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ORIGINAL ARTICLE

IGS Tide Gauge Benchmark Monitoring Pilot Project (TIGA): scientific benefits

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Abstract The establishment of a long-term stable global reference frame is important for studying sea level records for, e.g., climate-related studies. GPS stations connected to the tide gauge benchmarks provide the necessary technique. However, the analysis of existing GPS solutions showed inconsistencies within the time series especially for the height component. To solve related issues, in 2001 the IGS Tide Gauge Benchmark Monitoring Pilot Project was established. The aim is the processing and re-processing of GPS data of stations at or near tide gauges in order to provide homogeneous and high-quality estimates of the vertical motion. A second objective is the establishment, maintenance and expansion of existing network of GPS stations at tide gauges. During the recent years six different analysis centers have processed overlapping GPS at tide gauge networks and are providing individual solutions allowing now to provide a combined solution. The ansatz for the combination is explained and quality measures are given. In addition, on the basis of the reconstruction of sea level anomalies, the benefit of using the combined TIGA solution is demonstrated.

Keywords IGS · GLOSS · TIGA · Seal level · Tide gauge · GPS · Geodetic benchmark monitoring

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1 Introduction

In the past centuries, manual and later automated tidal readings have been made in ports or along rivers. Besides the prediction of waterway clearances, the establishment of a local chart datum for both hydrographic and cartographic mapping has been a focus. Almost all readings have been tabulated and published, providing today an invaluable source of information for, e.g., studies of ocean mass and volume changes or post-glacial rebound. Throughout history also the geodetic fixing of the tide gauge zero has been improved allowing to relate the readings from different epochs to a common local datum. However, even with a large number of well-distributed benchmarks the tidal readings and derived sea level quantities remain in a local reference frame. One of today's challenges is the establishment of a height reference connected to a global long-term stable reference system (e.g., Carter et al. 1989; Carter 1994; Blewitt et al. 2006) and the establishment of a global vertical height datum (e.g., Ihde et al. 2007; Sanchez and Krügel 2006).

With the advent of the GPS technology in the 1980s, the establishment of an easily to access and global stable reference system became feasible. Starting around 1990, the number of GPS stations increased and in 1994 the first continuous GPS stations started operation near tide gauges. Over the years the number of co-located stations has increased constantly. A workshop held in Pasadena in 1997 (Neilan et al. 1997) brought together the oceanographic and geodetic community and started with the implementation of a long-term plan for the establishment of a global network of GPS-equipped tide gauges. A technical committee was jointly setup by the International GNSS Service (IGS, formerly International GPS Service), the Permanent Service for Mean Sea Level (PSMSL) and GLOSS to define the technical standards for stations (Bevis et al. 2002). A GLOSS workshop (Group of Experts Meeting) in Hawaii (IOC 2001) concluded the findings, and a Charter and Terms of References for a dedicated IGS Pilot Project were drafted. The IGS formally established the Tide Gauge Benchmark Monitoring Pilot Project (TIGA) in 2001 (http://adsc.gfz-potsdam.de/tiga).

2 TIGA objectives and structure

The IGS plays a leading role in the establishment, densification and maintenance of a global geodetic reference frame. With over 300 continuously operated GPS stations participating, several high-quality products—ranging from precise satellite orbits and clock products to station coordinates and their velocities—are provided, uninterrupted and with a very short latency. Over the time, the quality and network density for the reference frame realization increased constantly leading to an improvement of the service provided. The IGS runs a series of working groups and pilot projects aiming on specific products and services.

The main objective of TIGA is to bring the expertise of the GPS community to solve issues related to the accuracy and reliability of the GPS height component at tide gauge sites. Several scientific issues are benefiting of the results of TIGA, e.g., satellite altimetry calibrations (e.g., Mitchum 2000), global isostatic adjustments and separation between crustal movement and sea level changes (e.g., Zerbini et al. 1996; Baker et al. 1997; Nerem et al. 2001; Teferle et al. 2006) or other GPS related studies (e.g., Schmid et al. 2007). TIGA aims on the establishment of a network of high-quality continuous operating GPS stations at or near tide gauges, to process their GPS data and to provide time series of vertical motion in a well-defined global reference frame. The project specifically addresses height changes, as this is the most important component for the establishment of a vertical reference network. Here, for the first time, it is not the intention of the IGS to provide results with a very low latency, but to have products for a dedicated and as complete as possible station network.

The main components of TIGA are the TIGA Analysis Centers (TAC) and the TIGA Observing Stations (TOS). The later are forming the global station network. A third component are the TIGA Data Centers (TDC), responsible for long-term storage of GPS and metadata.

2.1 TIGA Observing Stations

One of the objectives of TIGA is to establish, maintain and expand the global network of co-located GPS and tide gauge stations. In this context, TIGA does not operate tide gauges or GPS stations but relies on voluntary contributions by agencies, universities or other organizations. However, on the basis of the recommendations in Plag et al. (2000) and Bevis et al. (2002), the stations have to follow some specific standards before accepting them for TIGA. The basic requirement is the co-location of the GPS benchmark and the tide gauge zero to an accuracy better than 1 mm/a. A second pre-requisite is free data exchange and the availability of metadata information. All accepted stations are operated according to GLOSS standards (e.g., IOC 2006)

Within the pilot project IGS stations as well as non-IGS stations are processed. All non-IGS stations have to follow the IGS standards (Moore 2007). The number of contributing stations has increased since the beginning of the TIGA project. Starting in 2001, with only a few stations, it today comprises more than 100 stations providing data on a regular basis (Fig. 1). However, the global inventory maintained by Wöppelmann et al. (2007a) (Fig. 2) contains more than 300 potential stations. This discrepancy is primarily due to the missing co-location information, e.g., leveling between the GPS sites and tide gauge benchmarks. Other reasons are the unavailability of tide gauge data at international data centers or the smaller distance criteria between the GPS and tide gauge site applied by TIGA.

2.2 TIGA Analysis Centers

Within the IGS several global and regional analysis centers participate with individual solutions. On the basis of the mission of the IGS they process GPS data on a regular basis with a very short latency providing orbit and clock products of different quality and station coordinate time series.

