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GPS data processing at GFZ for monitoring the vertical motion of global tide gauge benchmarks — technical report for projects TIGA and SEAL

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Abstract

As a technical memorandum for the TIGA/SEAL project, this report describes the procedure and scheme of GPS data processing and product provision at GFZ for monitoring the vertical motion at tide gauge benchmarks to study the global eustatic sea level change. As one of the TIGA analysis centers (TAC), GFZ is processing data from about 370 GPS stations in three lines: backward reprocessing till 1994, forward processing with 66-week latency and one-week delay processing in parallel with IGS as part of IGS activities. The quality of the station coordinate solutions is assessed by comparing with official IGS combination solutions and other TACs' solutions. The consistency with IGS solutions is 4 - 1 mm in the horizontal components, and 8 - 4 mm in the height component, improving with time. The larger discrepancy in earlier time indicates the improvement of TIGA reprocessing. The consistencies with other TACs are not as good as that with IGS. This may come from twofold effects. On the one hand, GFZ TIGA solutions also contribute to IGS. So, the IGS combination solutions should be internally consistent with GFZ TIGA solutions to a certain extent. On the other hand, the differences on software package, strategy and the size of network may also cause a worse consistency among each other. However, the combination of various TACs' solutions gives feedback to improve the single contribution and by this the final products.

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1 Introduction

The global sea level change has been concerned seriously in recent decades due to its direct and indirect effects on the habitat of the human being. In studying the sea level change, tide gauges play a very important role with the direct measurements of the water level and the long observation history. For example, some tide gauges in Sweden (Goteborg-Klippan, Varberg, Ystad, Kungholmsfort) provide sea level records since 1887. Generally, a tide gauge is installed on the crust which can move vertically caused by tectonic movement and post glacial rebound. Therefore, the tide gauge measurements cannot infer an absolute sea level change unless the vertical crustal motion near tide gauges are well known. Fortunately, the continuous GPS (cGPS) measurements provide an unprecedented approach to monitor the crustal motion at tide gauges.

Oceanographic community requires an accuracy of better than 1mm/yr on vertical motion rate of the tide gauge benchmarks. Subject to the network densification, the updates of GPS satellites, the improvements of models and data processing techniques, getting such an accuracy becomes promising. Under this motivation, the International GPS Service (IGS) launched a pilot project, TIGA (GPS Tide Gauge Benchmark Monitoring - Pilot Project) [15], aiming at monitoring the tide gauge benchmarks by analyzing long-term GPS time series.

Several TIGA Analysis Centers (TACs) around the world have been involved, including

- Australian Surveying and Land Information Group (AUSLIG), Australia;
- Deutsches Geodätisches Forschungsinstitut (DGFI), Germany;
- EUREF Subcommission, Belgium;
- Finnish Geodetic Institute, Finland;
- GeoForschungsZentrum Potsdam (GFZ), Germany;
- National Coordination Agency for Surveys and Mapping, Indonesia;
- University de La Rochelle (ULR), France;
- The University of Canberra, The University of Tasmania, The Australian National University (CTA), Australia.

As one of the TIGA analysis centers, GFZ IGS group began to process the related GPS data since August 2002.

The results also contribute to another cooperative research project, SEAL (Sea Level Change: An Integrated Approach to Its Quantification), initiated by Alfred Wegener Institute for Polar and Marine Research (AWI), GFZ, and GKSS Research

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Centre Geesthacht (GKSS), which studies eustatic sea level change by interdisciplinary approaches, including sea level observation and calibration, ice mass transfer, ocean modelling and data assimilation, and glacial isostatic adjustment (GIA).

This report describes the strategy and the stream line of the GPS data processing at GFZ. The quality of the solutions are assessed by comparing with IGS combination and other TACs' solutions.

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2 General procedure

Till the end of 2006, the TIGA GPS network (see Figure 1) is composed of about 370 GPS stations, in which about 180 are TIGA observing stations (TOS). To reduce the time of data processing and overcome the computer memory limitation, the GPS stations are divided into several clusters. Each cluster itself is a global network consisting of about 100 stations (see Table 1). About 30 stations are common to all clusters that are used for combining the cluster solutions to the whole-network solution. The network is still undergoing enlargement for the late joined stations. Additionally, a Canadian network composed of 6 GPS stations (BAKE, KUUJ, PICL, VALD, BAIE, HLFX) established by GFZ for studying the GIA is also included.

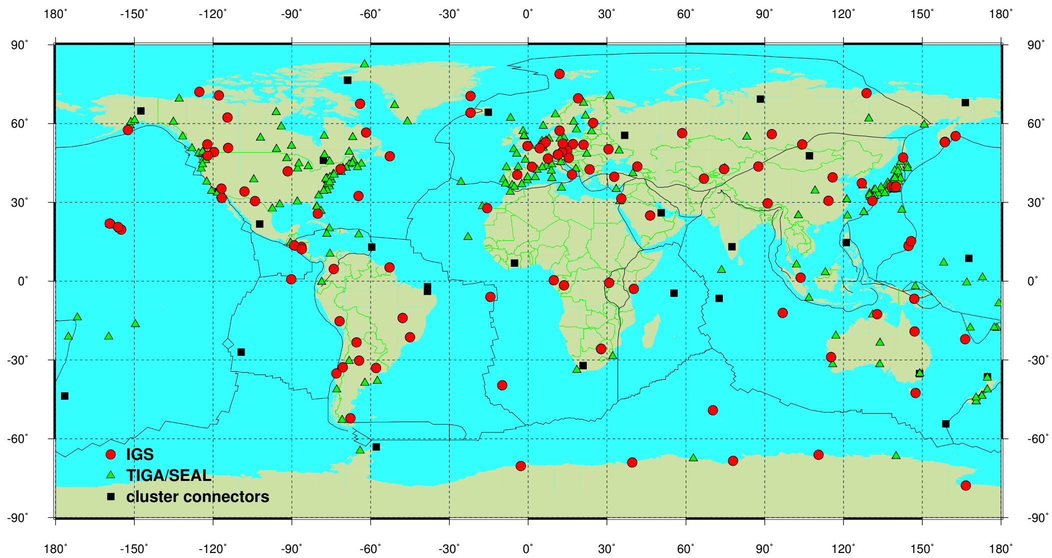

Figure 1: GPS network processed at GFZ for TIGA and SEAL. Some IGS stations that are used for TIGA purpose still marked as IGS sites.

