A Multi-Year Combination of Tide Gauge Benchmark Monitoring (TIGA) Analysis Center Products: Preliminary Results

AGUFM2014 G21B-0454

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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 1995 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 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 centre at the University of La Rochelle (www.sonel.org). The TAC solutions contain a total of over 700 stations. Following the recent improvements in processing models and strategies, this is the first complete reprocessing attempt by the TIGA WG to provide homogeneous position time series. The TIGA Combination Centre (TCC) at the University of Luxembourg (UL) has computed a first multi-year weekly combined solution using two independent combination software packages: CATREF and GLOBK. These combinations allow an evaluation of any effects from the combination software and of the individual TAC contributions and their influences on the combined solution. In this study we will present the first UL TIGA multi-year combination results and discuss these in terms of geocentric sea level changes.

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. 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 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 of five TACs solutions have been completed 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 (Figure 1). It is noteworthy that all three contributing TACs have analyzed global networks with a consistent set of reference frame stations, i.e. the IGb08 core stations.

Until the remaining two TACs have completed their re-processing and in order to improve the redundancy of this preliminary combination we have also included the solution from IGS Analysis Center (AC) at the Massachusetts Institute of Technology (MIT) (Figure 1).

In this study we present preliminary results for the first multi-year combination by the TIGA working group computed by the TCC at the University of Luxembourg (UL). The combination incorporates the three TAC solutions and the IGS AC at MIT solution using two independent combination software packages: Combination and Analysis of Terrestrial Reference Frame (CATREF) (Altamimi et al, 2002) and Global Kalman Filter VLBI and GPS analysis program (GLOBK) (Herring and King, 2006). The following box gives details on the GPS re-processing and the reference frame definition.

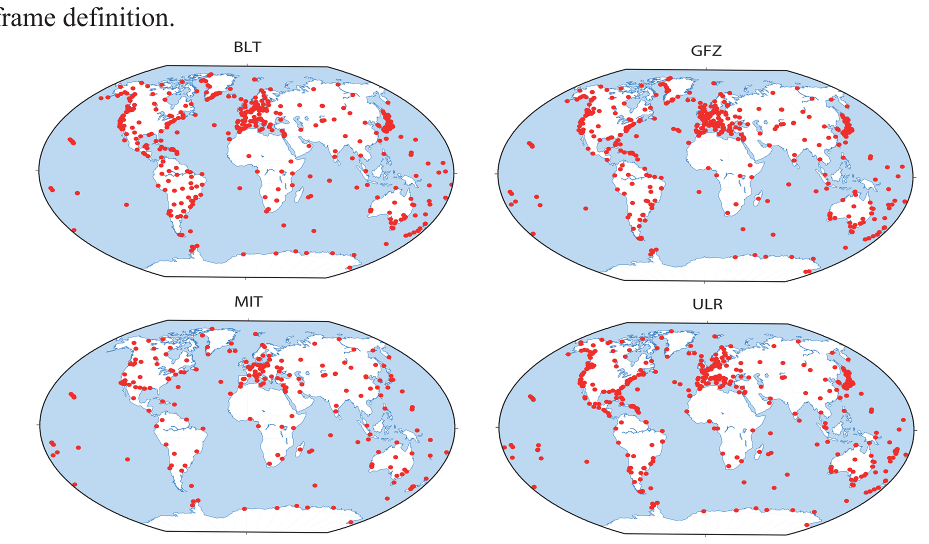


Figure 1. TIGA and IGS AC solutions used for the TIGA combination in this study.

GPS Processing and Reference Frame Definition

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. In preparation for the TIGA re-processing campaign, 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).

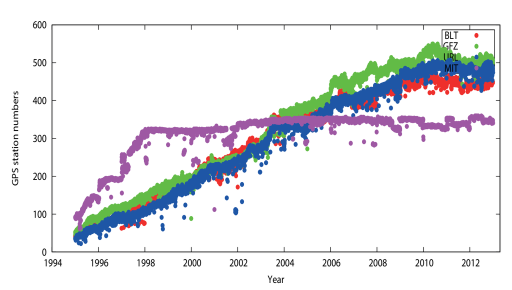


Figure 2: The number of sites available in TIGA and IGS AC SINEX files. All TACs process well over 400 stations since 2005 onwards.