One aim of TIGA is to provide time series of vertical motion for a network of tide gauge stations as complete as possible. To achieve this objective, the processing is done with a latency of up to 460 days, which is much higher than the latency of all other IGS products. This approach allows very remote stations, e.g., in Antarctica, to contribute. Hence, the processing has to be done outside the normal IGS processing stream. Since there has been a long research interest in the processing of GPS at tide gauges for detecting different signals (e.g., Bosch et al. 1999; King et al. 2003; Tregoning et al. 2004; Zhang et al. 2007; Wöppelmann et al. 2007b) expertise in this research field exists within several centers. Currently, six centers or consortia are contributing with individual solutions employing different GPS processing software

- [ULR] Centre Littoral de Géophysique, University La Rochelle (ULR), France
- [DGF] Deutsches Geodätisches Forschungsinstitut (DGFI), Germany
- [ETG] EUREF (combination of individual contributions by Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt, Germany)

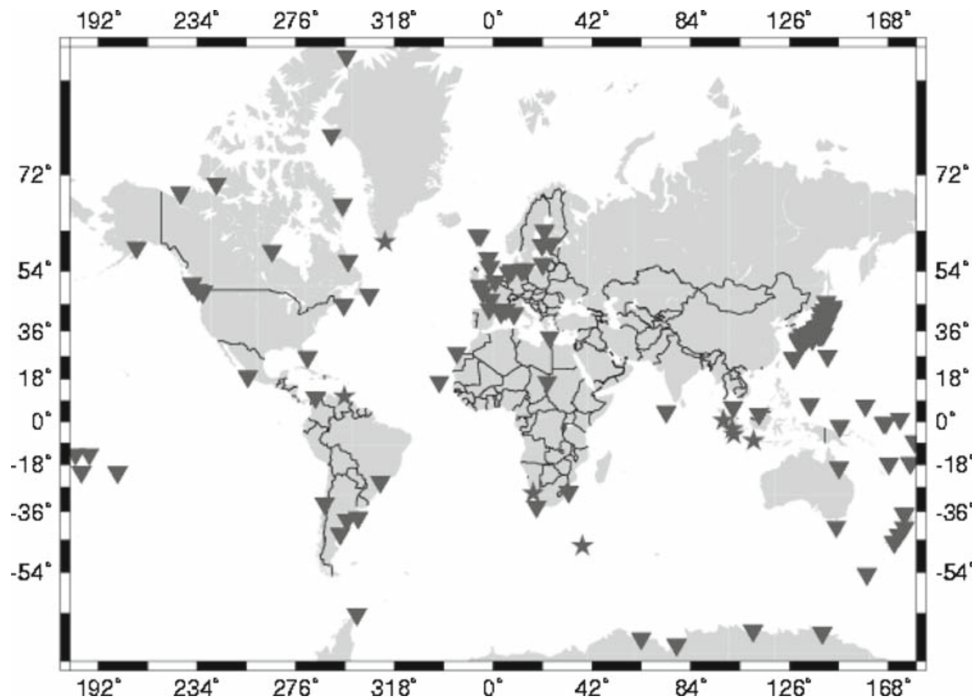

Fig. 1 Current network of TIGA Observing Stations (TOS). *Triangles* are fully operational stations; *stars* are those stations currently under review for participation

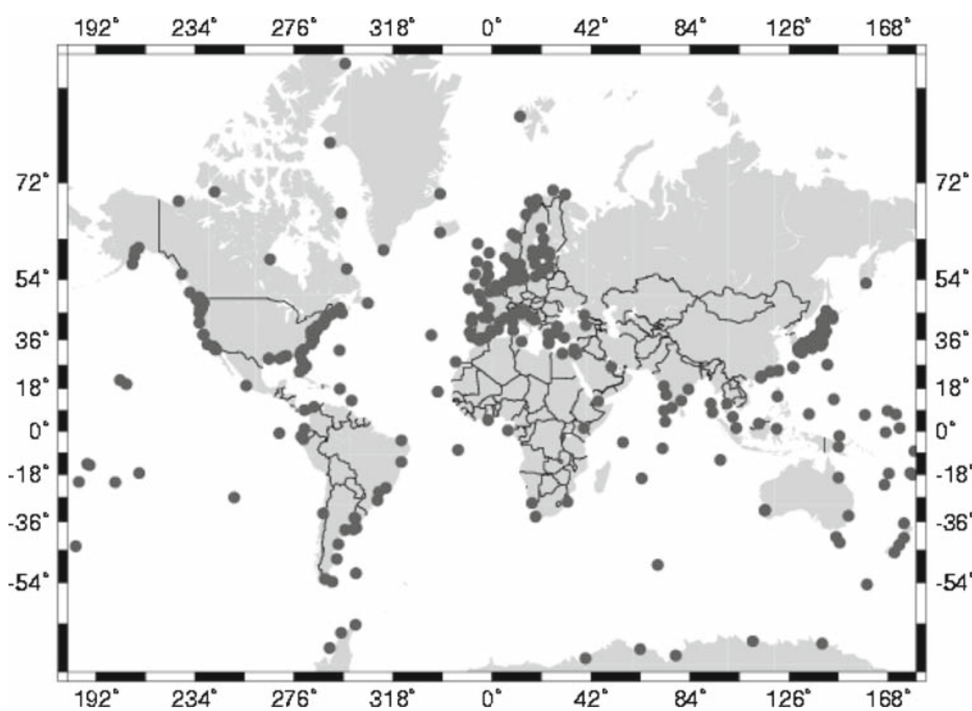

Fig. 2 GPS stations near tide gauges according to the survey of Wöppelmann et al. (2007a)

- [GFT] GeoForschungsZentrum Potsdam (GFZ), Germany
- [AUT] GeoScience Australia, Geodetic Division, Australia, and
- [CTA] University of Canberra, University of Tasmania, and Australian National University, Australia.

Each TAC provides weekly solutions using the SINEX format (SINEX Working Group 1996). The files are located in weekly sub-directories at the anonymous ftp-site ftp.gfz-potsdam.de (change to /pub/transfer/kg_igs/igstiga/solutions/).

3 Individual TIGA solutions and their combination

Contrary to the IGS Analysis Centers, all TACs processing the data on a best-effort basis instead of a schedule with strict deadlines. As a consequence, the individual contributions differ in terms of the time span that is covered by the weekly solutions.