As the data processing algorithm for analyzing huge GPS network was recently developed [6] and implemented in the GFZ GPS software, it's possible to process all

Table 1: GPS network clusters

cluster	purpose	# sta.
1	IGS extension 1	107
2	TIGA	119
3	IGS basic	99
4	IGS extension 2	74
5	New TIGA stations	74
6	New TIGA stations	68
7	All TIGA stations	184

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stations in one network solution in future reprocessing.

The GFZ TAC is processing the data in three chains by using the EPOS software package developed at the GFZ [8]. The first chain, with 1-week latency beginning from 2002.0, is also a part of the GFZ/IGS activities. The second chain, with 66-week latency waiting for the late coming data, is dedicated to TIGA as a proposed permanent routine service. The last chain, the backward reprocessing back to the year 1994, is initially carried out with a 4-week time step to check the models, the data availability and the processing strategy. Later on, the data back to 1994 have been completely analyzed.

The main scheme of data processing is similar to that adopted by GFZ IGS solution [9]. Here, it is described in some detail to make the report as a technical memorandum.

The basic observation is the ionosphere-free linear combination of phase observables

$$L_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 L_1 - f_2^2 L_2\right) \ . \tag{1}$$

The corresponding combination of code observables

$$P_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 P_1 - f_2^2 P_2\right) \tag{2}$$

is also used to obtain the clock solution. In the above equations, f_1, f_2, L_1, L_2, P_1 and P_2 are the frequencies, phase measurements and code measurements for the two bands of GPS carrier signals.

The data processing procedure includes several separate steps for a daily processing:

1. Restoring data from the local IGS archive.

2. Scanning available data centers to retrieve data for new added stations.

3. Restoring existing IGS products, e.g. data cleaning information files (internally so-called “log files”), initial orbit elements, orbit files, clock files, Earth shadow files, yaw attitude files, and so on.

4. RINEX-level data preprocessing, including data sampling, receiver-dependent corrections, single-station-oriented data editing by removing outliers, detecting and repairing cycle slips, and so on.

5. Data cleaning station-by-station by analyzing residuals from precise point positioning (PPP) analysis based on existing orbit and clock products (called “PPP”).

6. Data cleaning by analyzing the residuals from network solution (called “net clean”).

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7. Ambiguity fixing to resolve as many as possible integer double-difference ambiguities.

8. Final network solution with resolved integer ambiguities as constraints (called "final solution").

9. Combining cluster normal equations to get daily solution.

10. Combining daily normal equations as 3-day normal equation and finally to generate weekly SINEX solution.

In the above procedures, every step has an "ok" flag file created after the step is finished. This is to avoid repeating everything while the data processing is interrupted at any points by computer crash, full-filled disk, or any other unexpected errors. After "final solution", the solution quality is controlled by checking the root mean squares (RMS) of the L3 residuals of satellite-station pairs. If the maximum RMS is larger than 2 cm, the data processing will be repeated from "net clean" to "final solution". Then, the residual RMS is checked again. If there are still residual RMS larger than 2 cm, the related stations will be cleaned again by PPP, and the data processing is repeated again from "net clean" to "final solution". If no residual RMS larger than 3 cm, the processing is finished normally. Otherwise, the processing for the day stops and a warning message is sent to the operator via email.

To speed up the data processing, the software is refined to run as automatic as possible. For the first chain, a basic cluster for IGS is processed first. The other clusters use the orbit product (in SP3 format) from the basic cluster to speed up the data cleaning procedure. The software automatically detects the availability of SP3 files for the week by a daemon job. Once the SP3 files are detected, the data processing for the related days will start immediately. The software also automatically checks the failed days and clusters to process them again.

For the second chain, which has a latency of 66 weeks, the software starts the weekly processing from 00 UT of every Monday. The failed days will be also detected and "picked up" automatically for another try of processing. After the whole week is finished, the weekly solution (in SINEX format) is generated by combining seven 3-day combinations. Before the weekly SINEX file is sent to the ftp server for TIGA solutions, it is checked on two aspects :

1. The completeness of the SINEX file by checking the ending flag "%ENDSNX". Sometimes, if marker, receiver or antenna information for the solved-for stations is not correct, the SINEX file will not be created completely. This incompleteness also occurs when any bad satellites exist and cause failure in the normal equation combination.

2. The number of stations in the solution compared with the 5 nearest earlier weeks. Sometimes, a computer network problem occurs while retrieving data from external data centers and the data of many stations can be lost.

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If the SINEX file passes the above examination, it will be sent to the ftp server for the TIGA community.

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3 Data pre-processing

The RINEX-level data preprocessing (including programs *cc2noncc*, *trimble_corr*, *short_find* or *TurboEdit*) is based on 30-second RINEX observations. The data files with higher sampling rate are sampled to 30-second interval first. Then, two kinds of receiver-dependent corrections (*cc2noncc* and *trimble_corr*) are implemented. Subsequently, RINEX-level data cleaning (*short_find* or *TurboEdit*) is carried out. After these steps are finished, the data will be further cleaned in a PPP solution and finally in a network solution.

3.1 RINEX-level pre-processing

3.1.1 *cc2noncc* correction

The *cc2noncc* correction is to correct the pseudorange observations obtained by cross-correlation (cc) style receivers to new generation non-cross-correlation (noncc) observables. This correction is only meaningful when using mixed types of receivers to make the solution, especially for the clocks, consistent [IGS Mail #2744 (15 March 2000) and IGS Mail #2320 (24 June 1999)].

The (C_1, P_2') pair available from cross-correlation style receivers (e.g., AOA TurboRogue and Trimble 4000) have satellite-dependent biases compared with the (P_1, P_2) observables provided by newer generation receivers (e.g., Ashtech Z-XII, AOA Benchmark/ACT, etc). To avoid mixing data with different satellite biases, which would degrade the IGS satellite clock products, since April 2, 2000, the IGS Analysis Centers have agreed to adopt a common pseudorange bias convention by modifying data from the older receivers to be compatible with the newer generation observables.

Specifically, this involves transforming data from cross-correlation style receivers by:

$$C_1 \longrightarrow C_1 + f(i) \quad \text{[becomes compatible with modern } P_1\text{]} \tag{3}$$

$$P_2' \longrightarrow P_2' + f(i) \quad \text{[becomes compatible with modern } P_2\text{]} \tag{4}$$

where $f(i)$ are empirically-determined long-term average bias values $< P_1 - C_1 >_i$ for satellites PRNi. The value of $f(i)$ reaches up to 2 nanoseconds. In this way, a mixed network of receiver types can be used together consistently.

