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The 2008 DGFI Realization of the ITRS: DTRF2008

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Abstract A new realization of the International Terrestrial System was computed at the ITRS Combination Centre at DGFI as a contribution to ITRF2008. The solution is labelled DTRF2008. In the same way as in the DGFI computation for ITRF2005 it is based on either normal equation systems or estimated parameters derived from VLBI, SLR, GPS and DORIS observations by weekly or session-wise processing. The parameter space of the ITRS realization comprises station positions and velocities and daily resolved Earth Orientation Parameters (EOP), whereby for the first time also nutation parameters are included. The advantage of starting from time series of input data is, that the temporal behaviour of geophysical parameters can be investigated in order to decide whether the parameters can contribute to the datum realization of the ITRF. In the same way, a standardized analysis of station position time series can be performed in order to detect and remove discontinuities. The advantage of including EOP in the ITRS realization is twofold: (1) the combination of the coordinates of the terrestrial pole – estimated from all contributing techniques – links the technique networks in two components of the orientation, leading to an improvement of consistency of the Terrestrial Reference Frame (TRF) and (2) in their capacity as parameters common to all techniques, the terrestrial pole coordinates enhance the selection of local ties as they provide a measure for the consistency of the combined frame. The computation strategy of DGFI is based on the combination of normal equation systems while at the ITRS Combination Centre at IGN solutions are combined. The two independent ITRS realizations provide the possibility to assess the accuracy of ITRF by comparison of the two frames. The accuracy evaluation was done separately for the datum parameters (origin, orientation and scale) and the network geometry. The accuracy of the datum parameters, assessed from the comparison of DTRF2008 and ITRF2008, is between 2 – 5 mm and 0.1 – 0.8 mm/yr depending on the technique. The network geometry (station positions and velocities) agrees within 3.2 mm and 1.0 mm/yr. A comparison of DTRF2008 and ITRF2005 provides similar results for the datum parameters, there are larger differences for the network geometry.

The internal accuracy of DTRF2008 – that means the level of conservation of datum information and network geometry within the combination – was derived from comparisons with the technique-only multi-year solutions. From this an internal accuracy of 0.32 mm for the VLBI up to 3.3 mm for the DORIS part of the network is found. The internal accuracy of velocities ranges from 0.05 mm/yr for VLBI to 0.83 mm/yr for DORIS. The internal consistency of DTRF2008 for orientation can be derived from the analysis of the terrestrial pole coordinates. It is estimated at 1.5 – 2.5 mm for the GPS, VLBI and SLR parts of the network. The consistency of these three and the DORIS network part is within 6.5 mm.

Keywords combination of space geodetic techniques · ITRF · GPS · VLBI · SLR · DORIS · EOP · combination on normal equation level, reference frame

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1 Introduction

The International Terrestrial Reference Frame (ITRF) is a global reference frame, consisting of station positions and velocities of globally distributed space geodetic observation stations. It is the basis for positioning and navigation at the Earth and in the Earth's near environment and for scientific applications, e.g. the referencing of processes within the Earths system. The requirements on the ITRF w.r.t. accuracy and long-term stability are very high. For example, the determination of global sea level rise needs a long term stability of the reference frame of much better than 1 millimetre per year, which is not achieved so far.

The ITRF is provided by the International Earth Rotation and Reference Systems Service (IERS). The ITRF realizes the International Terrestrial Reference System (ITRS), a conventional Earth related reference system defined by the IERS Conventions (*Petit and Luzum*, 2010). The ITRF is computed by combining data of different space geodetic techniques: Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Doppler Orbit determination and Radiopositioning Integrated on Satellite (DORIS). The different observation types are characterized by individual strengths for the determination of geodetic parameters.

Starting with the ITRF2005 (*Altamimi et al.* (2007), *Angermann et al.* (2007)), the ITRF is based on time series of input solutions of the different techniques and the corresponding variance-covariance matrices, provided in SINEX format (http://www.iers.org, 2010-06-18). The parameters contained are station positions and EOP. The time series of weekly or session-wise data are provided by the corresponding services of the International Association of Geodesy (IAG). These services are the International GNSS Service (IGS), the International VLBI Service for Geodesy and Astrometry (IVS), the International Laser Ranging Service (ILRS) and the International DORIS Service (IDS). The time series with their high temporal resolution provide the possibility to generate and analyse time series of the station positions and of the geophysical parameters as the origin – which is defined to be the centre of mass of the Earth – and the scale of the ITRF. Possible systematic effects occurring in the time series, such as discontinuities and non-linear station movements, which would limit the accuracy of ITRF, can be identified and considered within the combination process. Since ITRF2005, EOP have also been included as the parameters are common to all techniques. The combination of the EOP provide a further link between the techniques in addition to the combination of station coordinates. Furthermore, they provide valuable information in order to validate the consistency of the combined frame.