The work effort for the TACs has increased recently as the IGS decided to change its processing strategy from a relative to an absolute modeling for antenna phase center variations (PCV). This change in the a priori modeling primarily affects the height component so that a reprocessing of the entire data using the new antenna model has become an important issue for the TIGA project. However, due to limited resources it is clear that up to now not all TACs have managed to fully reprocess the TIGA data using the new antenna model.

As a consequence of this situation, one must distinguish between two different types of TAC contributions: series of weekly SINEX files based on the old IGS standards for antenna models (i.e., relative PCV) and series of solutions based on the new IGS standards (i.e., absolute PCV). Table 1 summarizes the status of the TAC contributions based on the old IGS standards. It is clear that this time series of SINEX files has been discontinued because all solutions issued after the official switch should follow the new IGS standards. The status for the new solutions (as of 21 December 2007) is summarized in Table 2.

The individual solutions provided by the TAC do not cover the same network of stations, and, moreover, are generated by applying different analysis strategies. The networks processed by the individual TACs can be shortly characterized as follows:

- AUT: regional network with Antarctica, Australia, and Pacific region

Table 1 Time span covered by those TAC contributions using the old IGS standards

AC	First week	Last week	Time span	# Weeks available	# Weeks missing
AUT	0782	1295	514	514	0
CTA	0938	1198	261	260	1
DGF	1066	1332	267	129	138
ETG	1021	1399	379	379	0
GFT	0785	1251	467	219	248
ULR	0887	1341	455	439	16

Table 2 Time span covered by TAC contributions that were computed using the new IGS standards (as of 21 December 2007)

AC	First week	Last week	Time span (weeks)	# Weeks available	# Weeks missing
AUT	0887	1399	513	513	0
DGF	1042	1452	411	408	3
ETG	1400	1449	50	48	2
ULR	0992	1341	350	308	42

- DGF: regional network for the Atlantic region
- CTA: regional network for Antarctica and Australia
- ETG: regional network for Europe
- ULR: global network
- GFT: global network.

To minimize the so-called analysis noise and to provide station coordinates for all TOS in one common reference frame, a combination of all six individual contributions into one final weekly solution is highly desired. This implies that a rigorous combination of the TACs should be carried out similar to the procedure that is already applied for the official weekly IGS product (see Ferland et al. 2005). Unfortunately, resources to carry out such a combination for the entire time span only have become available recently. As the solutions following the new IGS standards are thought to deliver more reliable time series for the station height, the effort concerning the weekly combination has been focused on these type of solutions.

3.1 Status of reprocessed solutions

As already mentioned, in 2005, the IGS decided to change its processing strategy from a relative to an absolute modeling for antenna PCV. This change took effect starting from GPS week 1400 (i.e., 5 November 2006). Some TAC already provided a new series of weekly SINEX files using the absolute PCV model (Table 2). Namely *AUT*, *DGF* and *ULR* have already reprocessed the TIGA network. In the case of the EUREF contribution (*ETG*), only the solutions after GPS week 1400 follow the new IGS standards, whereas the older data are not reprocessed and, thus, are still based on the relative modeling for the antenna phase centers. All TAC are processing data on a best effort basis. Therefore, the time span covered by the individual contributions strongly differs concerning the start epoch as well as concerning the length of the time series (see Table 2). As a consequence, the number of TAC contributions that are available for one week varies, and a maximum number of only three single TAC solutions are available per week at the moment.

3.2 Weekly combination

At present, the weekly combination is done only for those contributions that use the new IGS standards. Only the contributions by *AUT*, *DGF*, *ETG* and *ULR* fulfill this requirement, and a combination makes sense only if at least two contributions are available. Therefore, it becomes obvious from Table 2 and Fig. 3 that only the time span of GPS weeks 0992 up to 1449 can be considered. For the combination, the Bernese GPS Software version 5.0 (Dach et al. 2007) is used.

In a first step, datum-free normal equation systems are derived from the information provided in the SINEX files.

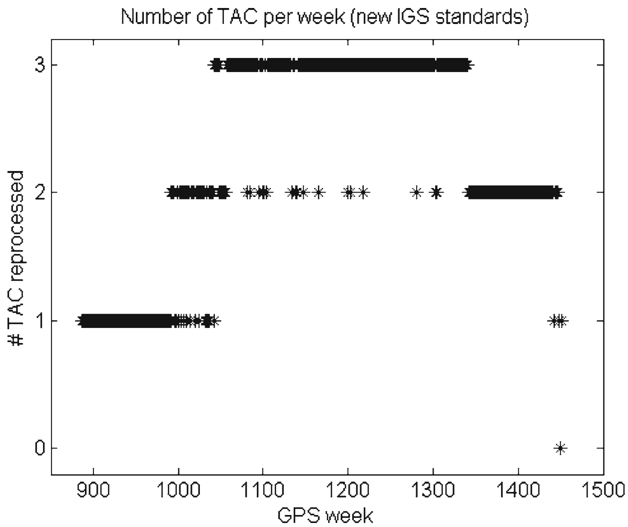

Fig. 3 Number of SINEX files available per week for the TAC contributions using the new IGS standards (as of 21 December 2007)

For this purpose, the estimated variance–covariance matrix as well as the matrix of constraints is inverted to get normal equation (NEQ) matrices. Subsequently, the NEQ matrix containing the constraints is subtracted from the full NEQ matrix so that a normal equation matrix free of all constraints results from this processing step. This procedure is possible for the contributions by *AUT*, *DGF* and *ETG*. Unfortunately, this is not possible for the files provided by *ULR* as only the solution itself (i.e., the estimated parameters and their variance–covariance matrix) is stored in the SINEX files, whereas the a priori information about the constraints and the statistical information are not extractable (for details see Altamimi et al. 2002). Subsequently, only the estimated variance–covariance matrix is inverted. This implies that the resulting NEQ for the contribution by *ULR* still contains constraints, especially all datum information.

In the second step, the NEQs of the individual TAC contributions are combined on a weekly basis. Considering that, on one hand, the NEQs for the *ULR* contribution are not datum-free NEQs due to the problems mentioned earlier, but, on the other hand, the combined solutions should have a well-defined datum, the datum information contained in the *ULR* NEQs have to be removed. This is done by setting up seven Helmert parameters (three translations, three rotations and one scale parameter) for each weekly *ULR* contribution. Although there is no guarantee that this procedure exactly removes the datum information that was originally applied when the solution provided in the SINEX file was generated, there is no other possibility to handle this problem for the moment. The weekly combined solutions are aligned to the IGS realization of ITRF2005 (Altamimi et al. 2007) using no-net-rotation and no-net-translation conditions for the IGS reference frame stations.