In addition, a few models of non-cross-correlation receivers (e.g., Leica CRS1000) report C_1 rather than P_1. For these only C_1 is replaced by

$$C_1 \longrightarrow C_1 + f(i) \quad \text{[becomes compatible with modern } P_1\text{]} \tag{5}$$

and the P_2 observable is left unchanged.

Among our data, the first non-cross-correlation receiver, ASHTECH P-XII3, at station SIO3, is used since July 7, 1993. However, the correction table is only available

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since April 2, 2000. Before this date, no correction is applied on cross-correlation style observables. In principle, the effect of inconsistence is mainly on the clocks and the ambiguity fixing algorithm. The station coordinates should not be affected significantly.

3.1.2 *trimble_corr* correction

Receiver clock readings can drift temporally, increasingly or decreasingly. For convenience, the millisecond parts can be corrected on observation time tag and on both of pseudorange and phase observables before producing RINEX observation files. For some types of receivers (e.g. TRIMBLE 4000 and ASHTECH Z-XII), this correction is only implemented on time tag and pseudorange, but not on phase observables (These files are violating the RINEX definition!). This has to be done by the data analyst by checking the consistency of the variations between pseudorange and phase observables. This is the task of the program *trimble_corr*, which corrects the inconsistent millisecond jumps in phase observables from some Trimble alike receivers.

The consistency check can be implemented by comparing the incremental full-millisecond values of pseudorange and phase observables from a specific frequency. For example, we can concentrate on carrier frequency f_1 and compare phase range L_1 with P-code range P_1. C/A code range C_1 is also capable of this check because 1 millisecond jump, corresponding to 3×10^5m in distance, is far greater than 30 m, the nominal accuracy of C/A code range.

Given two consecutive epochs, t_1 and t_2, the integer millisecond incremental from t_1 to t_2 is

$$m_P = \left\langle \frac{P_1(t_2)}{c} - \frac{P_1(t_1)}{c} \right\rangle^{\mathrm{ms}} \tag{6}$$

at code range P1, and

$$m_L = \left\langle \frac{L_1(t_2)}{c} - \frac{L_1(t_1)}{c} \right\rangle^{\mathrm{ms}} \tag{7}$$

at phase range L_1. In above equations, $\langle \cdot \rangle^{\mathrm{ms}}$ is an operand to round off the time to integer milliseconds, c is the speed of light. If

$$\Delta m = m_P - m_L \neq 0 \quad , \tag{8}$$

then, the phase ranges on frequencies f_1 and f_2 at epoch t_2 and subsequent epochs should be corrected with the value Δm

$$L_1(t_i) = L_1(t_i) + \Delta m \tag{9}$$

$$L_2(t_i) = L_2(t_i) + \Delta m \ , \ i = 2, 3, \cdots \tag{10}$$

After this correction, the temporal millisecond change in pseudorange and phase range should be equivalent.

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3.1.3 RINEX-level data editing

There are two programs in the EPOS software package to clean the data station by station based upon merely RINEX observation files. For the data before May 2000, that were contaminated by Selective Availability (SA), a program *short_find* could be used. Without SA, we can utilize the program *TurboEdit* coded according to reference [4]. This step of data preprocessing cleans the data mainly on the following aspects:

- To remove the short data spans.
- To remove the outliers.
- To detect and flag the cycle slips.

All the preprocessing information is registered in a so-called log file. The observation files of selected sites corrected for *cc2noncc* and *trimble_corr* together with preprocessing log files will be used to generate a single data file in the format for the EPOS software. Compared with keeping a preprocessed data file, the advantage of using such editing log file is to keep all preprocessing information in a relatively small-size file to save computer storage space. Another advantage is to make data-editing operations more visible for any checking. With these log files, it is also possible to edit the data by hand by editing the corresponding log files.

3.2 Data editing in post-processing

3.2.1 Data format conversion

In this step, the individual RINEX observation files are merged into a single data file in EPOS format, the so-called session file. The following operations are carried out in the conversion by a program named *xinses.out* :

- To correct integer millisecond clock bias on observation time tag and on code and phase observables.
- To screen data according to elevation angle cutoff.
- To read meteorological data if required.
- To delete the bad data points and intervals according to data editing log files.
- To insert cycle slip flags in the data according to data editing log files.
- To edit the table of number of ambiguities according to the data editing log file for parameter arrangement in the network solution.

The converted data file will be used by the orbit program to produce observation equations.

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3.2.2 Data cleaning in precise point positioning

To save data processing time in the network solution, the data are further cleaned station by station by analyzing the residuals resulted from precise point positioning (PPP). This procedure takes advantage of the existing IGS products at GFZ, including satellite orbits, satellite clocks, and Earth rotation parameters (ERP). By analyzing the residuals, bad observations or observation intervals, and obvious cycle slips can be detected. The preprocessing information is appended to the log files created in the previous preprocessing step by the program *short_find* or *TurboEdit*. Before March 15, 1998, there is no archived GFZ IGS product available, and this step of data cleaning is skipped.

Detecting cycle slips and outliers is carried out in a program *xamb_find.out* with observation residuals as input. The criterion for recognizing a cycle slip is 45 mm for the ionosphere-free combination. The outliers are detected as well with a criterion of 30 mm. If the number of observation points between two cycle slips is less than 4, the observation arc will be flagged as short arc in the log file and will be deleted.

A station, for which the mean residual RMS greater than 100 mm, will be removed from the list of data processing by registering it into the file LOG_GLOBAL, which controls the removal of a station or satellite globally for a day.

3.2.3 Data cleaning in the network solution

Small cycle slips and outliers, that are not perceived by the above procedures, can be further detected in the network solution. This possibility is benefiting from the higher strength in parameter estimation compared to PPP solution. As in PPP cleaning, the program *xamb_find.out* is again used to detect cycle slips, bad data points and short data arcs by analyzing the observation residuals. The network cleaning procedure is carried out iteratively. In every iteration, only the most significant cycle slip will be recognized. Then, the data are processed again to produce new observation residuals. The iteration stops when no more cycle slip is found. With the help of PPP cleaning in advance, 5 iterations are normally enough. For the data analysis (data before 1998) without PPP cleaning, more than 10 iterations are needed. Again, the newly detected cycle slips and bad observations will be registered in the data-editing log files.