Following the release of ITRF2005 in 2006 (*Altamimi et al.*, 2007), the Technique Centres (TC) of the international technique services implemented strategies to improve the analysis of the space geodetic observations. The input data of ITRF2008 also benefit in matters of consistency from the first initial steps towards a homogenization of modelling. Because of the availability of three additional years of observation data (2006.0-2009.0), the installation of new observing stations and the improved modelling, as an improvement of ITRF2005 the computation of a new realization, the ITRF2008, was required.

Three ITRS Combination Centres operate under the auspices of the IERS: the Institut Géographique National (IGN), Paris, the Deutsches Geodätisches Forschungsinstitut (DGFI), Munich, and the Institut Natural Resources Canada (NRCan), Ottawa. Comparisons of the independent solutions improve the reliability and provide an assessment of the accuracy of the ITRF.

Two realizations of the International Terrestrial Reference System are computed at the ITRS Combination Centres DGFI and IGN using different computation strategies. This paper deals with the computation of a new realization of the ITRS at the ITRS Combination Centre at DGFI. The solution is labelled as DTRF2008. It contains positions and velocities of about 920 stations (including the positions and velocities, which are introduced in order to consider discontinuities in the time series of a station) and EOP. All parameters – about 43000 in total – are estimated simultaneously and consistently in a single adjustment.

The DTRF2008 solution is available at ftp://ftp.dgfi.badw.de/pub/DTRF2008, the ITRF2008 solution at http://itrf.ensg.ign.fr/ITRF_solutions/.

2 DTRF2008 computation strategy at DGFI

The general concept of the combination strategy used at DGFI is based on the combination of constraint-free normal equation systems resulting from the observation analysis of space geodetic techniques GPS, VLBI, SLR and DORIS (combination on NEQ level). Constraint-free in this context means, that no conditions or constraints are imposed which are related to the parameters included in the normal equations. Additionally, no conditions are given in order to fix datum parameters, which cannot be realized from the technique observations themselves. However, some of the a priori reduced technique-specific parameters, like for example empirical parameters of the orbit modelling or tropospheric parameters in case of VLBI, are - and of course must be - constrained individually.

The combination approach applied is a very good approximation of the combination of the original space geodetic observations – i.e. the common analysis of these observations in one software – if the reduction models and parameterizations used for the analysis of the different observation data are homogenized (*Seitz* (2009), *Rothacher et al.* (2010)). The combination is performed with the software DOGS-CS, the combination part of the software package DOGS (DGFI Orbit and Geodetic Parameter Estimation Software) (*Gerstl et al.*, 2000).

The combination procedure consists of two main parts: (1) the generation of a multi-year normal equation system comprising all available data of one technique and (2) the combination of the techniques multi-year normal equation systems to one common solution. Fig. 1 shows a simplified flowchart of the combination process.

The combination strategy followed by the Combination Centre at IGN is based on the combination of technique-specific solutions (combination on solution level) (*Altamimi et al.*, 2011). The main differences between both approaches will be discussed after a short introduction into the mathematical fundamentals of the DGFI combination model.

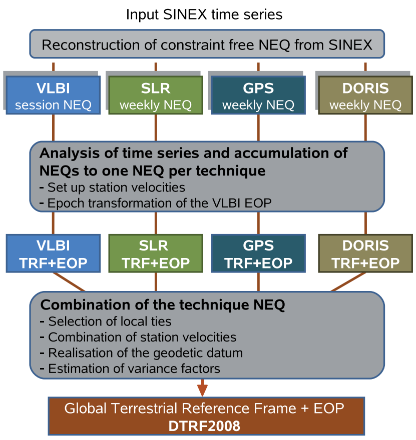

Fig. 1 Simplified flowchart of the DGFI computation procedure.

The DGFI model is based on the combination of constraint-free normal equation systems of the form:

$$\hat{\mathbf{x}} = \mathbf{N}^{-1}\mathbf{y} \quad \text{(normal equation system)} \tag{1}$$
$$\hat{\sigma}^2 = \frac{\mathbf{l^T P l} - \mathbf{y^T}\hat{\mathbf{x}}}{n-u}$$

wherein, $\hat{\mathbf{x}}$ is the vector of the estimated parameters and $\hat{\sigma}$ is the a posteriori variance factor. The normal equation matrix $\mathbf{N}$, the product $\mathbf{y} = \mathbf{A^T P l}$, the square sum of the vector observed minus computed $\mathbf{l^T P l}$, and the numbers of observations and unknowns n and u, respectively, are the given input quantities. Herein, $\mathbf{A}$ is the coefficient matrix, $\mathbf{l}$ is the observation vector and $\mathbf{P}$ is the weight matrix of the observations. The covariance matrix $\mathbf{C_{\hat{x}\hat{x}}}$ of the estimated parameters is computed with:

$$\mathbf{C_{\hat{x}\hat{x}}} = \hat{\sigma}^{\mathbf{2}}\mathbf{N^{-1}}. \tag{2}$$

