Assessment of BLT Tide Gauge Benchmark Monitoring (TIGA) repro2 solutions

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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 1994 to 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 Centres (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 centre at the University of La Rochelle (www.sonel.org). Following the recent improvements in processing models and strategies, this is the first complete reprocessing attempt by the BLT TIGA Analysis centre to provide homogeneous position time series. We report the quality of the multi-year daily solutions from the consortium of the British Isles continuous GNSS Facility (BIGF) and the University of Luxembourg TIGA Analysis Centres (BLT) based on the Bernese GNSS Software Version 5.2 using a double difference (DD) network processing strategy.

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 time series of vertical land movement in a well-defined global reference frame. 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 (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 (Dach et al. 2007) using a double difference (DD) network processing strategy, following largely that of Steigenberger et al. (2006). BLT has completed two solutions (SOL1 and SOL2) more or less the complete TIGA archive hosted at the University of La Rochelle (ULR). The SOL1 product was planned to contribute a solution to the IGS as an additional input to the next release ITRF but later found to be affected by a bug in the implementation of the Vienna Mapping Function (VMF1) in Bernese V5.2 (Figure 1 show the effect on the a priori zenith delay for two different stations). Soon after the discovery of the bug and later fixed, a second reprocessing made available at BLT (SOL2). In this study, we present our reprocessing 2 (repro2) strategy and quality assessment of our BLT solution.

One of the objectives of the TIGA Working Group is to produce consistent station coordinates on a daily/weekly 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 TAC solutions have been completed and a fourth one due to be completed soon. These include BLT, the GeoForschungsZentrum (GFZ) Potsdam, and of the University of La Rochelle and the fourth one from the Deutsches Geodätisches Forschungsinstitut (DGFI) (Figure 3). It is noteworthy that all four contributing TACs have analysed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations. The combination is underway, waiting for the official release of the latest ITRF reference frame.

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

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.

Veinna Mapping Function Bug in Bernese V.5.2 Implementation

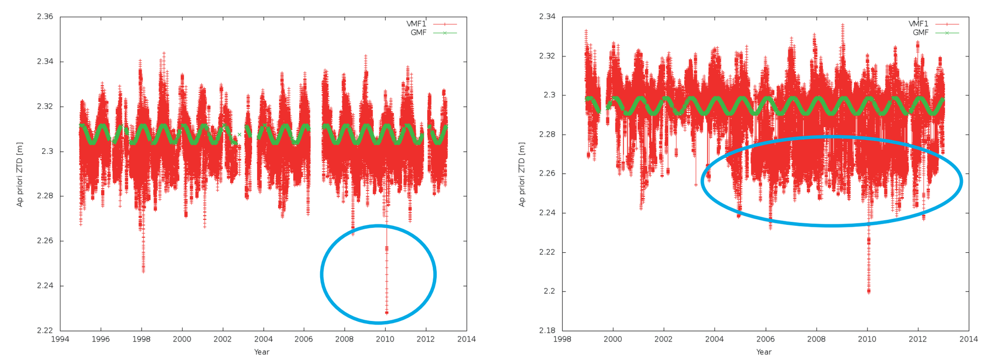

Figure 1. Suspected bug in VMF implementation in BSW5.2 before it was corrected. A priori ZTD estimates of two different sites from GMF (green) and VMF (red) models.

Acknowledgements

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 University of La Rochelle.

GPS Re-processing at BLT

The IGS community has given a high priority to the harmonization of processing standards since the homogenous re-processing of all past available data up to the present is key to estimating geodetic parameters from 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 with a particular emphasis to GPS data close to or at tide gauges. The reprocessing strategy and model used at BLT is shown in Table 2.

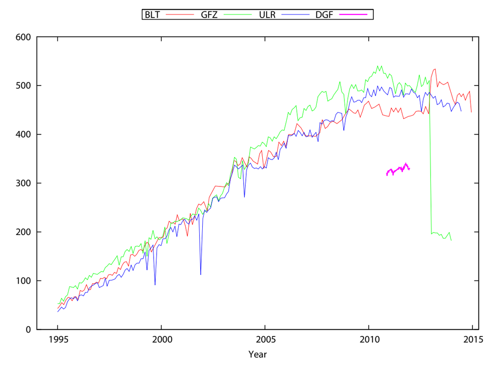

Figure 2: The number of sites available in TIGA and IGS AC SINEX files. All TACs process well over 400 stations since 2005 onwards, with the exception of DGF.