One important fact to consider when combining different contributions is the number of common parameters, i.e., the number of common observing sites in the case of the weekly TIGA combination. From the list above, it is obvious that *AUT* and *ETG* have no stations in common. The networks of *AUT* and *DGF* have only the station O'Higgins (Antarctica) in common, whereas *DGF* and *ETG* can be linked by about six common stations. Therefore, the main connection between all individual contributions must be done via the global network given by *ULR*. Spread over the whole time span listed in Table 2, the contributions by *AUT* and *DGF* have about 40 stations in common with the *ULR* network. The European network provided by *ETG* can be linked to the global *ULR* network by about 15 stations. It is clear that these numbers slightly vary from week to week.

Due to the fact that the global network is needed to derive a reasonable combined solution out of the individual contributions, only the GPS weeks from 0992 until 1341 are considered in the following when time series of station coordinates are generated. During this time span of 400 weeks, not all TOS are contained in every weekly solution. Those stations with most coordinate estimates are contained in about 350 weekly solutions, whereas others have only about 50 coordinate estimates. Figure 4 gives an overview of the number of weekly coordinate sets that are available for each TOS.

For the reconstruction of sea level anomalies (SLA) (see Sect. 4), the time series of the station heights derived from GPS is of special interest. To derive reasonable vertical trends it is indispensable to have a homogeneous time series of coordinates at hand. Exemplarily for the station Kerguelen (KERG, Fig. 5) it is demonstrated that such a homogeneous time series cannot be derived by using the official weekly IGS SINEX files. The jumps present in the time series are due to changes of the underlying reference frame. Contrary to this behavior, the time series derived from the TIGA combined solution is based on a homogeneous reference frame (i.e., IGS05), and, thus, shows no jumps.

Additionally for four TIGA stations, the time series for the station height derived from the weekly combined solutions are shown in Fig. 6. In most cases an annual signal, e.g., from atmospheric or hydrological loading, is present in the time series, although it is not as pronounced for all sites as, e.g., for the station Metsahovi (METS, Fig. 6a). The annual signal for the stations St. John (STJO, Fig. 6b) and Mawson (MAW1, Fig. 6c) is not equally pronounced every year. In contrast, the station Townsville (TOW2, Fig. 6d) has even almost no annual signal; however, a comparably large linear trend is visible.

On the basis of the coordinates estimated in the weekly combined TIGA solutions, vertical trends have been computed. Table 3 summarizes the vertical trends for those TOS sites used in Sect. 4 for the reconstruction of SLA. Unfortunately, not all of these GPS sites cover the whole time

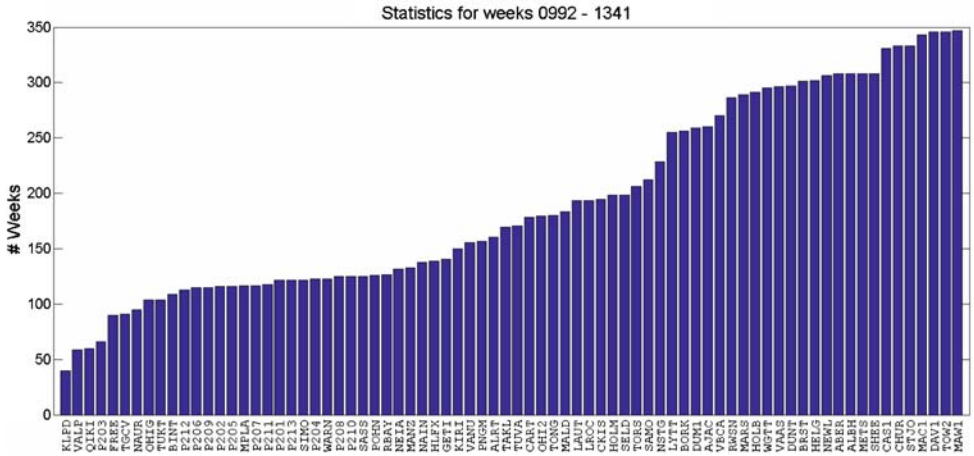

Fig. 4 Number of weekly combined solutions in which the TIGA observing stations are contained (considering the time span of GPS weeks from 0992 to 1341)

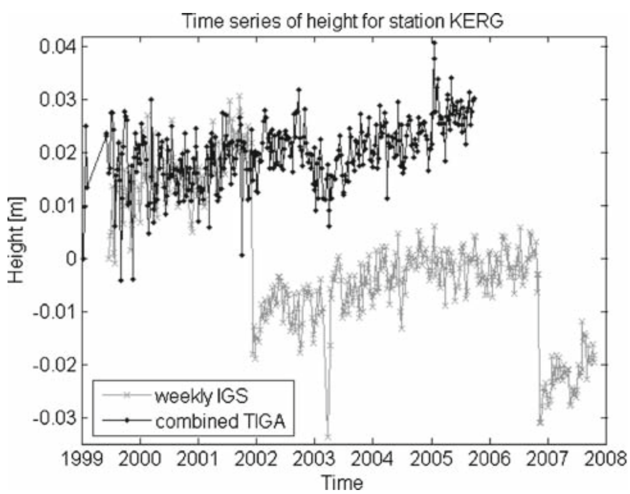

Fig. 5 Height time series of the weekly solutions derived from the official weekly IGS products and the weekly combined TIGA solutions

span of 6.7 years of the actual weekly TIGA combination (i.e., weeks 0992–1449). Therefore, the vertical trends for some sites, especially those sites covering only 2–3 years of data, have to be used with caution (see Blewitt and Lavallée 2002). To characterize the remaining information left in the time series after removing the linear trend, the scatter in the height time series is computed (see Table 3). The weighted RMS (WRMS) is at the level of 5–8 mm for most sites. It has to be noted that TIGA itself does not provide rate of height changes for individual stations but weekly coordinate sets. The users are encouraged to study the results and extract those quantities they need. For this reason, annual terms are not estimated here and the WRMS values in Table 3 are higher than in a full analysis.