The final normal equation system (1) is derived in two steps. In the first step, the time series of normal equation systems provided by the Technique Centres are combined to one normal equation system $\hat{\mathbf{x}}_\mathbf{i} = \mathbf{N_i^{-1}y_i}$ for each technique i (i=GPS, VLBI, SLR or DORIS), extending the weekly/session-wise normal equation systems by station velocities. In the second step the normal equation systems of the different techniques are combined:

$$\mathbf{N} = \sum_i \lambda_i \mathbf{N_i} \tag{3}$$
$$\mathbf{y} = \sum_i \lambda_i \mathbf{y_i} \tag{4}$$
$$\mathbf{l^T P l} = \sum_i \lambda_i (\mathbf{l^T P l})_\mathbf{i}. \tag{5}$$

λ_i are the weight factors estimated for the techniques. The equations presume that the a priori variance factors of the individual normal equation systems of the techniques are 1.0. After the accumulation of the normal equation systems the necessary pseudo-observations (w.r.t. local tie vectors, combination of velocities at co-location sites and the geodetic datum) are added and the normal equation system is solved.

VLBI input data are provided in SINEX format in form of normal equation systems, whereas the SINEX files of the other techniques contain the solutions of normal equation systems ($\hat{\mathbf{x}}_\mathbf{i}$, $\mathbf{C_{\hat{x}\hat{x}}}$, $\hat{\sigma}_i^2$, n and u). In order to enable the reconstruction of the constraint-free normal equation system from the solution, the variance-covariance matrix $\mathbf{C_{xx}}$ of the parameters computed from the constraints applied have to be stored in the SINEX file. The reconstruction of the constraint-free normal equation system of an epoch solution at epoch t (e.g. a weekly solution) is done using:

$$\mathbf{N_{i_t}} = \hat{\sigma}_{i_t}^2 \mathbf{C}^{-1}_{\hat{\mathbf{x}}_{\mathbf{i_t}}\hat{\mathbf{x}}_{\mathbf{i_t}}} - \hat{\sigma}_{i_t}^2 \mathbf{C}^{-1}_{\mathbf{x_{i_t}x_{i_t}}} \tag{6}$$
$$\mathbf{y_{i_t}} = \hat{\sigma}_{i_t}^2 \mathbf{C}^{-1}_{\hat{\mathbf{x}}_{\mathbf{i_t}}\hat{\mathbf{x}}_{\mathbf{i_t}}} \hat{\mathbf{x}}_{\mathbf{i_t}} \tag{7}$$
$$\mathbf{l^T P l_{i_t}} = (\hat{\mathbf{v}}^\mathbf{T}\mathbf{P}\hat{\mathbf{v}})_{\mathbf{i_t}} + \mathbf{y}^\mathbf{T}_{\mathbf{i_t}}\hat{\mathbf{x}}_{\mathbf{i_t}} \tag{8}$$

Therein, $(\hat{\mathbf{v}}^\mathbf{T}\mathbf{P}\hat{\mathbf{v}})_{\mathbf{i_t}}$ is the square sum of residuals. A more detailed description of the mathematical background of the combination model is given in (*Angermann et al.* (2004) and *Seitz* (2009).

The main differences between the combination model and the strategy applied by IGN (*Altamimi et al.*, 2011) are:

- When combining normal equation systems, corrections of the original observations are estimated. In case of combining solutions, the parameters of the input solutions are corrected.
- If normal equation systems are used as input data, in principle no a priori datum conditions in form of pseudo-observations are added to the individual input normal equations. In case of combination of solutions the input solutions have to be generated applying datum conditions. In order to ensure undeformed input data sets, so called minimum conditions are necessary.
- In order to be free to select the geodetic datum of the reference frame, in case of combination of solutions it is necessary to estimate parameters of a similarity transformation between the final and the input solutions. The estimated transformation parameters, which should represent the datum differences, might absorb non-modelled station movements. This can lead to biases in the estimated station coordinates and can affect the realization of the geodetic datum parameters origin and scale (*Drewes*, 2009a). A further aspect to be kept in mind is, that the results depend on the selection of stations used for the transformation.

3 Input Data

The input data are time series of weekly solutions in case of GPS, SLR and DORIS and session-wise VLBI normal equation systems (one session comprises about 24 h) provided by the responsible Technique Centres of the international services
- IGS (http://igscb.jpl.nasa.gov, 2011-01-18),
- ILRS (http://ilrs.gsfc.nasa.gov, 2011-01-18),
- IDS (http://ids-doris.org, 2011-01-18) and
- IVS (http://ivscc.gsfc.nasa.gov, 2011-01-18).

According to the services, the data are processed applying state-of-the-art models and parameterizations. Thus, a complete reprocessing was done for ITRF2008 by all the services. The main improvements realized for the different techniques since ITRF2005 and relevant to ITRF are summarized in Tab. 1. The effects on the station positions range from a few millimetres to about two centimetres.