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4 Ambiguity fixing

It is well known that resolving the integer ambiguities can obviously improve the estimation accuracy [3, 5, 7, 13, 14]. Essentially, due to the uncalibrated phase delay originating in satellite and receiver, the estimated zero-difference ionosphere-free ambiguities cannot be resolved as integers due to the unknown portion of wavelength at the transmitter and receiver ends. However, this unknown portion can be eliminated by forming a double difference (DD) of the phase observations between two satellites and two receivers. Then, the double-difference ambiguities are integers in nature. So, only the DD ambiguities can be resolved as integers. After all the possible-to-be-fixed DD ambiguities are resolved, the integer DD ambiguities will be used as strict constraints to improve the strength of the solutions.

In the ambiguity-fixing procedure, several kinds of ambiguities are involved. Given b_1 and b_2 are the ambiguities in the carrier frequency f_1 and f_2, respectively, for a pair of receiver and satellite, the estimated zero-difference ionosphere-free ambiguity holds

$$B_c = \frac{{f_1}^2 \lambda_1 b_1 - {f_2}^2 \lambda_2 b_2}{{f_1}^2 - {f_2}^2} \ , \tag{11}$$

where λ_1 and λ_2 are wavelengths of the two carrier frequencies. The wide-lane ambiguity is

$$b_\delta = b_1 - b_2 \ , \tag{12}$$

with wide-lane wavelength as

$$\lambda_\delta = \frac{c}{f_1 - f_2} \approx 86.2 \text{ cm} \ . \tag{13}$$

The following relation holds for the above ambiguities

$$B_c = \frac{f_2}{f_1 + f_2} \lambda_\delta b_\delta + \lambda_n b_1 \ , \tag{14}$$

where narrow-lane wavelength λ_n reads as

$$\lambda_n = \frac{c}{f_1 + f_2} \approx 10.7 \text{ cm} \ . \tag{15}$$

Usually, b_1 can be called narrow-lane ambiguity because of the narrow-lane wavelength λ_n as its multiplier in equation (14).

In principle, the basic steps to resolve the integer ambiguities are as follows. The double difference is between satellite i, j and station k, l.

- To resolve wide-lane DD ambiguities ${b_\delta}_{kl}^{ij}$ by taking advantage of its long wavelength. The wide-lane DD ambiguities can be obtained directly from observations by forming wide-lane combination of phase and pseudo- ranges

$$\lambda_\delta b_\delta = \frac{1}{f_1 - f_2} \left(f_1 L_1 - f_2 L_2 \right) - \frac{1}{f_1 + f_2} \left(f_1 P_1 + f_2 P_2 \right) \tag{16}$$

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- To resolve narrow-lane DD ambiguities ${b_1}_{kl}^{ij}$ by utilizing the resolved wide-lane ambiguities and the estimated DD ionosphere-free ambiguities B_{ckl}^{ij} from solution according to equation (14). The success probability of resolving the integer narrow-lane ambiguities depends on the estimate accuracy of B_{ckl}^{ij}.

- After both wide-lane and narrow-lane ambiguities are successfully fixed as integers, the DD ionosphere-free ambiguities can be fixed to integer according to equation (14).

Since only DD ambiguities can be resolved as integers, independent set of baselines should be searched to form independent DD ambiguities. In our solution, about 97% of the DD-ambiguities can be resolved as integers [7].

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5 Network solution with fixed ambiguities

With the resolved DD ambiguities as constraints, the network solution is carried out to get the final cluster solution. The main product of the solution is the normal equation for the cluster.

The scheme of the network solution is similar as that adopted in GFZ IGS/AC solution [9]. The data sampling rate is 5 minutes. The elevation angle cutoff is 7°. The weight of the observations is composed of two parts. The basic part is the *a priori* standard deviation, which is 1 cm for phase observation and $200 * f_a$ cm for pseudorange. The adjustment factor f_a ranges from 1 to 300. Additionally, to safely utilize the low-elevation observations, that are normally contaminated by long-distance propagation through atmosphere, an elevation-dependent factor is applied which is modelled as a function of zenith distance as follows [10]

$$f_{we} = 4\cos^2(z) \quad \text{if} \quad z > 60^\circ \ , \quad \text{else} \quad f_{we} = 1 \ . \tag{17}$$

Wind-up correction [16] is applied for phase observations. Yaw attitude control is implemented in both shadow and noon periods [1]. Ocean tide loading displacement was modelled based on FES95.2 ocean tide model including semi-diurnal constituents M_2, S_2, N_2, K_2 and diurnal constituents K_1, O_1, P_1, Q_1. The long period constituents M_f (fortnight), M_m (monthly), S_{sa} (semiannual) are not accounted for. The 8×8 JGM2 Earth gravity model is used. Other models follow the IERS Conventions (1996) [11]. To improve the data fitting, an empirical orbit impulse at the mid of the orbital arc is estimated additionally. The impulse is modelled with three components of instantaneous accelerations.

The solved-for parameters include satellite state vector, dynamical parameters (e.g. solar radiation pressure coefficients), station coordinates, Earth rotation parameters, ionosphere-free ambiguities, satellite and receiver clocks every epoch, tropospheric zenith total delays (ZTD) for every station every 4 hours as well as ZTD gradients in east and north directions every 12 hours.

In the daily solution, stabilization (namely *a priori* constraint) is applied on normal equation for all the parameters. The stabilization is realized by adding a factor on the diagonal elements of the normal matrix. The factor is calculated by

$$f_i = a_{ii} \times 10^{-s_i} \ , \tag{18}$$

in which a_{ii} is the ith diagonal element, s_i is an empirically specified number ranging from 1 to 7. Obviously, a smaller s_i means a stronger constraint. The stabilization is used to realize the reference frame and to avoid ill-conditioned normal matrix. For example, the coordinates of the IGS reference stations normally have a factor 1 or 2 depending on the historic performance of the stations. For new TIGA stations which performance is unknown, a larger factor 7 is normally applied.

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6 Combination of solutions

6.1 Daily solution by combining cluster results

By combining the normal equations of the individual clusters for a specific day, a combined daily solution can be obtained. During the combination, the common stations among the clusters play the role of the connectors. To get a unified daily solution for the whole network, the connector stations should distribute globally as uniformly as possible. A problem arising from this combination procedure is that the contributions of the common stations are accounted for repeatedly. This is still an open question for discussion, and the final behavior of the results of the common stations should be observed carefully. An optimal way to avoid such repeat contribution is to select different sets of common stations for different clusters. For example, the set C_{ij} is the common stations between cluster i and j. C_{ij} and C_{jk} have no common stations, i.e. one common site connects only two clusters. By this way, the amplified contribution of the common stations may be avoided. This can be tested by one-day solution for the accumulation effect of the common sites.