4 Scientific benefits of TIGA

On the basis of the individual TIGA solutions a broad variety of scientific results have already been published (e.g., Tregoning et al. 2004; Tregoning and van Dam 2005; Ge et al. 2005; Schoene 2006; Sanchez and Krügel 2006; Wöppelmann et al. 2007b,c; Zhang et al. 2007). Here, an example is shown aiming at the reconstruction of SLA using GPS corrected tide gauge time series and altimetry data.

A major problem in estimating sea level changes over the last century is the spatial non-uniformity. Regional estimates in eustatic sea level rise give a broad range of results. Church et al. (2004) showed that a reconstruction scheme that takes into account the regional differences can produce reliable estimates. This technique makes use of both the short near-global coverage provided by satellite altimetry data as well as the relatively long but spatially sparse set of tide gauge time series. Since tide gauge measurements are affected by land movement, a correction must be applied to separate these natural or artificial processes from the actual sea level changes. This is commonly achieved by applying a global isostatic adjustment (GIA) model (e.g., Davis and Mitrovica 1996; Lambeck et al. 1998; Peltier 2004). In this example, a similar reconstruction procedure is used, but improved by accounting for the effect of land movement by applying vertical land movement trends extracted from the combined TIGA dataset of co-located GPS stations to the tide gauge data set.

For the reconstruction of SLA, a modified optimal interpolation (OI) algorithm (Kaplan et al. 1997) is applied. Fully corrected and harmonized monthly altimetric sea surface height anomaly data derived from the Altimeter Database and Processing System ADS (http://adsc.gfz-potsdam.de/ads) are gridded into 1° × 1° maps and are used to estimate the global covariance structure as expressed in empirical orthogonal functions (EOFs). Thereafter, the amplitude of these EOFs is estimated using tide gauge records. In this way, the main spatial patterns of SLA are extracted from the satellite data, while their amplitude time series are reconstructed using the tide gauge data. The land movement part of the tide gauge records is corrected using vertical trends derived from the TIGA combination.

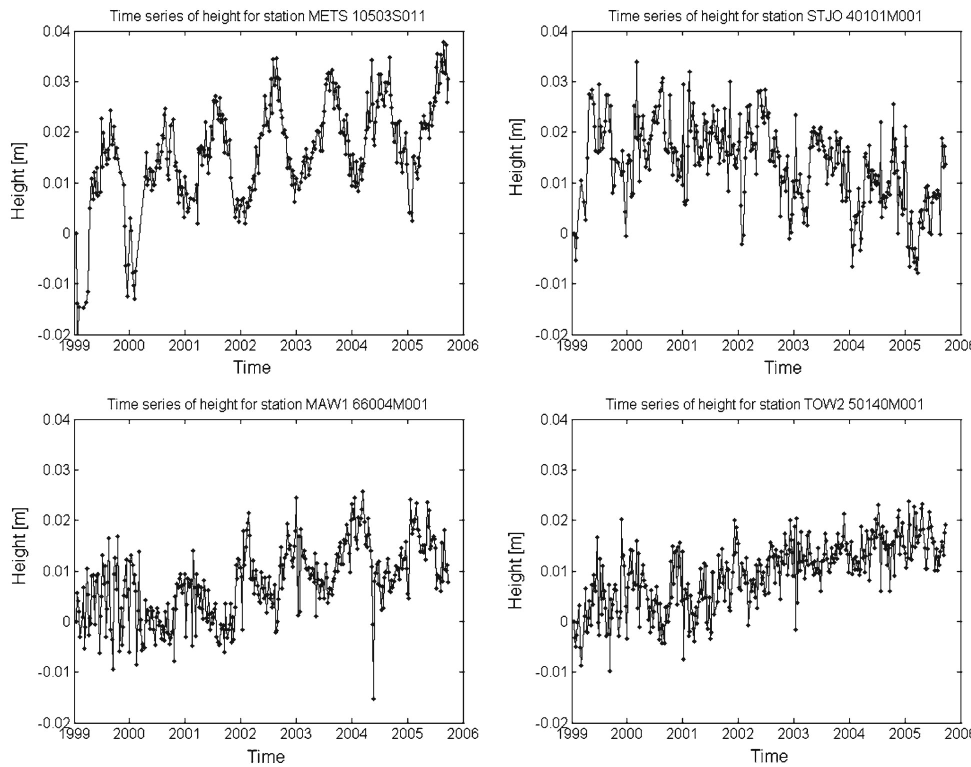

Fig. 6 Time series of weekly combined station coordinates for selected TOS stations; **a** Metsahovi (METS), **b** St. John (STJO), **c** Mawson (MAW1), **d** Townsville (TOW2)

Table 3 List of TOS used in reconstruction, with annual vertical trends and scatter (weighted rms) in the height time series after removing a linear trend

Latitude	Longitude	Station Name	GPS ID	PSMSL ID	Distance (m) to TG	GPS vertical trend (mm/a)	Length of GPS time series (years)	Number of epochs	WRMS height (mm)
57.14	357.92	Aberdeen	ABER	170011	10	−0.28	6.69	308	6.87
48.39	236.51	Albert Head	ALBH	822101	12000	−2.31	6.69	308	9.22
53.56	6.75	Borkum	BORK	140015	750	−1.00	5.15	270	7.30
48.38	355.50	Brest	BRST	190091	350	−0.72	6.96	315	7.02
−21.20	200.20	Cook Island	CKIS	785001		3.78	4.30	208	7.18
6.23	102.11	Geting	GETI	550021	5	5.62	3.72	141	7.42
1.35	172.92	Kiribati	KIRI	730008		2.04	3.42	164	7.53
4.19	73.53	Maldives	MALD	454011	5	1.80	5.31	183	10.70
−38.04	302.47	Mar del Plata	MPLA	860101	5	−2.26	3.24	128	7.67
−25.02	−47.93	Cananeia	NEIA	874051	10	−2.03	3.20	132	9.25
39.02	141.75	P-Ofunato	P205	642022	1	0.00	2.28	116	6.56
6.96	158.21	Pohnpei	POHN	710031		5.22	2.67	138	6.65
51.45	0.74	Sheerness	SHEE	170101	10	−0.48	6.69	308	6.63
47.60	307.32	St. John’s	STJO	970121	5000	−1.19	6.96	347	8.53
62.02	353.24	Torshavn	TORS	015/011	2110	−2.49	4.37	206	4.99
−8.53	179.20	Tuvalu	TUVA	732011		1.24	4.05	181	5.83
−33.03	288.37	Valparaiso	VALP	850033	25	−6.45	3.51	59	9.81
−41.29	174.78	Wellington	WGTT	690012	800	−1.54	6.04	309	7.37