The two other TACs, GFZ and URL, also provide re-processed GPS solutions following the IGS repro2 standards and bias models using the EPOS and GAMIT software packages, respectively, i.e. the three currently available TAC solutions use different software packages. In order to increase the redundancy we have included the repro2 solution from the IGS AC at MIT. The solutions include SINEX files from GPS week 0782 (Jan. 1995) to GPS week 1721 (Dec. 2012). Figure 2 provides evidence of increasing number of stations used by the individual TAC/IGS AC solutions for this period.

The IGb08 reference frame stems from the careful analysis of GNSS-only solutions computed by IGS ACs. It excludes sites affected by recent large earthquakes at the time of its design. The IGb08 network has a list of priority or "core" and substitute sites (Rebischung et al. 2012) (see Figure 3). For frame definition and stabilization for each of the weekly combined solutions the combination relies on the availability of core stations. If these are not available for a particular day, substitute sites are being used as proposed in Rebischung et al. (2012). This ensures consistent network geometry from day to day and provides a hierarchical approach for the definition of the reference frame.

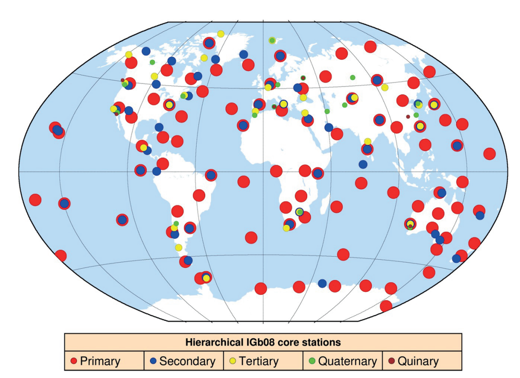


Figure 3. Global network stations (core in red(91)), substitutes sites [in blue (66), green (), yellow () and brown (6)] in order of their priority list that are used to align daily position estimates to IGb08 reference frame.

For the TIGA combination, we used a minimum constraint, or so called generalized constraint, technique in which seven Helmert parameters (3 translation, 3 rotation, and 1 scale) are estimated in such a way that adjusted to a priori value differences of selected core and substitute stations are minimized. Applying minimum constraints depends on the spatial coverage of the available IGb08 core stations. Hence the realization can degrade if the global station distribution is affected for a given week.

The SINEX files form the different TACs/IGS AC contain the parameter vector, the associated full variance-covariance matrix, and the full a priori variance-covariance matrix. The latter is crucial to get the information concerning the applied constraints in their respective solutions. The availability of consistent global core stations for the frame realization is an important component in estimating the VLM as it is highly dependent on the location of the origin and the temporal stability of both the origin and scale in the applied reference frame.

Network Combination Methodology and Results

The main purpose of the combination is to determine better coordinate estimates for all TIGA stations expressed in the current IGb08 reference frame. The combination provides a higher resolution of stations than any of the individual TAC solutions and the possibility of enhanced reliability of the coordinate estimates through outlier detection and variance-covariance component analysis. Prior to combination the TACs solutions are pre-processed and checked for completeness and conformity of their SINEX files. This also includes checks for station name inconsistencies. Then the constraints applied to the individual solutions are removed and the normal equations of the parameter set of interest are added together. The resulting loose normal equation matrix should be singular, resulting from the three degrees of freedom from the unobserved network orientation. To remedy the rank deficiency and to define a uniform reference frame, constraints are imposed to estimate the final solution through the Least-Squares (LS) and Kalman-Filter procedures implemented in CATREF and GLOBK, respectively (Altamimi et al., 2002; Dong et al., 1998).

We present the results of the TIGA combination using three TACs solution and the solution from the IGS AC at MIT for GPS Weeks 0782 -1721. Figure 4 shows the number of common stations available for a particular week. This figure indicates that there are more overlapping stations between the TACs compared to previous TIGA solutions (Schöne et al., 2009). One of the requirements for TIGA reprocessing is that TACs include all IGb08 core stations.