Tab. 2 gives an overview on the time spans, the solution types, and the temporal resolutions of the input data. In case of GPS, SLR and DORIS, the constraint-free normal equations have to be reconstructed from the provided solutions. The SLR input solutions are generated using loose constraints, which are by default not provided in the SINEX files. The analysis of the geodetic datum of the weekly SLR solutions shows, that the orientation of the network has a standard deviation of about 10 cm. Thus, the normal equation systems are computed using equations (6) - (8) without subtracting the terms containing $\mathbf{C}^{-1}_{\mathbf{x_{i_t}x_{i_t}}}$ in equation 6. Both, the GPS and the DORIS SINEX files contain solutions, which were solved by applying minimum conditions (*Ferland and Piraszewski* (2008), *Valette et al.* (2010)). However, the SINEX files do not contain the variance-covariance matrices of these constraints $\mathbf{C_{x_{i_t}x_{i_t}}}$. Thus, the constraint-free normal equation system cannot be reconstructed from the SINEX file. As the geodetic datum of these weekly solutions is defined with standard deviations of smaller than 1 mm, the datum information has to be removed by extending the normal equation systems by seven parameters of a similarity transformation. In principle, the extension by three orientation angles would be sufficient, but as the origin of the ITRF solution should be realized only from SLR observations and the scale only from SLR and VLBI observations – as it will be shown later – all seven datum parameters are set up for each weekly NEQ.

The input data are combined data computed by the corresponding Technique Centres from contributions of the AC. The combination procedures used by the TC are different. While IVS combines data on the NEQ level, IGS, ILRS and IDS compute the weekly solutions by combination on the solution level. According to this, the number of observations and unknowns of the technique contributions differ strongly. Tab. 3 gives an overview about the characteristics of the input data.

The parameter space of ITRF comprises station coordinates and EOP. Tab. 4 gives an overview on the parameters included in the solutions, while the global distribution of the technique-specific station networks is shown in Fig. 2. Because of one-to-one correlations to orbit parameters, the satellite techniques cannot provide in principle UT1-UTC and nutation offsets but their respective rates (*Rothacher et al.*, 1999). Rates of the terrestrial pole are provided from GPS and VLBI data, and LOD is delivered from all techniques, except DORIS.

4 TRF per space geodetic technique

In the first part of the combination process, a normal equation system containing all observation data is prepared for each technique. This preprocessing step is of

Table 1 Improvements in modelling of space geodetic observations since ITRF2005.

Technique	Modelling improvement	Reference
GPS	- adoption of absolute instead of relative antenna phase center corrections for satellite transmit and ground receive antennas	reference for all GPS related improvements: http://acc.igs.org/reprocess.html
	- use of IGS05 as reference frame (*Ferland*, 2006), which is consistent to the absolute antenna phase center corrections	
	- improved modelling of tropospheric refraction	
	- updated model for ocean tidal loading	
VLBI	- homogenization of pole tide correction model	*Böckmann et al.* (2010)
	- modelling of thermal deformation of VLBI antennas	*Nothnagel* (2009)
	- improved modelling of tropospheric refraction	
SLR	- revised range biases, data weighting, station specific center-of-mass corrections, new tropospheric refraction model	*Mendes and Pavlis* (2004)
DORIS	- improved models for solar radiation pressure	*Gobinddass et al.* (2009)
	- improved atmospheric drag estimation	*Gobinddass et al.* (2010)
	- three more years of data from a four satellite constellation	

Table 2 Input data for ITRF2008.

Technique	Service/TC	Time Span	Temporal resolution	Type	Remarks
GPS	IGS/NRCan	1997.0-2009.0	weekly	solution	minimum constraints, not booked in SINEX
VLBI	IVS/IGG	1980.0-2009.0	session-wise	constraint-free normal equation system	
SLR	ILRS/ASI	1983.0-1992	15 days	solution	loose constraints
		1993.0-2009.0	weekly	solution	loose constraints
DORIS	IDS/CLS-CNES-GSFC	1993.0-2009.0	weekly	solution	minimum constraints, not booked in SINEX

Table 3 Overview about input data: number of unknowns, number of observations, type of combination performed at the Technique Centres.

Technique	number of unknowns, reduced parameters are not considered	number of observations	type of combination at TC	disc space needed for the multi-year NEQ
GPS	18735	5321024	solution level	2.67 GByte
VLBI	24253	52675482	NEQ level	4.49 GByte
SLR	14847	462080	solution level	0.33 GByte
DORIS	12666	911858	solution level	1.23 GByte

Table 4 Parameter included in ITRF2008 input data. Resolutions: d=daily, 3d=three-daily, s=24h-session-wise, w=weekly.