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

The three other TACs, DGF, GFZ and URL, also provide re-processed GPS solutions following the IGS repro2 standards and bias models using the Bernese, EPOS and GAMIT 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 2 provides evidence of increasing number of stations used by the individual TAC/IGS AC solutions for this period. While Figure 3 shows stations distributions for the individual TIGA Aanaysis centres and the combined network.

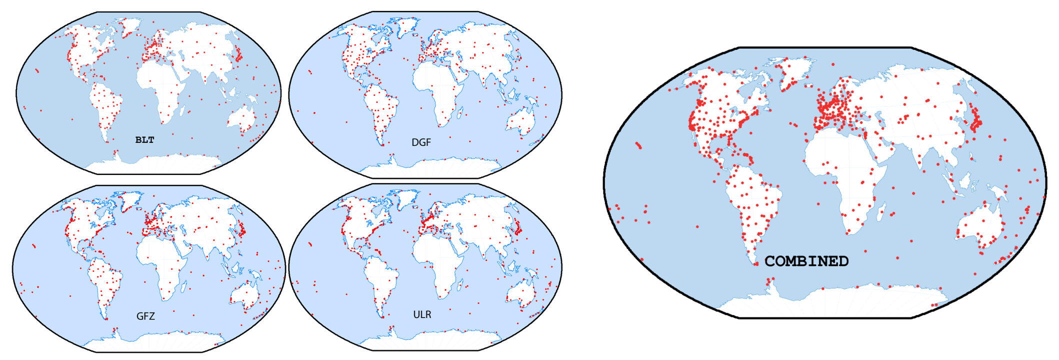

Figure 3. Spatial distribution of the stations for individual TACs and the combined network.

Preliminary combined solution

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 on long-term sea level trends while minimizing the uncertainity level. A preliminary combined solution from our TIGA solution indicate that the error bound grows using the existing ITRF2008 or its derivative (IGb08) datum as the time series goes far from the reference frames epoch origin (See Figure 4).

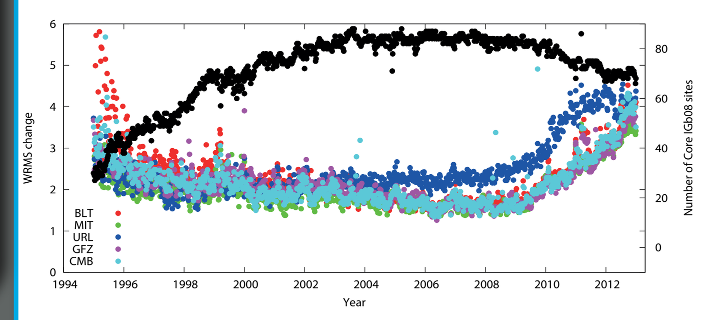

Figure 4. The cumulative weighted RMS of the weekly solutions of the stabilized sites. The black dots represent the number of core sites that are used to realize the frame w.r.t to IGb08 frame.

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 CATS software package (Williams et al. 2004) 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 annual and semi-annual, an offset due to discontinuities that are common in GPS time series and a linear trend. The discontinuites are mostly attributed to the GPS hardware. Where as the the seasonal signal is typically represented by sums of sinusoids with annual and semiannual frequencies. It is essential to model these seasonal signals since it can affect our parameters of interest from the residual time series, particularly the station velocity. The metrics we are looking are power spectra, weighted root mean square and amplitudes of annual and semi-annual signals and station velocities and the effect of discontinuity on velocity estimate.

Spectral Analysis

We have estimated the power spectra of the post-fit residual position time series from our repro2 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 power spectra for those sites that have more than five years of data interval and those station which are not affected by earthquakes. To discriminate dominant features in the power spectra, we have applied a smoothing using a moving average boxcar filter (trend1d), following Ray et al. (2008). Figure 5 shows a stacked normalized Periodogram from BLT repro2 solutions. All 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 at the fortnight even though it is also clear in the horizontal components.