Distance information is not always available. Information for the full list of stations is available at the TIGA web page

In this particular study, 18 tide gauges (Table 3) are selected from the global TIGA network. Tide gauge data for the period 1994–2001 are taken from the PSMSL data archive (Woodworth and Player 2003). The selection is based on several criteria: first of all, only tide gauges with revised local reference (RLR) data quality for the 1994–2001 period are used. Minor gaps ranging from 1 to 3 months in the time series were accepted and corrected using the mean value, while time series showing major gaps were rejected. Also, stations located in semi-enclosed oceanic regions (Hudson Bay, Baltic Sea) were not used. Second, only GPS stations with time series lengths exceeding around 2.5 years were considered reliable (for a detailed discussion, see Blewitt and Lavallée 2002). Third, we only consider tide gauges which exhibit at least medium to strong correlation with the satellite altimetry data at one of the nearest grid points over the common 8-year period. This way, we aim to observe the eligibility standards for tide gauges in a sea level reconstruction established by, e.g., Douglas (2001); excluding, e.g., tide gauges located in estuaries. Of the nearest grid points, we apply the tide gauge corrections to the one with the best correlation. In cases where two tide gauges located close to one another cover the same nearest grid point, the tide gauge with the better data quality (in terms of absence of gaps, tide gauge and GPS time series lengths) was used.

The lengths of the available GPS time series range from around 6 years for the North Atlantic and New Zealand stations, to less than 3 years for some of the Western Pacific Islands and Japan. For all sea level time series only one average GPS value for the vertical velocity is applied. When comparing the GPS land movement trends with those determined by, for example, Peltier (2004) in his VM4 GIA model (Fig. 7), it is apparent that, especially in the Southern Hemisphere, the model tends to underestimate the GPS derived trends. However, for the moment, several GPS-derived trends are extracted from very short time series only.

4.1 Comparison with original satellite altimetry data

In the reconstruction example, the first 25 area-weighted EOFs are used, which cover over 91% of the global variability. It has been shown (Church et al. 2004) that this number of EOFs is sufficient for an OI reconstruction. The small number of tide gauges satisfying all the selection criteria mentioned earlier, however, is responsible for the fact that the reconstruction is not yet altogether accurate.

As an example, we compare the reconstruction results using GPS vertical corrections (Fig. 8b) with the one using GIA model corrections (Fig. 8c) as well as the original TOPEX altimetry data (Fig. 8a) for December 1997. We deliberately chose an example month showing a comparably poor agreement; with RMS differences of 3.45 cm (GIA correction) and 3.25 cm (GPS corrections), respectively. The dominant signals here are the positive anomaly resulting from the 1997/1998 El Niño event, and the Indian Ocean Dipole event (IOD) (Feng and Meyers 2003) with its characteristic warming (positive anomaly) in the Indian Ocean, as well as a distinct cooling (negative anomaly) in the Indonesian/Western Pacific region. It is apparent that both reconstructions slightly overestimate the positive anomaly in the Northern Pacific around the Aleutian Islands, as well as the negative anomaly located directly to the south.

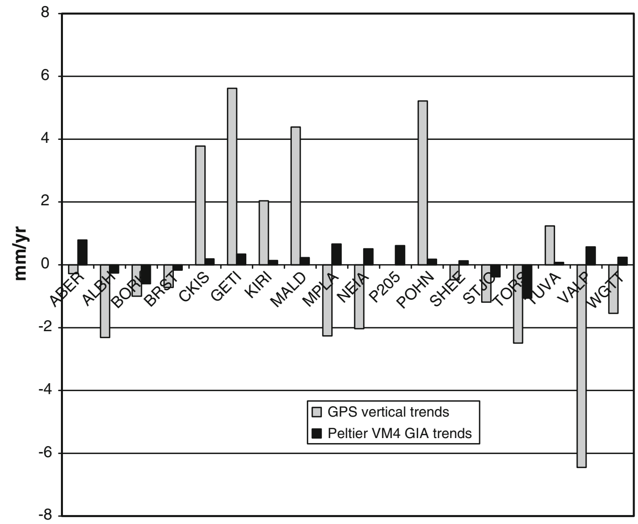

Fig. 7 Comparison of land movement trends from the TIGA combination and from Peltier's VM4 GIA model (Peltier 2004) (in mm/year)

With the continuation of the TIGA project, more tide gauges meeting the eligibility criteria will become available and, therefore, improve the reconstruction.

4.2 Comparison of GIA versus GPS corrections

When applying the corrections for land movement, it is assumed that the GPS vertical trends describe ongoing, long-term processes. Hence, the corrections are applied to not only to the period of time over which the trend was determined, but also project these trends into the past. In this study, we apply the respective corrections from the beginning of the reconstruction period (1994) to its end in 2001. For a comparison of the reconstruction using the GIA versus GPS corrections, we chose a month at the end of the reconstruction period, where the influence of the respective corrections will be most visible. However, it should be noted that, due to the nature of the reconstruction algorithm, the influence of the tide gauges may not be strictly local in some cases.

In the comparison of the reconstructions for December 2001 (Fig. 9a–c), the advantage of the GPS-corrected reconstruction is most visible in the rendition of the positive anomaly around the Western Pacific Islands (with GPS stations POHN, KIRI, TUVA and CKIS). Here, the GPS-correction leads to a better coverage of the intensity of this anomaly. This, of course, is to be expected, since the influence of the GIA signal is dominant mainly in Fennoscandia and Canada, but not in the equatorial Pacific region. Also, the GPS-corrected reconstruction is slightly better in recovering the warming (positive anomaly) in the Northern Pacific region. Both reconstructions