Parameter	GPS 1997.0-2009.0	VLBI 1980.0-2009.0	SLR 1983.0-1992	SLR 1993.0-2009.0	DORIS 1993.0-2009.0
station positions	w	s	15 days	w	w
offsets of terrestrial pole	d	s	3d	d	d
rates of terrestrial pole	d	s			
UT1-UTC		s			
LOD	d	s	3d	d	
nutation offsets		s			

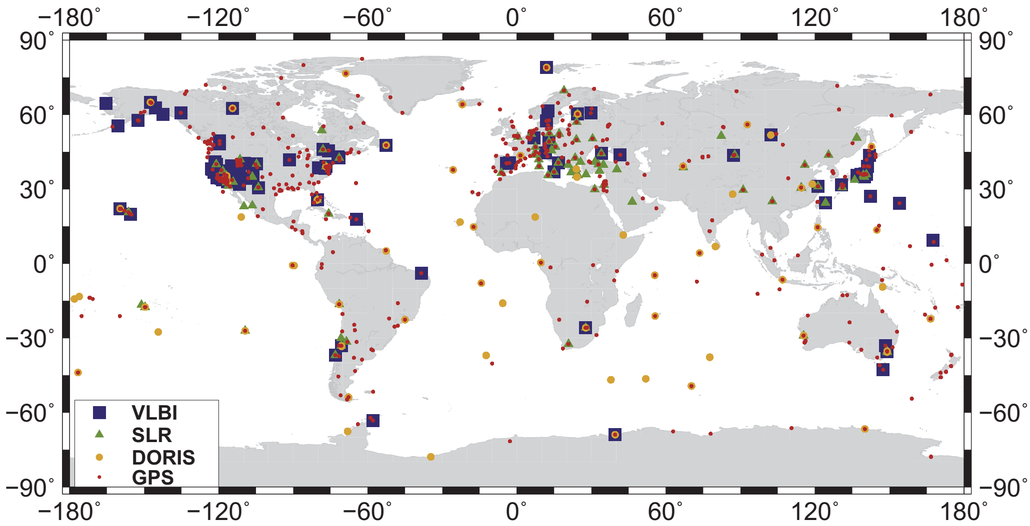

Fig. 2 Global distribution of technique-specific station networks.

high importance w.r.t. accuracy of the DTRF2008 solution, because the analysis of the station position time series is performed in order to identify discontinuities and outliers, which will be considered within the combination. Likewise, the analysis of datum parameter time series is performed in view of variability and homogeneity in time.

In order to generate station position time series, a preliminary combined TRF solution was computed for each technique by combining all normal equations per technique to one normal equation system including all data. In advance, epoch normal equation systems (weekly / session-wise) are extended by applying station velocities. The accumulated normal equation systems are solved by applying minimum conditions, adequate to realize the geodetic datum.

For the application of the datum conditions, a set of good and globally well distributed stations per technique was used. In case of GPS, no-net-rotation (NNR), no-net-translation (NNT) and no-net-scale (NNS) conditions are applied w.r.t. IGS05 solution (*Ferland*, 2006). For DORIS the same condition types as for GPS are used w.r.t. ITRF2005 (*Altamimi et al.*, 2007). In case of VLBI, NNR and NNT conditions w.r.t. ITRF2005, and for SLR NNR conditions w.r.t. *ITRF2005 SLR rescaled* (http://itrf.ensg.ign.fr/ ITRF_solutions/2005, 2011-01-18) are used. The reason for applying IGS05 instead of ITRF2005 for GPS is that the observation data fit much better to this frame, because IGS05 was transformed to be consistent to absolute antenna phase center corrections, while ITRF2005 was computed with the relative phase center correction values. In case of SLR, *ITRF2005 SLR rescaled* was used as this frame is consistent to SLR w.r.t. the realized scale.

After solving the TRF solutions, the epoch normal equation systems are solved and aligned to the preliminary TRF solutions by applying the same types of datum conditions as for the corresponding TRF solutions, except for the time dependent part of the conditions. The epoch solutions are then transformed by a seven parameter similarity transformation to the corresponding TRF solution. The resulting residual time series of station positions and the estimated datum parameter time series are analysed w.r.t. discontinuities, non-linear behaviour and outliers.

Refined TRF solutions are computed considering the identified discontinuities and outliers. The procedure is iterated as long as no more discontinuities and outliers are detected; usually, two to three iterations are needed. The compilation of the list of stations used for datum realization is integrated in the iterative process as well.

4.1 Analysis of station position time series

Fig. 3 shows the percentages of techniques at the ITRF-2008 station network. GPS dominates the frame very clearly, whereas SLR, VLBI and DORIS contribute about the same number of stations.

4.1.1 Discontinuities

Starting with the time series analysis, initial discontinuity tables provided by IGS, IVS and ILRS were available. Discontinuities are mainly caused by equipment changes or geophysical effects like e.g. earthquakes. The time series analysis for discontinuities was performed

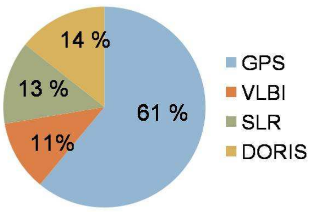

Fig. 3 Station positions per technique in ITRF2008 [%].

using a mathematical algorithm based on a four sigm criterion (the use of a three sigma criterion, commo for many applications, would lead to a fragmentation (the time series and thus to a decrease of reference fram stability). Even if VLBI and SLR stations provide tl longest observation time series of up to 20 years, they show very few discontinuities compared to GPS and DORIS. The reasons are, that equipment changes are complex and expensive and are, thus, performed rarely compared to GPS and DORIS and, in addition, very elaborate tests and calibrations are performed for every component, which is replaced in order to minimize the number of discontinuities due to equipment changes. So, only a few discontinuities are identified for VLBI and SLR station position time series in addition to the initial list provided by the services. In case of GPS and DORIS the analysis of the time series required more effort. GPS shows about 370 discontinuities on its own and as the initial list also contained information derived from the older, not reprocessed IGS solutions, it had to be re-compiled. In order to ensure comparability of the two ITRS realizations, DGFI and IGN spent much effort to harmonize their discontinuity lists.