6.2 3-day solution by combining three daily solutions

To stabilize the orbit of GPS satellites, 3 days (one day before, and one day after) of normal equations are combined to get a 3-day-arc daily solution. In the combination, orbit continuity constraint is applied at the day boundaries [2]. Theoretically, such sequentially 3-day-arc daily solutions are not independent. So, when generating daily time series, daily cluster-combined solutions are directly used.

6.3 Weekly solution by combining 3-day solutions

For the TIGA Pilot Project, a proposed permanent service is to provide weekly solutions in SINEX format with a latency of 66 weeks. The weekly SINEX solution are generated by combining the seven 3-day-combined daily normal equations. There is a disadvantage of such combination: the contribution of the mid days are accounted for repeatedly, and the contributions of different days are not homogeneous. In fact, the seven 3-day normal equations come from nine days of solutions (one day before and one day after the week). Then, the 1st and 9th day contribute to weekly solution once, the 2nd and 8th day contribute twice, the 3rd - 7th days contribute thrice. The more straightforward and homogeneous way is to combine the nine days of daily solutions to produce weekly solution. However, test is still needed to verify the quality when "bad" orbits are used.

Several constraints are applied while generating weekly SINEX solutions.

The first is the inner constraint, including constraints on the rotation of positions and the geocentric positions by a set of selected high quality stations.

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The second is the aforementioned stabilization applied to the normal matrix by adding a diagonal stabilization matrix in which the elements are built in terms of equation (18). For different parameters, the factor s_i is specified as follows:

- Satellite antenna offset in nadir direction (with parameter name SATA_Z), $s_i = -6$. This is a very tight constraint.
- Station coordinates (with parameter name STAX, STAY, STAZ), $s_i = 8$. This is a relatively loose constraint.
- ERP parameters (with parameter name XPO, XPOR, YPO, YPOR, LOD), $s_i = 8$.
- UT1 of the first day of the 9 days is fixed.
- UT1 of the rest days, $s_i = 12$. The constraint is rather loose.

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7 Quality of the solutions

To monitor the quality of TIGA solutions, the weekly SINEX files are routinely compared with the official IGS combination solutions. For comparison, the TIGA free network solutions are first aligned to IGS solutions by a 7-parameter Helmert transformation to make the comparison under the same reference frame. The Helmert transformation used here reads as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{IGS}} = \left(\begin{bmatrix} t_X \\ t_Y \\ t_Z \end{bmatrix} + \begin{bmatrix} 1 & r_Z & -r_Y \\ -r_Z & 1 & r_X \\ r_Y & -r_X & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{TIGA}} \right) \cdot (1+s) \; , \tag{19}$$

where $[t_X, t_Y, t_Z]^T$ are translation components, $[r_X, r_Y, r_Z]^T$ are rotation components, s is the scale factor. Then, the coordinate residuals of the common sites are calculated.

The comparison is traced back to early 1999, before this time, IGS SINEX files are not available. Figure 2 gives the RMS of the residuals in height, east, and north. The number of common stations is also plotted in the figure. From the figure, it can be seen that the vertical consistency is about 8 - 4 mm, and the horizontal, 4 - 1 mm. The general trend is that the consistency is becoming better. Since the larger inconsistency over year 1999 to 2002 is due to the older models used at IGS ACs at that time, if the IGS solutions can be updated by reprocessing all the data, even smaller differences between TIGA and IGS solutions can be expected.

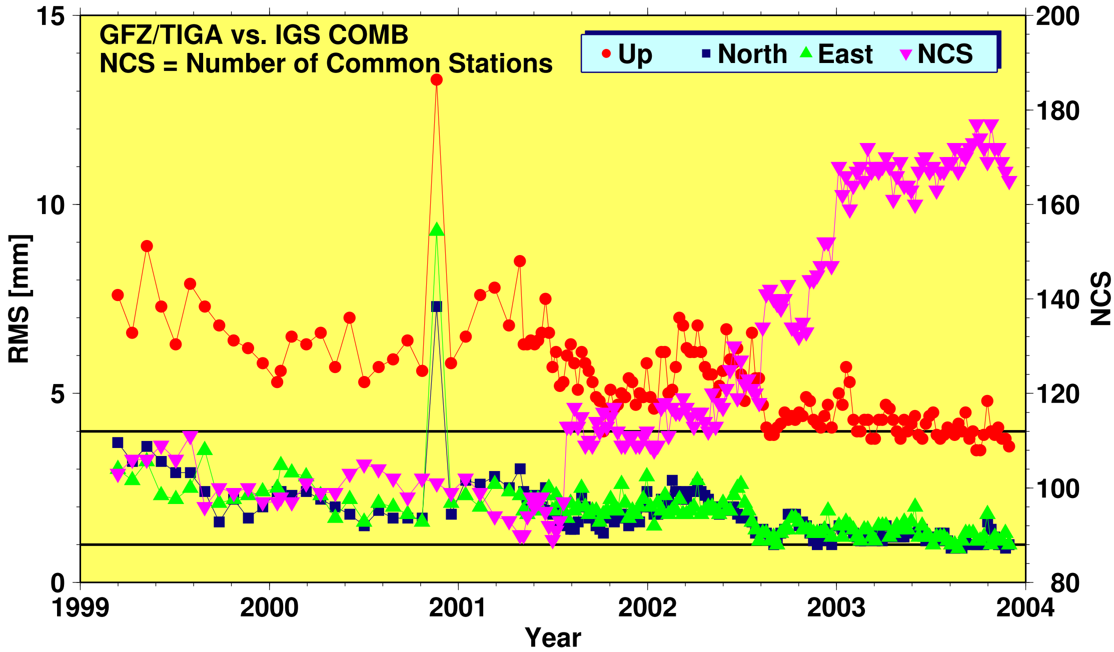

Figure 2: Station coordinate comparison between GFZ/TIGA and IGS combination solutions (SINEX).

To get an impression of the current data processing strategy, we compare the TIGA

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solution with the GFZ IGS/AC solution (see Fig. 3). The larger differences between the reprocessed TIGA and the old IGS/AC solutions indicate the progress achieved. The peak in the difference is due to a problem in the TIGA solution at GPS week 1089. This will be reprocessed.