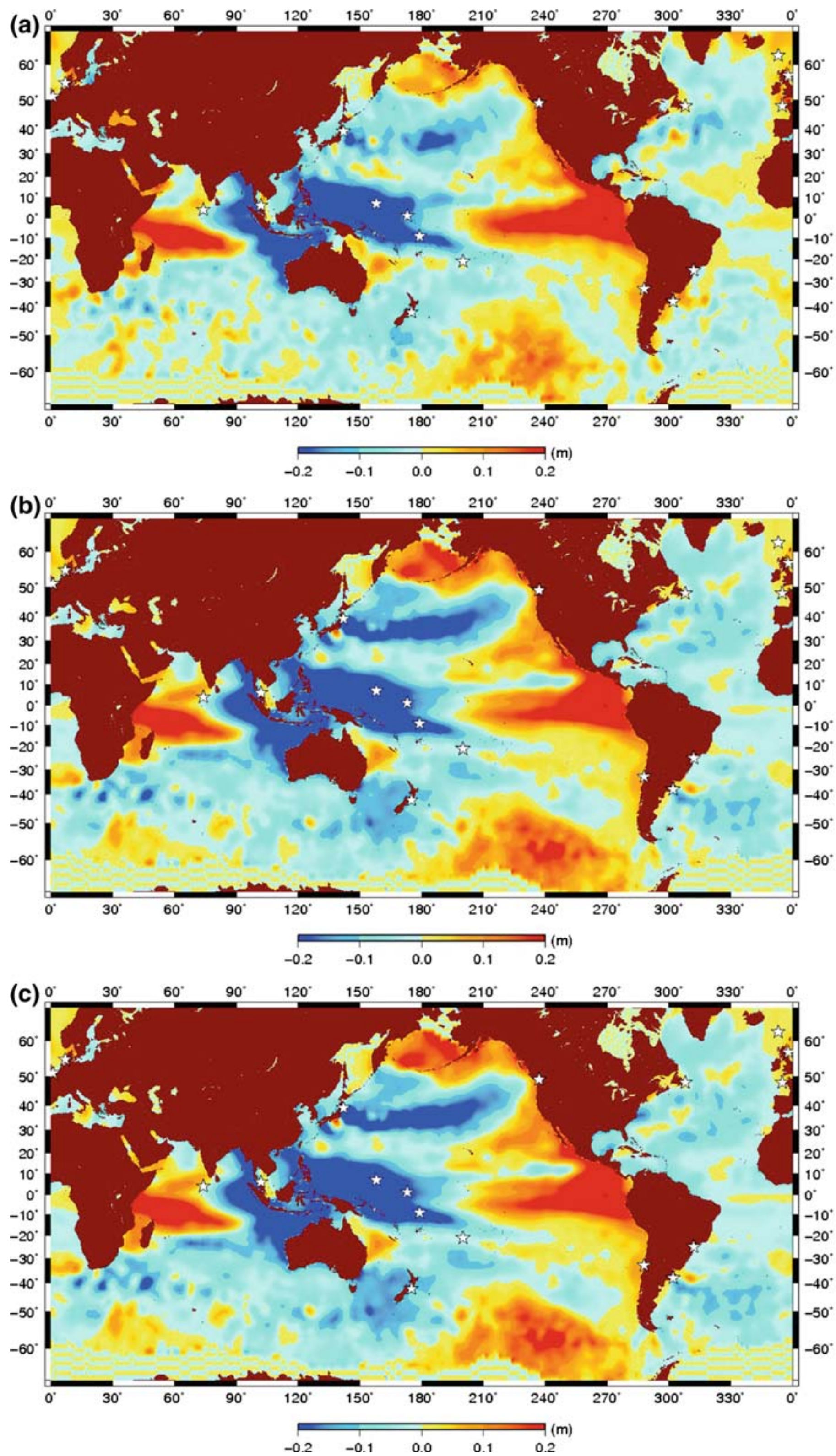

Fig. 8 **a** Sea level anomalies (SLA) for December 1997, TOPEX radar altimetry data. **b** SLA reconstruction for December 1997 using 18 tide gauges with GPS vertical corrections. Tide gauges used in the reconstruction are depicted as *stars*. **c** SLA reconstruction for December 1997 using 18 tide gauges with GIA model vertical corrections (Peltier 2004). Tide gauges used in the reconstruction are depicted as *stars*

fail to reproduce the warming in the North/Northwestern Atlantic, a fact that is possibly due to the deplorable lack of TIGA stations in the North American coast.

Most interesting in a comparison of GPS versus GIA corrections is their effect on the sea level trend. The results are depicted in Fig. 10. As mentioned, the current scarcity