In Fig. 4 the number of discontinuities per technique is shown. Most of the discontinuities are at GPS stations. Relating the number of discontinuities to the number of stations, 66.5% of GPS stations are affected.

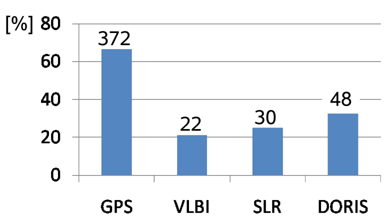

Fig. 4 Discontinuities in DTRF2008: Number of discontinuities per technique in relation to the number of technique sites [%]. The absolute number of discontinuities is given above each bar.

Stations, that are discussed in detail are the VLBI stations Gilcreek (Alaska, USA) and Pietown (New Mexico, USA). The position of Gilcreek was moved by the Denali Fault Earthquake on November 3, 2002. Subsequently, the station movement was dominated by a non-linear post-seismic relaxation with the typical shape of an exponential function (see Fig. 5). Linear station movement was reached again at the beginning of 2005. The station behaviour was approximated by six piece-wise linear functions. Continuity constraints were not applied, because this type of constraints has traditionally not been used in ITRS realization.

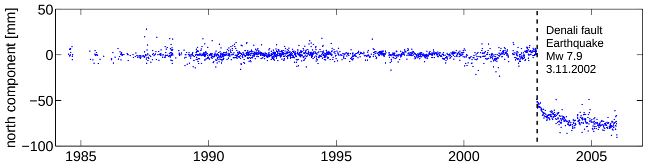

Fig. 5 Residual position time series of VLBI station Fairbanks (north component). Six individual sets of positions and velocities are estimated in order to approximate the post-seismic movement.

The VLBI station Pietown shows a significant long-term bow feature in the north and east component caused by an anomalous tilt of the antenna (*Petrov et al.*, 2009). The residual position time series is displayed in Fig. 6. The signal was approximated by three piece-wise linear functions.

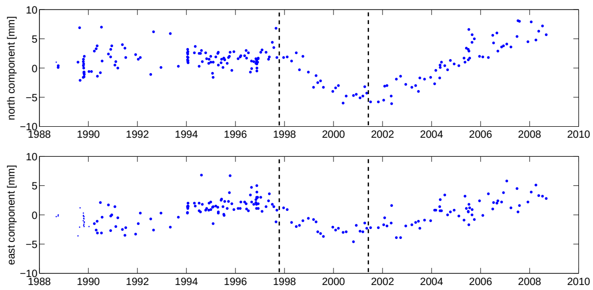

Fig. 6 Residual position time series of VLBI station Pietown. Three individual sets of positions and velocities are estimated for the three signed parts of the time series.

4.1.2 Non-linear station motions

An important aspect to be discussed are significant seasonal variations in station position time series. This became already visible during the ITRF2005 computation, the first ITRF computed from time series of input solutions (*Angermann et al.*, 2009). While site displacements due to Earth tides and ocean tide loading are reduced in the data analysis of all techniques, atmospherical and hydrological loading, non-tidal ocean loading and residuals caused by model deficiencies are not considered but mapped into the station position time series. As estimated amplitudes of annual signals are significant and provide values of up to 10 mm or sometimes even more (e.g. GPS station EIL1 shows an amplitude of the height component of 13.7 mm), seasonal variations have to be considered if precision and accuracy of the ITRF is to be improved. Most of the seasonal variations in station position time series are caused by mass load changes of the atmosphere and the continental hydrology, and by non-tidal ocean loading. Thus, mainly the height component of the stations is affected by seasonal variations. The IERS operates the Special Bureau of Loading (SBL) whose primary charge is to provide time series of surface mass load signals to the user community (*VanDam et al.*, 2002). However, for ITRF2008 loading models are not applied. The reason is, that the geophysical loading models have not yet been studied and validated sufficiently. Another central problem is, that most of the hydrology models are not available for the complete time span of ITRF2008 or have only a temporal resolution of one month, that might be too sparse w.r.t. the high variability of the mass load changes. While IGS, ILRS and IDS do not use loading models by default, IVS implemented the atmosphere loading model as a standard. For ITRF2008, the IVS reprocessed its time series without applying atmosphere loading corrections to be consistent to the data provided by IGS, ILRS and IDS (*Böckmann et al.*, 2010).