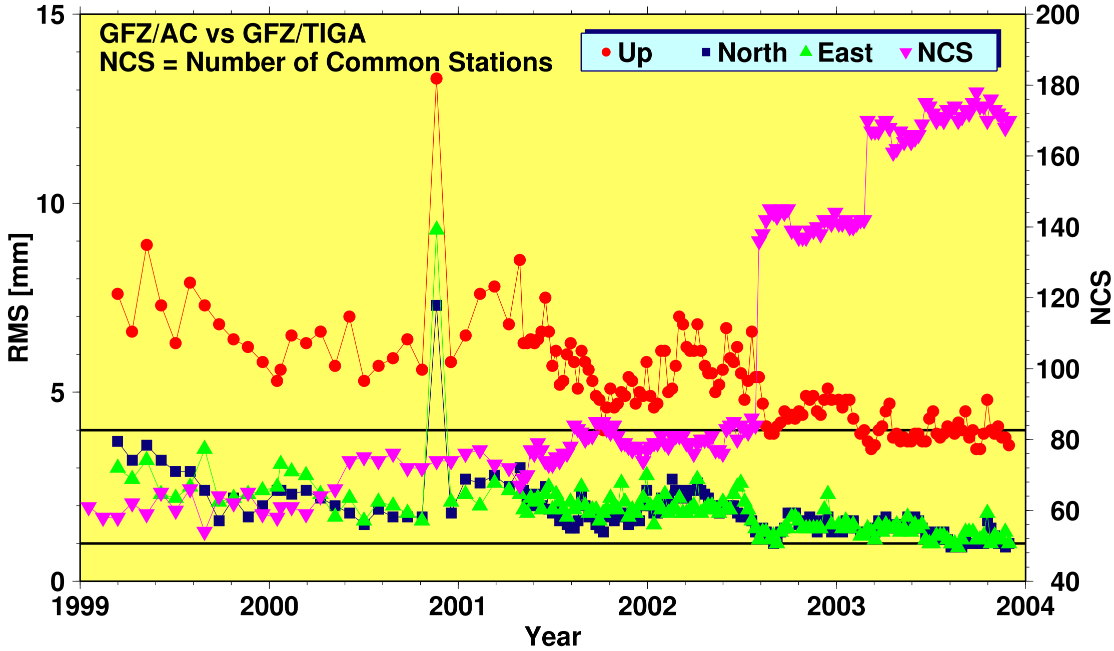

Figure 3: Station coordinate comparison between GFZ/TIGA and GFZ IGS/AC combination solutions (SINEX).

The cross-comparison with other TACs is also carried out to validate the consistency of the solutions. Figures 4, 5, 6, 7, 8 are for the comparisons between GFZ and ULR, AUT, CTA, DGF, ETG solutions following the same comparison scheme as above. The data processing schemes at other TACs are briefly summarized in Table 2. The better consistency levels with AUT, CTA, ETG than that with ULR may be due to the size of the network, since AUT, CTA and ETG are all processing regional networks. For a regional network, most systematic discrepancies are in common mode, and can be absorbed by 7-parameter transformation. The larger difference level between GFZ and ULR may come from the different software packages and data processing strategy. In general, the consistencies with TACs' solutions are not as good as that with IGS combination one.

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Table 2: Data processing schemes at TIGA Analysis Centers

TAC	Software	Network	# sta. in solution
AUT	Bernese V4.2	Regional Australia	∼ 35
CTA	GAMIT/GLOBK	Regional Australasian and Antarctic areas	∼ 25
DGF	Bernese V5.0	Regional Atlantic ocean	∼ 50
ETG	Bernese V4.2	Regional European North Sea	∼ 20
GFZ	EPOS	Global IGS + global TIGA	∼ 335
ULR	GAMIT/CATREF	Global TIGA + reference stations	∼ 150

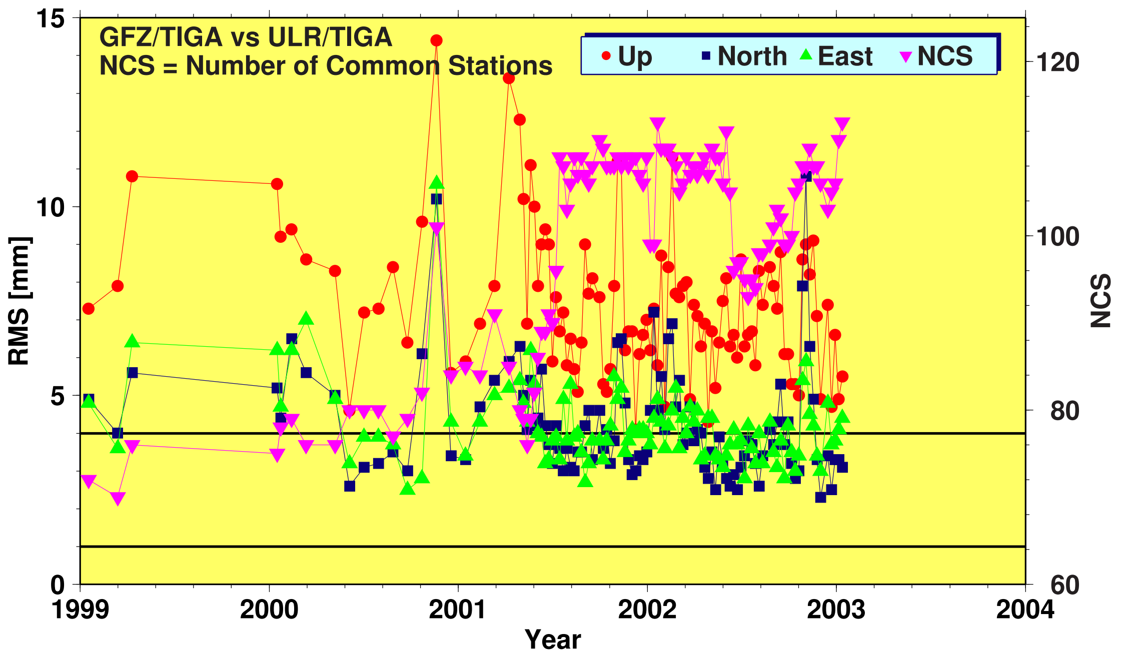

Figure 4: Station coordinate comparison between GFZ/TIGA and ULR/TIGA solutions (SINEX).