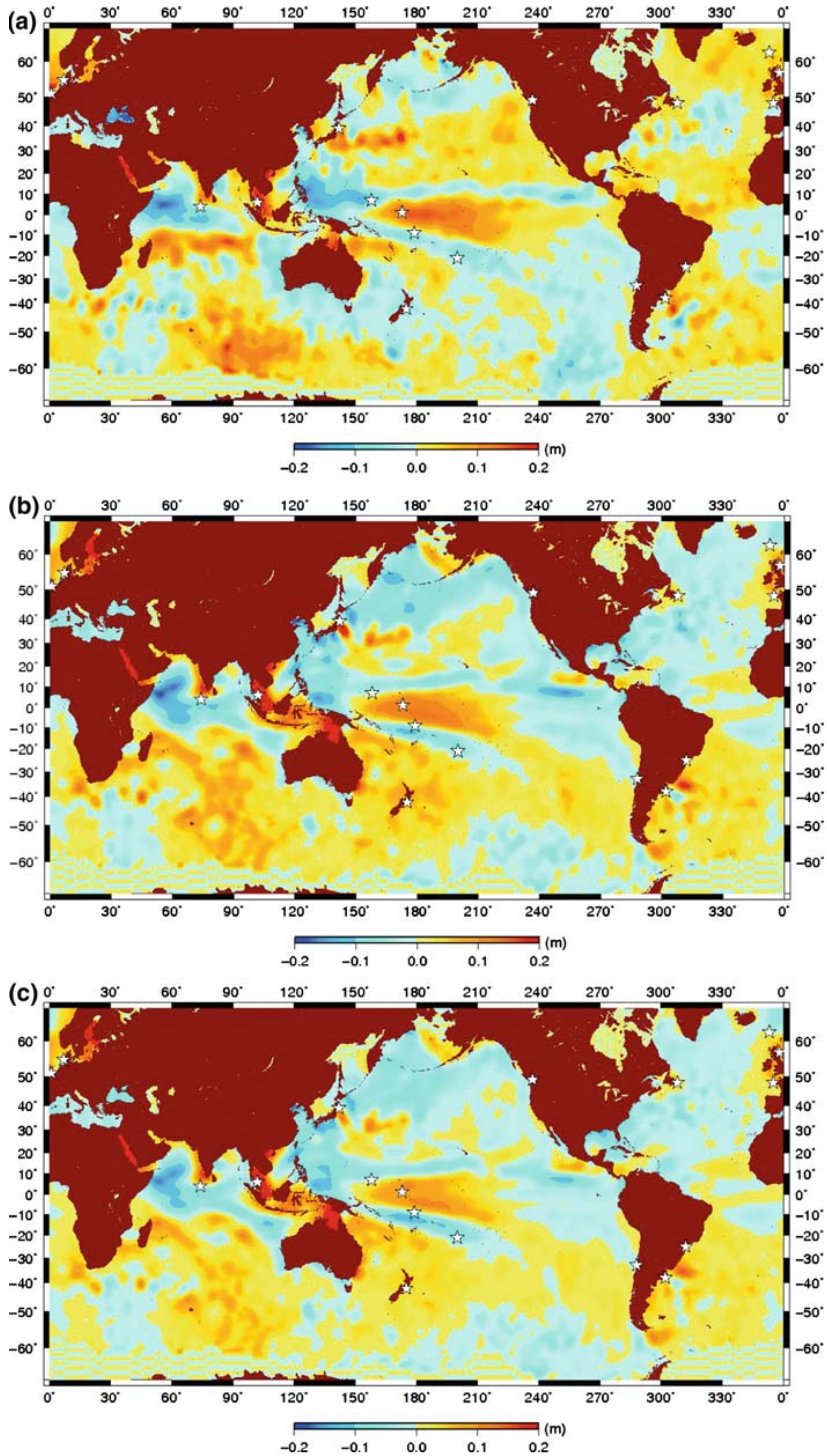

Fig. 9 **a** Sea level anomalies (SLA) for December 2001, TOPEX radar altimetry data. **b** SLA reconstruction for December 2001 using 18 tide gauges with GPS vertical corrections. Tide gauges used in the reconstruction are depicted as *stars*. **c** SLA reconstruction for December 1997 using 18 tide gauges with GIA model vertical corrections (Peltier 2004). Tide gauges used in the reconstruction are depicted as *stars*

of eligible tide gauge stations hinders an exact reproduction of the original trend. Again, it should be noted that, with the OI reconstruction algorithm, the amplitude of the EOF patterns in time, and therefore the trend, is determined solely by the tide gauge data. As described in Sect. 4.1, an erroneous overestimation of the cooling (negative anomaly) in

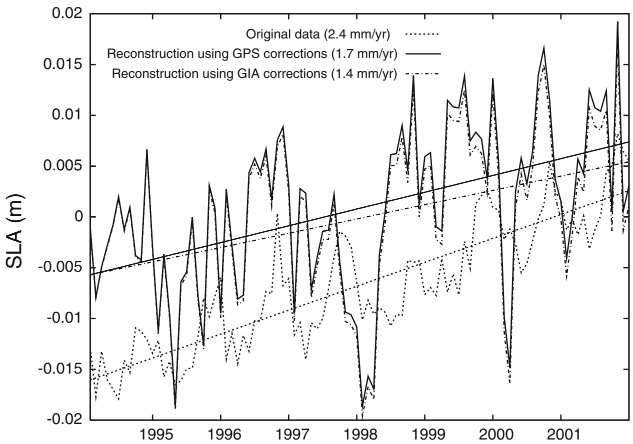

Fig. 10 A comparison of global SLA trends for the 1994–2001 period

the Northern Pacific in the first months of 1998 leads to a significant drop in SLA for both reconstructions. However, the GPS-corrected reconstruction, at 1.7 mm/year, arrives at a better estimate of the original trend than the GIA-corrected version at 1.4 mm/year.

In summary, the reconstruction example shows that GPS corrections can markedly improve the quality of an SLA reconstruction, as well as the trend. This is especially true in the Southern Hemisphere, where the GIA is not the dominant land movement signal, but also, of course, in regions where land movement stems from other geological or environmental causes.

5 Conclusions and outlook

Tide gauge readings are a prime source for studying sea level changes and ocean dynamics. For some tide gauge sites data records of more than a century exist providing some unique insight into changes of sea level over longer periods. However, it has been noted in many studies that the results are difficult to interpret due to the underlying and mostly unknown local land height changes.

Over the past two decades, efforts have been made to bring together oceanographers and geodesists to express the local sea level readings in a long-term stable reference frame. As a consequence, in 2001 the TIGA project was established to employ the GPS technique at tide gauge sites. In the past few years this project has become an important source for reliable estimates of height changes at or near tide gauges. For the first time, a reprocessing for a large set of IGS stations by a combined effort of many contributors was carried out. So far, most of the scientific results published are based on studies of individual TIGA solutions. However, it is evident from the above that the combination adds an additional value. Moreover, the pilot project not only comprises the reprocessing of GPS data using newest standards, but also has led to the growth of the numbers of participating stations.

Recently, the establishment of a conventional vertical reference system was proposed by the International Association of Geodesy (IAG), where the contribution of TIGA is an important part. Moreover, the GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC) defined a network of core tide gauge stations where GPS should be added for long-term monitoring. The network of TOS already contributes to these initiatives; however, a large hemispheric bias still exists.

For the moment, the combination of individual SINEX solutions of different TACs is just beginning. The recent change in the IGS processing strategy from relative to absolute PCV models has necessitated the reprocessing of the already existing solutions by the TACs. So far, only one global and three regional solutions are available. Hence, the combination is lacking sufficient overlap. Due to the problem with the *ULR* solution mentioned earlier (i.e., no a priori information is provided in SINEX), another contribution based on a global network is highly desirable. As soon as such a solution, using the new IGS processing standards, is available, a multi-year solution can be computed to derive a terrestrial reference frame (TRF) for TIGA. This TRF can then be used as a basis for the weekly combined solutions to get consistent time series of station coordinates.

As one example the reconstruction of SLA using TIGA-GPS corrected tide gauge values clearly demonstrates the advantage of using these data instead of, e.g., GIA model data. However, the benefit of using an absolute instead of a relative antenna PCV model for, example, reconstructing SLA still requires further investigation.

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