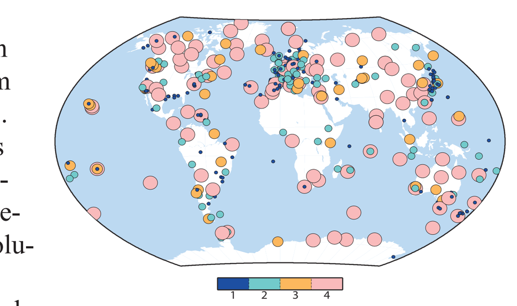


Figure 4. The number of TAC solutions per site for a particular GPS week

GLOBK Combination

Each of the SINEX files which is fed to the combination is initially converted to GLOBK native binary h-files. These daily h-files are combined to weekly solutions using the glred subroutine. Treating the h-files (SINEX files) from each day independently, thus providing a method for generating coordinate repeatability. This provides station repeatability for outlier detection and editing purposes. The weekly solution is then converted to SINEX format and where used in CATREF software package. Once the outlier detection is satisfactory, we realize the reference frame for each weekly solution through the applications of generalized constraints (stabilization). The Helmert transformation parameters in GLOBK is done through a minimization scheme in an iterative way, i.e. the departure from a priori values of the coordinates of a selected set of IGb08 stations while estimating a rotation, translation and scale of the frame. The general stacking is carried out through a subroune globk to produce a self-consistent set of coordinates for all the stations. To speed up weekly combination, we have implemented a parallelization technique using a freely available software package: GNU parallel (http://www.gnu.org/software/parallel/)

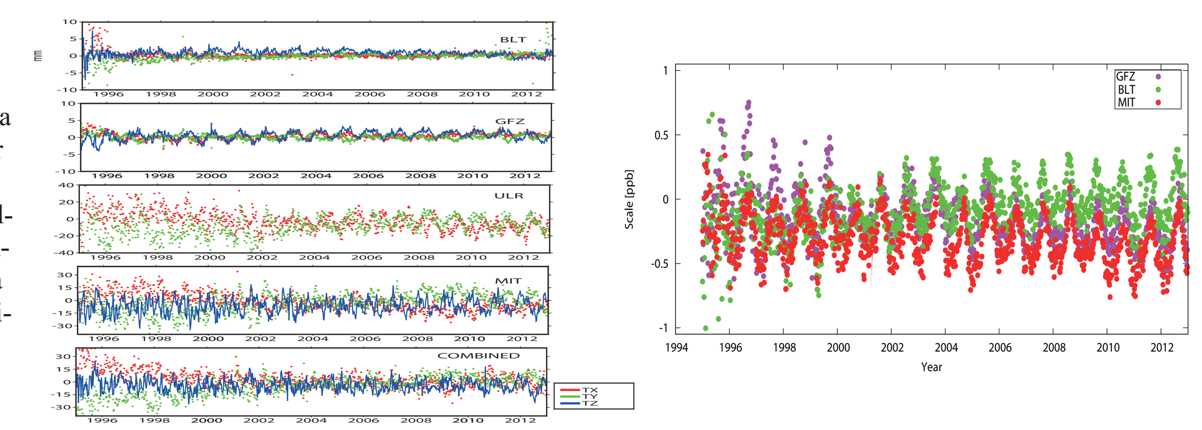


Figure 5. a) Translation parameters time series between BLT, GFZ, ULR and MIT solutions and the combined solution , b) the corresponding scale variatoion for the period: 1995-2013 using GLOBK.