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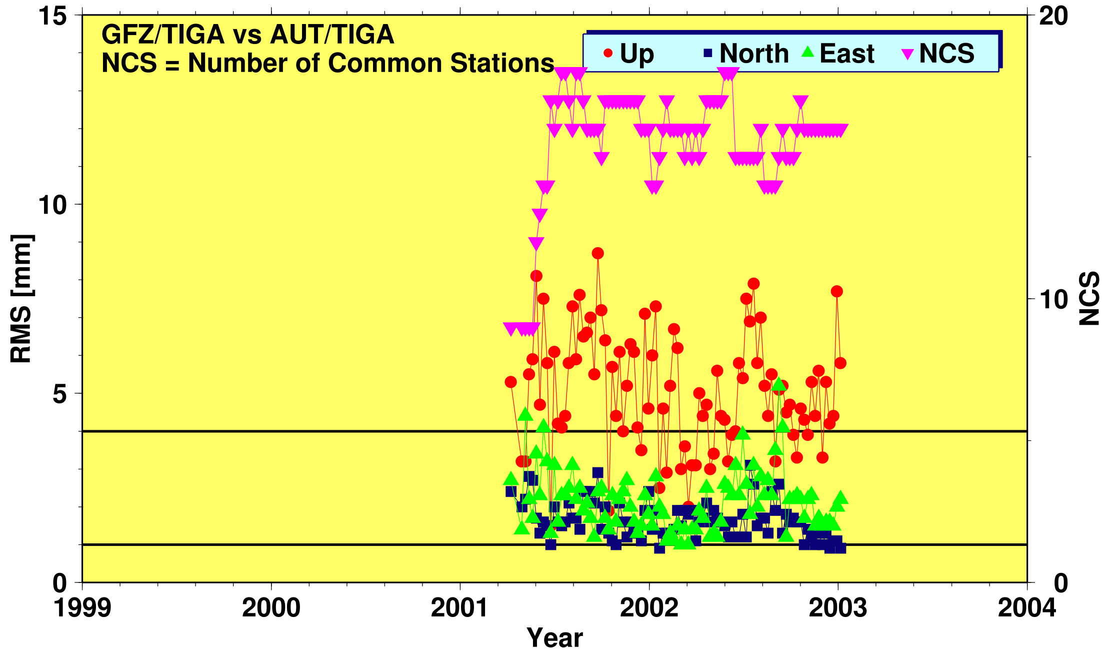

Figure 5: Station coordinate comparison between GFZ/TIGA and AUSLIG/TIGA solutions (SINEX).

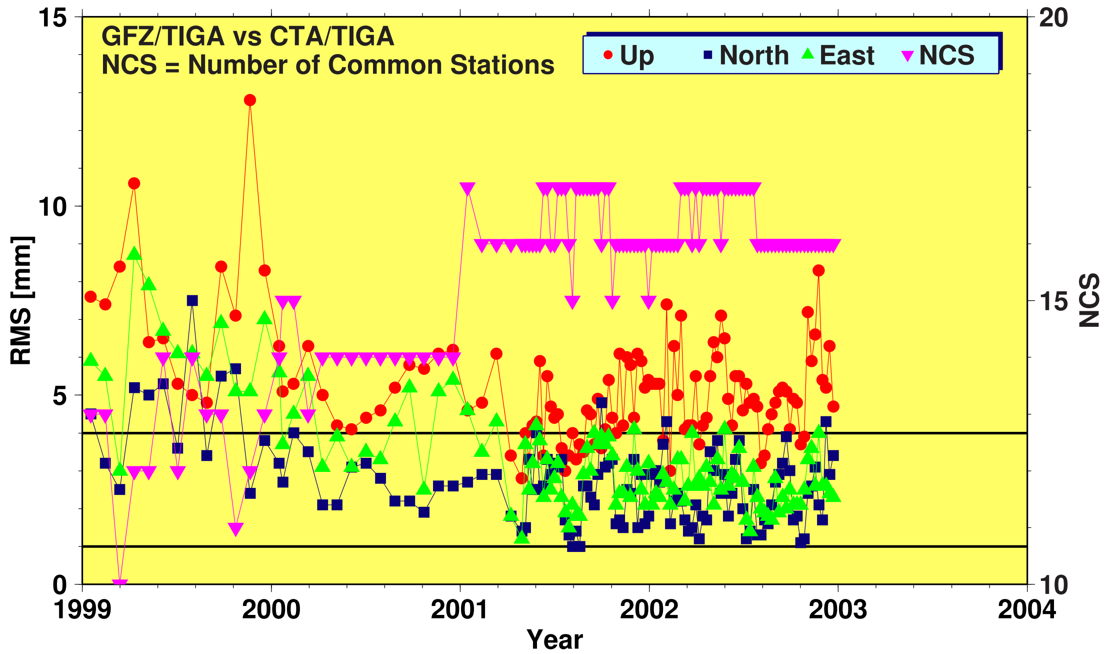

Figure 6: Station coordinate comparison between GFZ/TIGA and CTA/TIGA solutions (SINEX).

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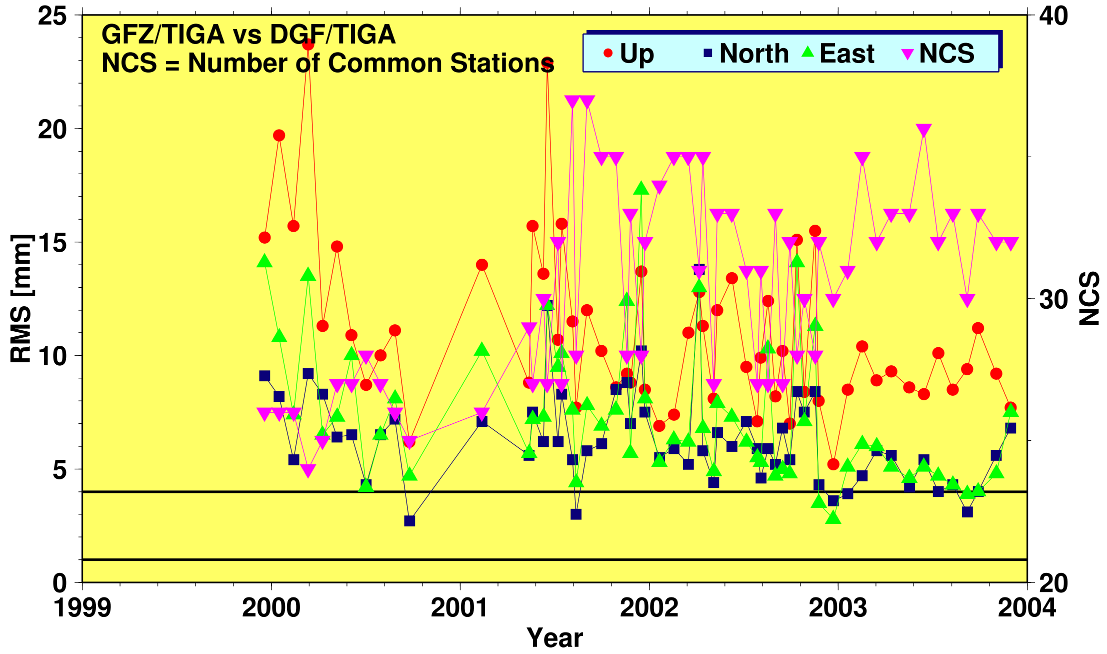