A closer look shows three power surges at the fortnight peak at periods of 13.7 the 14.2 and 14.8 days. The fortnightly bands are associated with an un-resolved diurnal and semi-diurnal tidal footprints that causes aliased periodic signals with respect to one solar day network solution strategy as implemented in Bernese software package. The power spectra of the GPS time series follow a well-known fractal distribution, i.e., the amplitude and the frequency are related by power law (Langbein and Johnson, 1997)

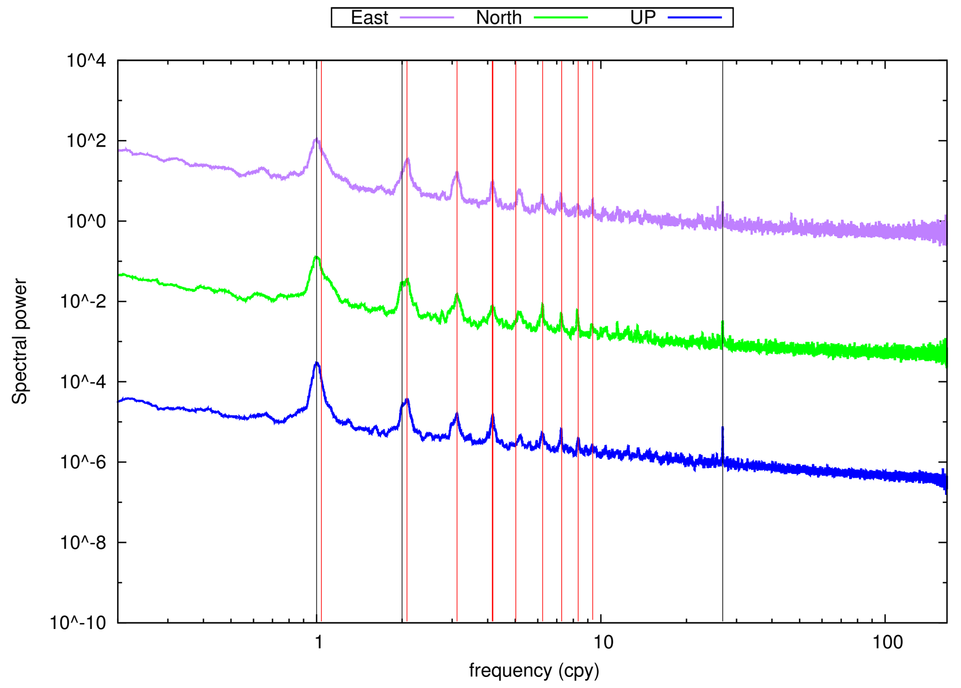

Figure 5. Smoothed stacked spectral features of the post-fit position residual time series. A small part of the spectrum that is affected by edge effects is removed from all the three components. A clear seasonal power surges as well as harmonics of the GPS draconitic frequencies are identified in all 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 are aligned onto the annual, semi annual and fortnight peaks. The red lines are aligned onto 9 of the harmonics of the GPS draconitic frequencies.

Weighted root mean square (WRMS)

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. However, there are only a small number of stations within -15 and +15 latitude bands as well as an imbalance in hemispherical distributions of stations. The north component WRMS show a smaller scatter compared to the east component, an indication that some of the ambiguities may not have been resolved. The Up component as expected has a higher noise floor compared to the horizontal components. (see Figure 6).