Helmert Parameters

Figure 5a shows the translation parameters for each of the contributing TAC solutions as well as the combined solutions. The translation parameters of BLT and GFZ show small periodic amplitudes compared to those for URL and MIT. The BLT and GFZ solutions were initially constructed through no-net-translation (NNT) criteria and our implementation in GLOBK was not able to loosen these constraints enough. On the other hand, the ULR solution shows a relatively large magnitude in only Z-translations not shown in the Figure 5 (see also Santamaria-Gomez et al. 2012). However, the translation parameters for the combined solutions are not affected by the inconsistency of the Z-translation from ULR solutions.. Table 1 lists the trend estimated for each of the ACs network scale variations from CATREF and GLOBK implementations

CATREF Combination

A key aspect of the CATREF combination process is the selection of a realistic weight for each of the contributing ACs. For this, an a posteriori variance factor (scaling) is applied to all individual covariance matrices in an iterative way until both the individual and global variances are unity. During this multi-year combination procedure, outlier rejection is applied to those stations having a normalized position residual (raw residual divided by its observation a priori error) exceeding a threshold of five. Here we only show the scale parameters of the individual contributing ACs in parts per billion [ppb]. This scale, as expected, shows clear annual signals. A similar variation is shown in Figure 5b from our implementation of GLOBK. The individual scale agrees well but there is a small departure from each other after 2003. This bias from the two ACs (GFZ, MIT) is apparent in both software packages but to a lesser extent in the scale estimation from the CATREF implementation. The scale parameter of the combined weekly solutions show no appreciable trend as evidenced in Figure 7.

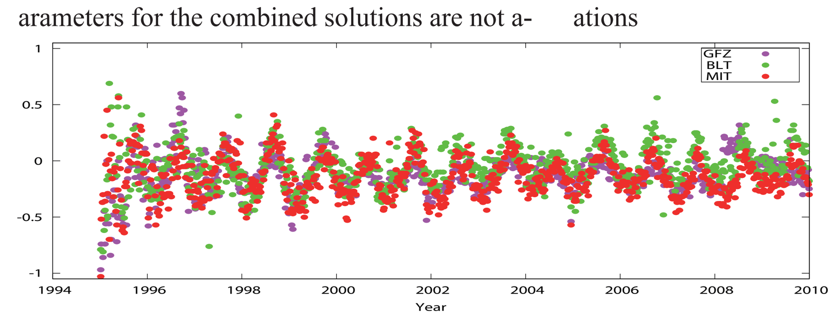


Figure 6. The scale variations for between BLT, GFZ, and MIT solutions for the period: 1995-2010 using *CATREFF*

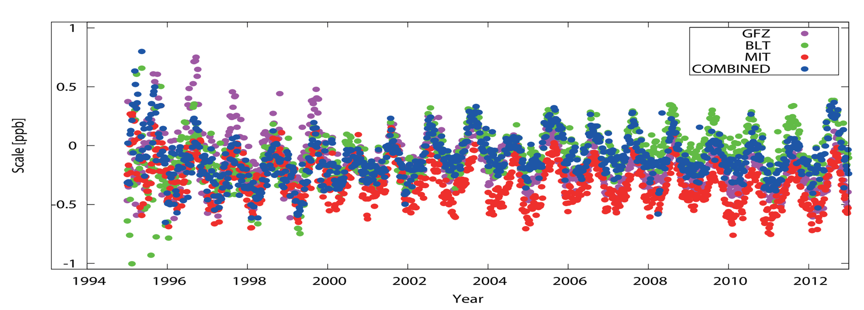


Figure 7. The scale variations for BLT, GFZ, and MIT solutions for the period: 1995-2013 using GLOBK. and the scale of the combined solution with respect to the IGb08 frame.

Weekly repeatbility

Here we look at the repeatability of the weekly IGb08 core sites (stabilization sites), which are used to define the reference frame of the TCC combined solutions. The IGS reference frame working group has made a strenuous effort in selecting reliable core and substitute sites to define a global network with consistent geometry over time that allows the alignment of individual TAC solutions to the IGb08 reference frame. Figure 8 shows the weighted RMS (wrms) of the individual and the TCC combined solutions computed for the reference frame sites on a weekly basis. For the early years, with the increase in available core sites, the wrms is reduced slightly. However, since 2009 there has been a significant increase in the wrms. The figure suggests that this might be a result of the decrease in the number of core sites in recent years, but another source is suspected and this will be further investigated.