4.2 Analysis of datum parameter time series

The geodetic datum of the ITRS is defined by the IERS Conventions as follows (*Petit and Luzum*, 2010):

- The origin of the ITRS is in the center of mass of the Earth (including the oceans and the atmosphere).
- The unit of length is the Meter (SI). The scale is consistent with the TCG (Geocentric Coordinate Time) time coordinate for a geocentric local frame.
- The orientation is initially given by the orientation of the BIH 1984.0 (BIH stands for Bureau International de l'Heure). The time evolution of the orientation is defined by no-net-rotation conditions with respect to horizontal tectonic motions over the whole Earth.

Based on the results of the datum parameter time series analysis, the origin of the former ITRF solution, ITRF2005, was realized adopting the origin of the SLR solution. The scale was realized using only the VLBI observations. The scale was realized consistent to the Terrestrial Time (TT), which deviates from the conventions (TCG). This was done because of practical reasons as the observations of the space geodetic techniques are related to TT and most of the ITRF applications require TT related coordinates. The orientation of ITRF2005 and its temporal evolution was defined by NNR conditions w.r.t. the previous ITRF solution (*Altamimi et al.*, 2007) and ITRF2000 (*Altamimi et al.*, 2002). The velocity field of ITRF2000 was aligned to NNR-NUVEL-1A (*DeMets et al.*, 1994).

4.2.1 Origin

In order to decide, whether the contributions of the individual techniques are reliable to contribute to the datum realization of ITRF2008, the time series of the datum parameters have to be analysed. Fig. 7 displays the temporal variations of the translation parameters obtained for the weekly SLR solutions w.r.t. the multi-year reference solution. The standard deviations for the z-component are shown, as an example. During the first years, while only LAGEOS 1 was observed, a sine-wave-like signal is detected, especially visible for the z-component. However, as it is nearly one complete sinus oscillation and the standard deviations are comparably large during the early years (see the lowermost plot), the influence of the years 1983-1992 on the realized mean origin is not significant. Thus, the complete SLR time series is used for realizing the DTRF2008 origin.

Besides SLR, the two other satellite techniques are also related to the center of mass of the Earth. In case of GPS, the center of mass is correlated with empirical orbit parameters (*Springer*, 2000). Thus, insufficiently modelled effects, e.g. solar radiation pressure, affect the origin realized by GPS. Therefore, weekly geocenter coordinates were set up by the IGS as additional parameters, in order to consider this effect. The geocentre coordinates give the offset of the center of mass realized by GPS w.r.t. the origin of the solution, which is realized either by no-net-translation conditions in case of GPS-only solutions or by SLR observations in case of DTRF2008 solution.

For DORIS, the translation time series given in Fig. 8 are obtained. They show clear long-term systematics, in particular for the z-component. After at first identifying a quite good correlation to the changes in satellite constellations, a comparison with the 11-year solar cycle was performed. The correlation between the series is obvious, and it can be concluded, that it is not the satellite constellation but rather the solar activity which is related to the signal. *Gobinddass et al.* (2009) discussed

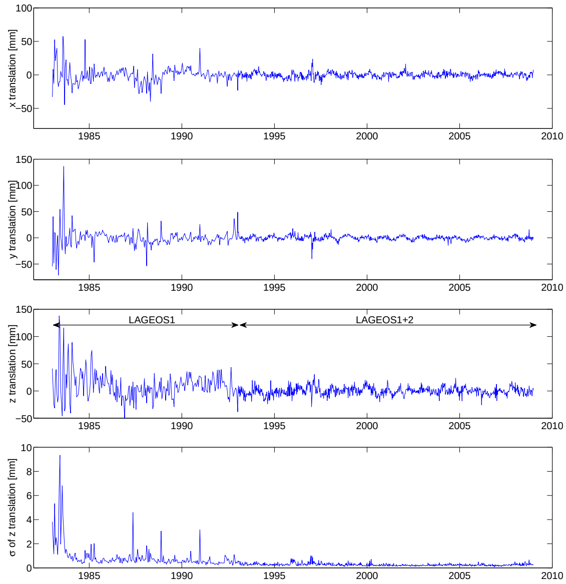

Fig. 7 Weekly translation of SLR derived center of mass w.r.t. a linear in time and Earth's crust based frame. Additionally, standard deviations are given for the z-component.

that the origin realized from DORIS data is affected by deficiencies of solar radiation pressure modelling for the satellite which is confirmed by these results.

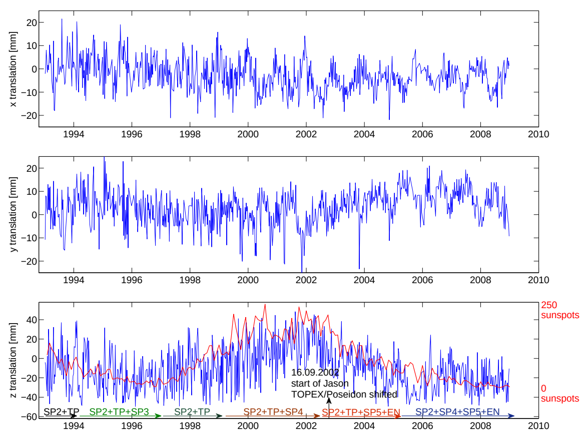

Fig. 8 Weekly translation of DORIS derived center of mass w.r.t. multi-year solution (blue). Number of sunspots (red). Given are also the satellite constellations. The abbreviations for the satellites are SP2, ..., SP5 (SPOT2, ..., SPOT5), TP (TOPEX/Poseidon), EN (ENVISAT). Note the different scales of the vertical axes.