Figure 7: Station coordinate comparison between GFZ/TIGA and DGFI/TIGA solutions (SINEX). (DGFI will reprocess the data again.)

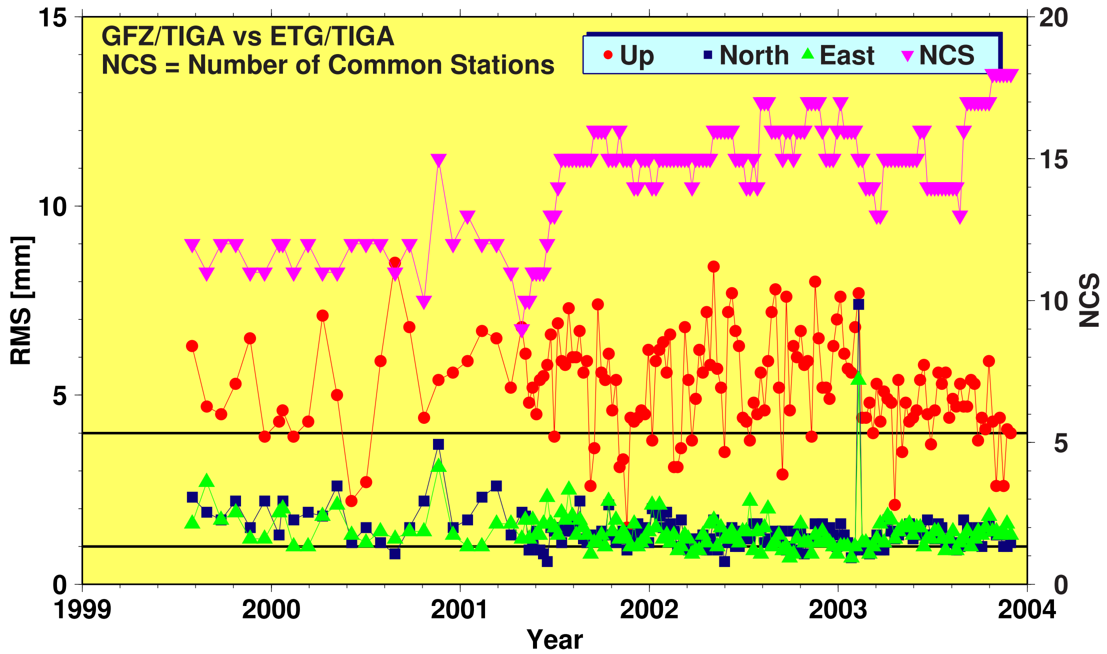

Figure 8: Station coordinate comparison between GFZ/TIGA and EUREF/TIGA solutions (SINEX).

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8 Summary and Discussion

This report describes the scheme of GPS data re-/processing at GFZ IGS/AC for monitoring the vertical land motion at tide gauges as an activity of the TIGA Pilot Project and the SEAL Project. The quality of the solution is validated by comparing with IGS combination solution and those from other TACs. From the comparison with IGS combination solutions, the consistency is about 4 - 1 mm at horizontal components, and 8 - 4 mm at height component, improving with time. The comparisons with other TACs' solutions show larger differences. The reasons may come from several aspects, e.g. the size of the network, the software package used, the data processing strategies, and so on. Another reason which should not be ignored is that GFZ TIGA solutions are also contributed to IGS with 2 clusters. The larger discrepancies among TACs' solutions remind us that cross calibration is very necessary, and much attention should be paid while combining these solutions. However, the inconsistencies among TACs may make the combination more meaningful considering their independencies.

There is still some space to improve our current solution. For example, the selection of common stations to combine cluster solutions into daily solution can be optimized, the ocean tide loading correction should include long period terms.

One main purpose of the current reprocessing is to clean the data. This will speed up the future reanalysis with further refined scheme. Some new models have been adopted by IGS as new IGS standards, such as absolute phase center variation, ITRF2005, FES2004 ocean tide loading model, new gravity models based on the recent LEO gravity satellites (e.g. 12×12 EIGEN-GL04C), and other models specified in the latest IERS Conventions (2003) [12]. Additionally, the atmospheric pressure loading induced displacement can be also applied in the data analysis. The reprocessing with new IGS standards is already under discussion within the TIGA community.

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9 Glossary of abbreviations

Abbreviation	Name Description
AC	Analysis Center
AUSLIG	Australian Surveying and Land Information Group
AWI	Alfred Wegener Institute for Polar and Marine Research
cGPS	continuous GPS
CTA	Canberra Tasmania Anu universities
DD	double difference
DGFI	Deutsches Geodätisches Forschungsinstitut
EOP	Earth orientation parameter
EPOS	Earth Parameters and Orbit determination System
ETG	EUREF subcommission TiGa solution
EUREF	IAG Reference Frame Sub-Commission for Europe
GFZ	GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GKSS	GKSS Research Centre Geesthacht (GKSS)
IGS	International GPS Service
ITRF	International Terrestrial Reference Frame
PPP	Precise Point Positioning
RINEX	Receiver INdependent EXchange format
RMS	root mean square
SA	Selective Availability
SEAL	Sea Level Change: An Integrated Approach to Its Quantification
SINEX	Solution INdependent EXchange format
SP3	Standard Product version No. 3
TAC	TIGA Analysis Center
TIGA	GPS Tide Gauge Benchmark Monitoring - Pilot Project
TOS	TIGA Observing Stations
ULR	University de La Rochelle
ZTD	Zenith Total Delay

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