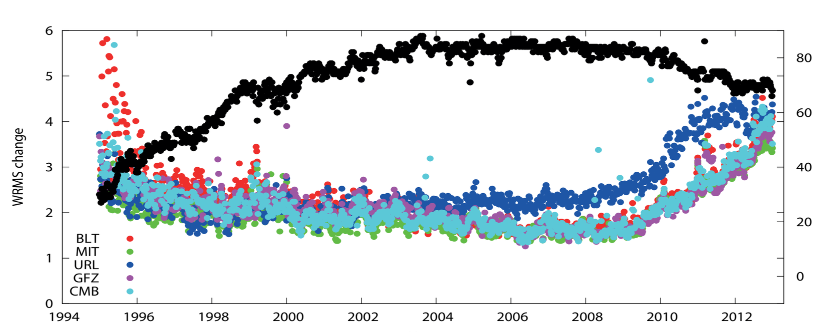


Figure 8. The combined weighted RMS of the weekly solutions of the stablized sites . The black dots represent the number of core sites that is used realize the frame w.r.t to IGb08 frame.

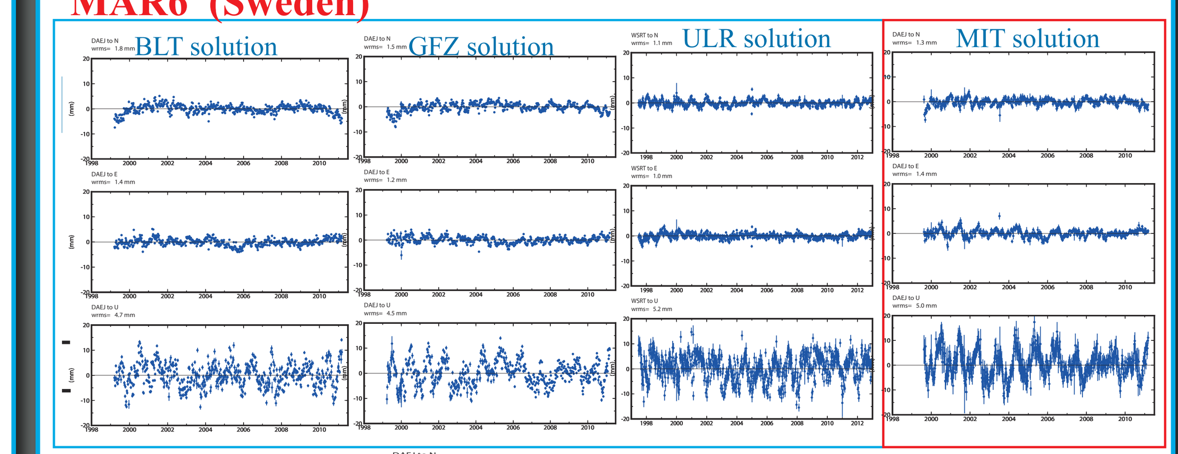
ACs	CATREF Slope [ppb]	GLOBK slope [ppb]
BLT	0.009	0.012
GFZ	-0.006	-0.015
MIT	-0.003	-0.010

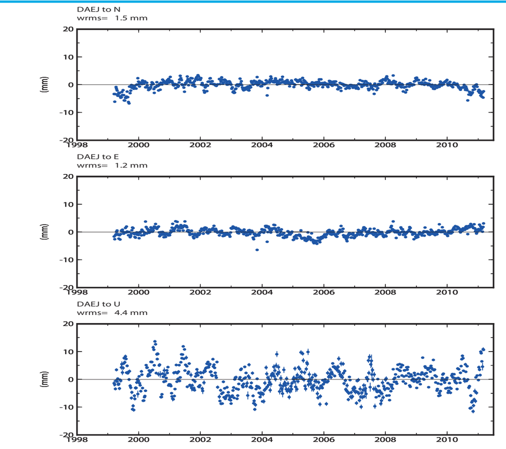
Table 1. The trend in scale of the network from BLT, GFZ, and MIT as implemented using CATREF and GLOBK .