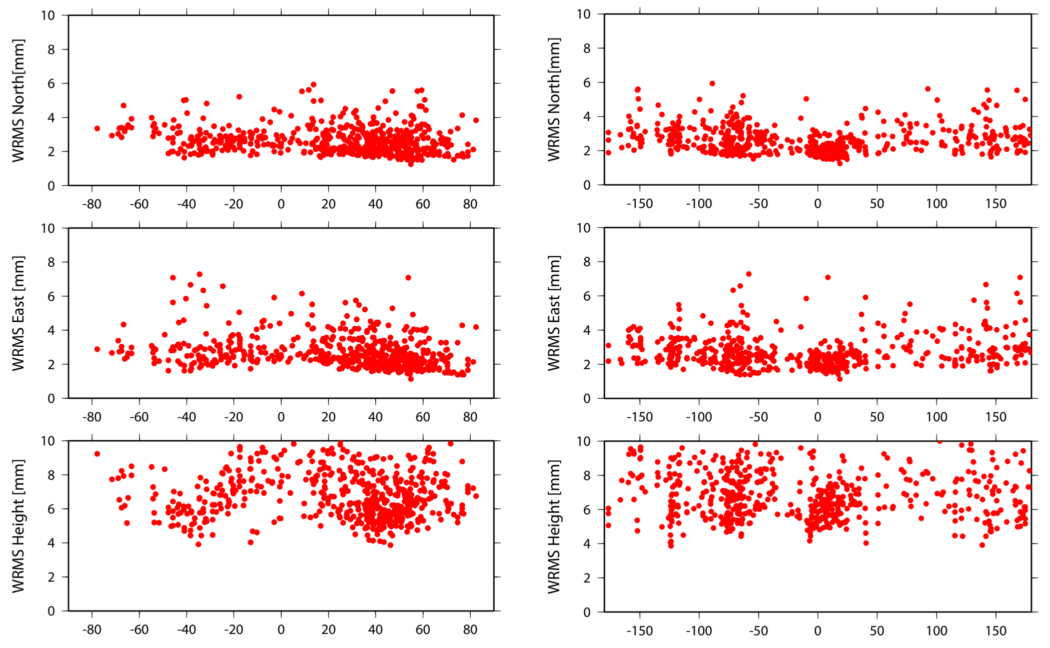

Figure 6. The WRMS variations for our BLT position residuals. The WRMS residuals are arranged with respect to latitudes to look into if there is any spatial correlations. It is clear that there is no apparent feature that indicated such correlation. However, there is only a small number if stations within -20 and +20 latitude bands as well as an imbalance in hemispherical distributions of stations. The north component WRMS show a smaller WRMS compared to the east component, an indication that some of the ambiguity resolutions may not have been resolved. The Up component as expected has a higher WRMS value compared to the horizontal.

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. Here we have plotted 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 ampltiudes is half the annual amplitudes

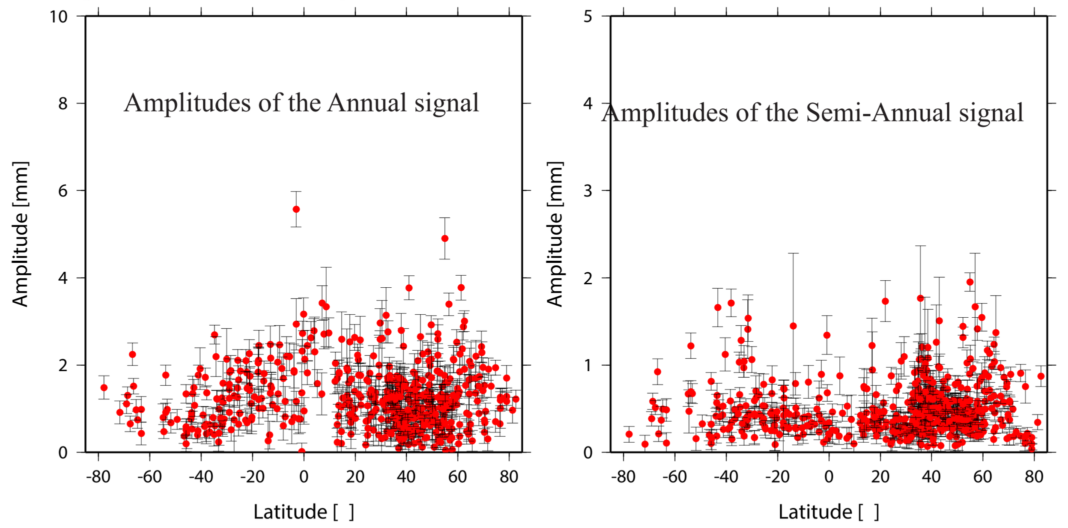

Figure 7. The amplitudes in units of mm for the model fit for the two prominent seasonal signals (annual & semi-annual). The amplitudes are below 2mm and 1mm, for the annual and semi-annual signals, respectively with no apparent spatial correlation. The scale of the semi-annual is half the annual. The error bar represents formal 1 sigma standard deviations.

Vertical rates from BLT repro2 solution

The multi-year repro2 from BLT consists of solutions for both station coordinates and vertical rates for over 600 sites. Figure 8 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).

