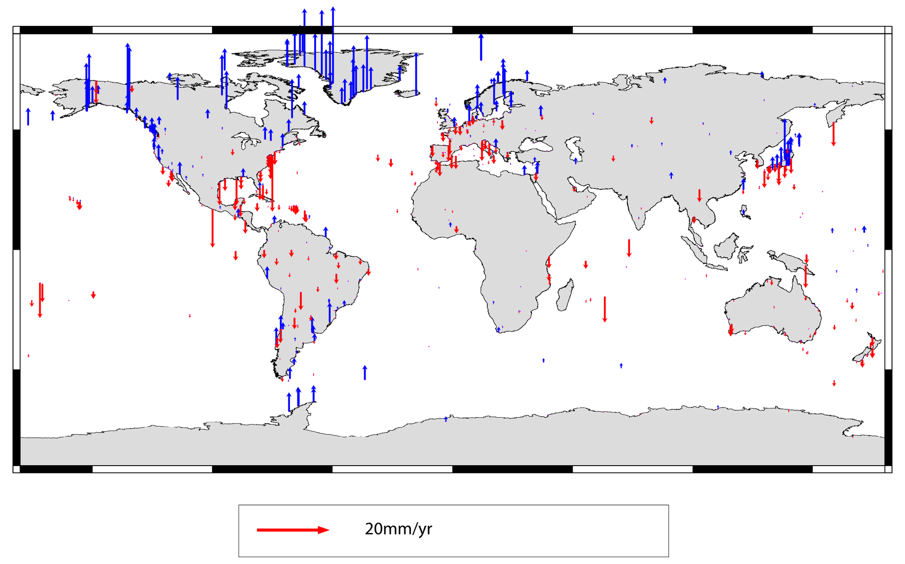

Figure 9.Vertical rate from our repro2 BLT solutions. The verates are expressed in the latest realization of the International Terrestrial Reference Frame (ITRF2008).

Vertical Rate difference between ULR and BLT repro2 Solutions

We have computed the vertical rate 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 10 shows the vertical rate 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.

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

RMS	Mean
0.8	0.1

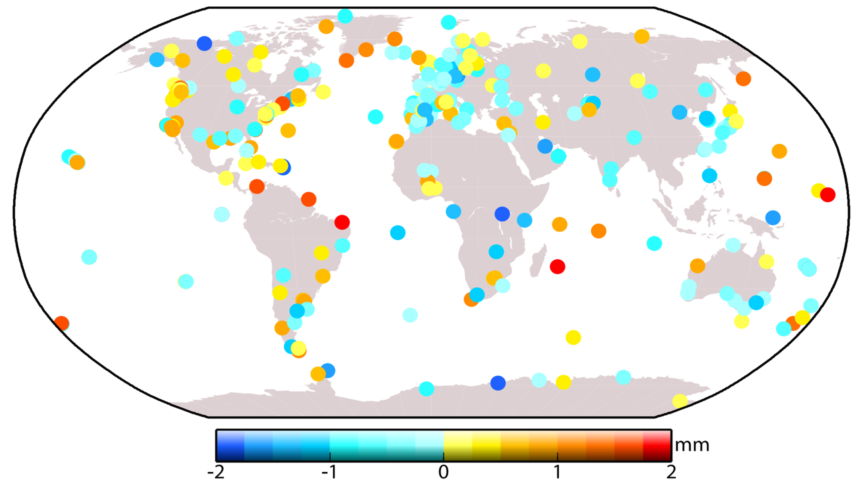

Figure 10. The vertical velocity differences between the two repro2 TIGA solutions (BLT- ULR)

Discontinuity in Residual Position Time Series

On average GPS station time series is 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 velocity estimates. Figure 11 shows how the vertical velocities can be adversely affected if one or more discontinuities are not accounted for. To account for nearly all discontinuties, all position residual time series have been inspected manually. Figure 12 shows the contributions of different offset sources.

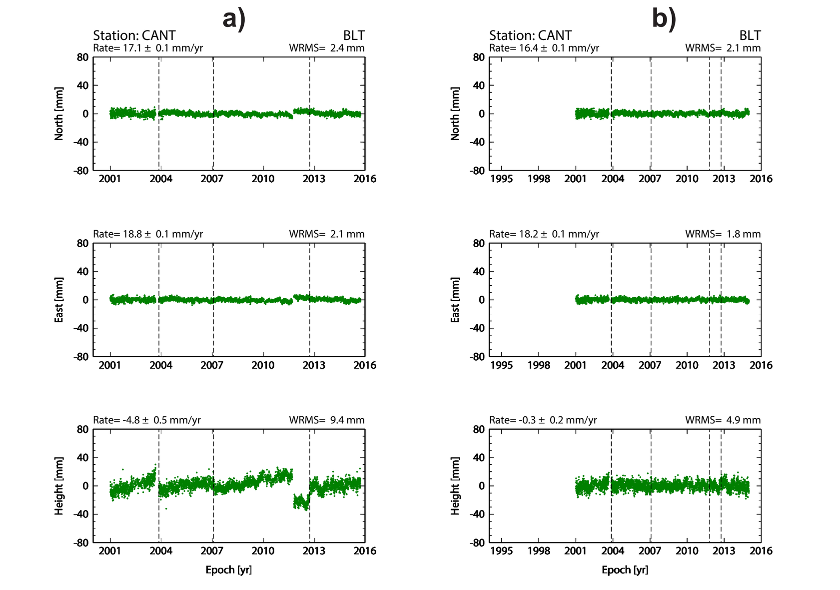

Figure 11. The daily residual position time series (green dots) at continuous GPS station CANT in Santander, Spain for the North, East, and Up components. The station is affected by many discontinuities. a) Shows the station has a vertical rate of -4.8 mm/yr if only three of the discontinuities were 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.

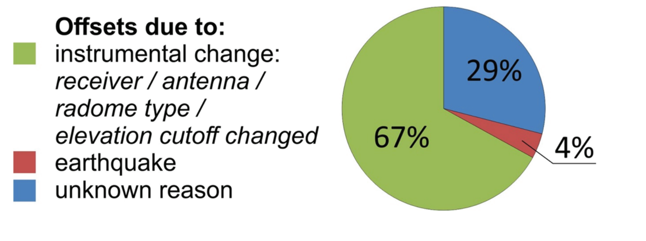

Figure 12. Offsets/discontinuities budget in BLT repro2 solution

Conclusions

BLT has completed its repro2 solution of the TIGA network for the period 1995 to 2015. As previously discussed 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 should therefore be thoroughly checked and validated.

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 vertical land movements product for sea level studies.

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 once all TAC solutions are available in

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