Time series residuals

Here we show the weekly residuals of position time series from the multi-year combination of the individual TACs and IGS AC solutions for two selected GPS stations compared to the combined solution from our GLOBK combination. For clarity the time series have been de-trended and de-meaned (Figure 9a, b).

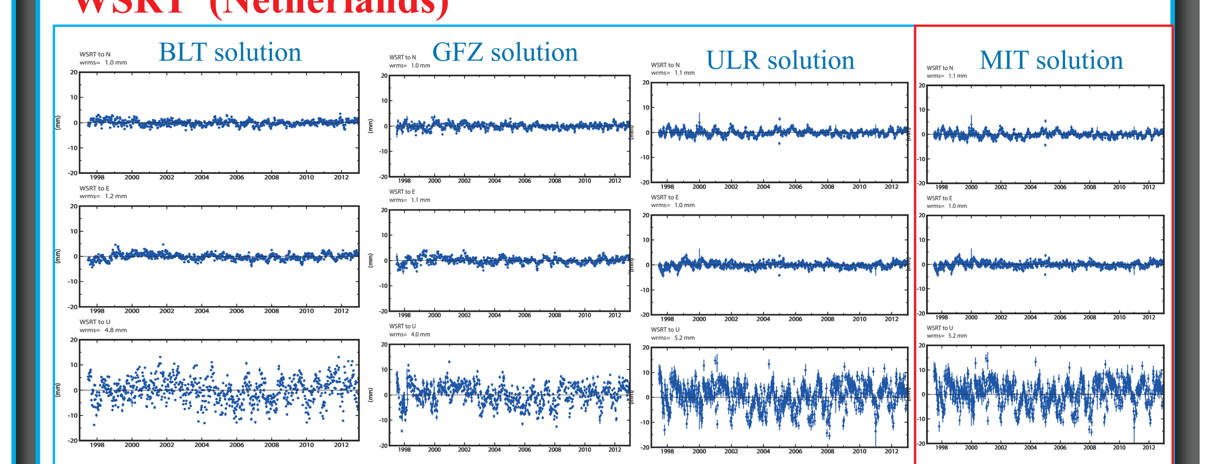
MAR6 (Sweden)

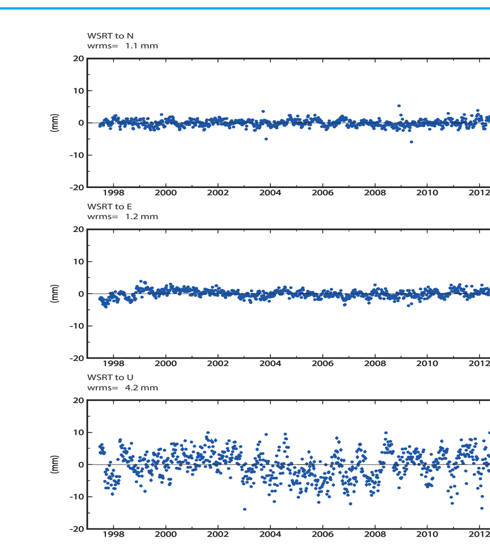




The weekly residual of position time series from GPS station MAR6 from the combined solution

WSRT (Netherlands)





The weekly residual of position time series from GPS station WSRT from the combined solution

Figure 9. a) Residual weekly position time series solutions from TAC and IGS MIT and the corresponding combined solutions for station MAR6 (Sweden) and b) for station WRST (Netherlands)

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.

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Conclusions:

1. The TCC at UL has made the first preliminary TACs multi-year combination (position only) using two independent software packages (GLOBK and GAMIT). The two software packages show a good agreement in estimating the scale of the individual TACs global network.
2. The combined solution minimizes possible effects from individual methods employed in different software. It is also a powerful tool for identifying outliers.
3. The IGb08 core sites, which are used to realize the TACs as well as the TCC combined solutions, show an increase wrms in recent years that corresponds with the decrease in the number of core sites since 2009.
4. For multi-year and large data sets, the combination requires a substantial CPU time. We were able to speed up the combination significantly using the GNU parallel implementation

Presented at: American Geophysical Union Fall Meeting 2014, San Francisco, CA, USA, 15-19 December