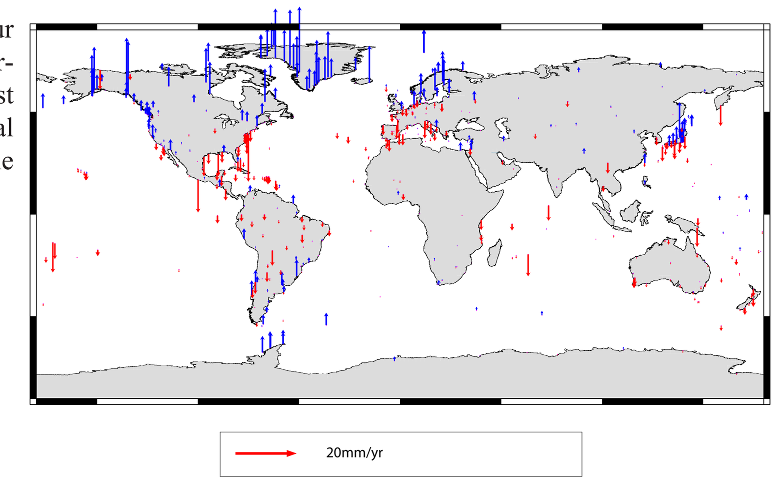

Figure 8.Vertical rate from our repro2 BLT solutions. The verates are expressed in the latest realization of the International Terrestrial Reference Frame (ITRF2008).

Vertical rate differnce 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 9 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

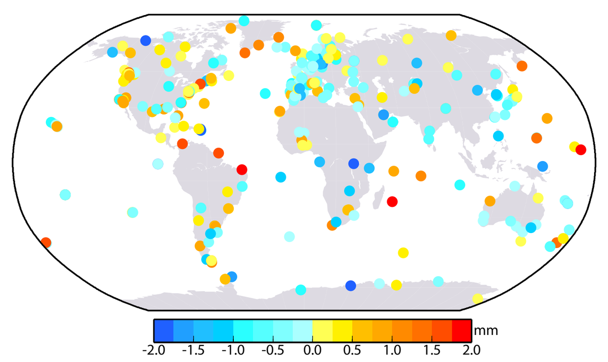

Figure 9. The vertical rate difference between the two repro2 TIGA solution (BLT-ULR)

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

RMS	Mean
0.8	0.1

Discontinuity in residual position time series

On average GPS station time series is affected by at least two discontinuities per decade. Discontinuity is especially severe for the Up component and hence the estimated vertical rate. Figure 9 shows how vertical rate can be adversely affected if one or many discontinuities is left undetected.

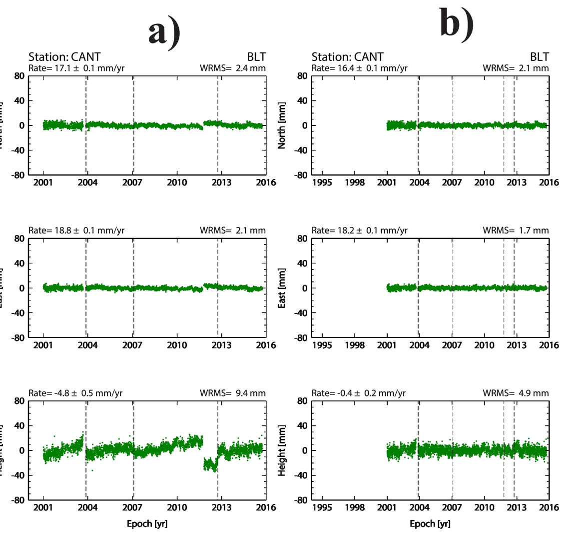

Figure 9. The daily residual position time series (**green dots**) at a continuous station CANT in Santander, Spain for North, East, and Up components. The station is affected by many discontinuities. a) Shows the station has a vertical rate of -4.8 mm/yr if only three of the discontinuities were modelled. b) The same station, but now all possible discontinuities 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. The BLT has completed repro2 solutions for the periods 1995 to 2015

2. Discontinuities adversely affect the vertical rate estimate at a tide gauge station and should thoroughly be checked and validated. This includes individual discontinuities should be available for each of the contributing TAC solution.

3. There are subtle velocity differences between each individual TIGA solution and an optimal combined solution from all TACs needs to be done rather than depending on individual rate estimation for sea level studies

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