4.2.2 Scale

Information about the scale is in principle provided by all the space techniques. But, because of the one-to-one correlation between GPS satellite antenna phase center offsets (SAOs) and the scale, the GPS scale was adapted to ITRF2005 in order to estimate the SAOs (*Schmid et al.*, 2007). Therefore, the scale information is not independent of ITRF2005 and correspondingly cannot be used for realizing the scale of ITRF2008 (*Ge et al.*, 2005). Fig. 9 shows the scale parameter time series obtained from the similarity transformation between SLR, VLBI and DORIS solution time series and the corresponding multi-year solutions. In case of SLR the same sine-wave-like feature during the years 1983-1992 as in the time series of the translation is visible. However, the influence on the realized mean scale is not significant. The same holds for the small drift in the early years of the VLBI time series. The DORIS time series shows a significant drift of about -0.28±0.01 ppb/yr (corresponding to -1.8 mm/yr at the Earth's surface) starting in 2001. The reason for this drift is unknown. Because of the drift, the DORIS scale is not reliable for ITRS realization.

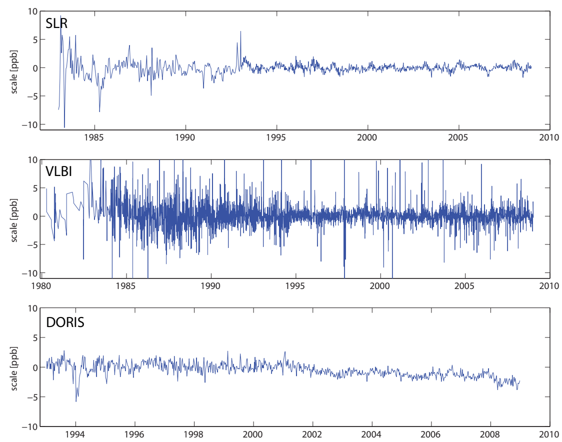

Fig. 9 Scale parameter time series derived from similarity transformation for SLR (upper plot), VLBI (middle plot) and DORIS (lower plot).

4.3 Generation of one normal equation system per technique

A normal equation system per technique is generated by accumulation of the time series of normal equation systems. Station velocities are set up as new parameters and discontinuities are considered by setting up new positions and velocities for the corresponding stations after the events. After a TRF solution per technique is computed, the velocities estimated for the individual solutions of one station were tested for significant differences. If they do not differ significantly ($< 3\sigma$), they are combined by applying constraints of the form

$vel_1 = vel_2$. In order to ensure the same variance level for all four techniques, variance components (VC) are considered. The estimation of the VC is described in paragraph 5.4.

5 Combination of the space geodetic techniques

The combination of the different space geodetic techniques is the most challenging step of the procedure. Common parameters, which can be combined directly, are only the EOP. The combination of the station networks becomes possible by introducing local difference vectors (local ties) between stations of different space techniques that are located close to each other (co-location sites). The distances could be a few kilometres in some cases but are usually shorter than one kilometre. In addition, station velocities at co-location sites are combined, provided that they do not differ significantly with respect to a 3-sigma criterion. Summarizing, the main steps of the inter-technique combination after the accumulation of the normal equation systems itself (see section 2) are (see also Fig. 1):

- Integration of local ties
- Combination of velocities
- Comparison and combination of the EOP
- Estimation of variance factors
- Datum realization

5.1 Integration of local ties

The local tie information is collected, prepared and provided by the ITRS Centre at IGN, Paris. It is available at http://itrf.ensg.ign.fr/local_surveys.php. The local tie measurements are performed partly by the local staff, see e.g. *Johnston and Dawson* (2004), *Sarti et al.* (2004) or by other groups, e.g. the IGN group which performed the measurements in Hartebeesthoek, South Africa (*Michel et al.*, 2005) and at other sites. Thus, the local tie measurements are done by different groups at different times (earliest in 1992) and were performed by applying different strategies. For about 50% of the local ties the full variance-covariance information of the adjustment of the local network is available. For the other local ties, the ITRS Centre added standard deviations depending on the length of the tie vector, and assuming a standard deviation of the station position of 3 mm (*Altamimi et al.*, 2002). Critical is the fact, that the information is based on experience but does not result from the analysis of the terrestrial measurements. Due to this situation, the local tie information is rather inhomogeneous. In order to provide the local tie information in a uniform format, local tie information not provided in SINEX files is transformed into SINEX format by the ITRS Centre (*Altamimi et al.*, 2011).

In order to ensure the local tie information to be as homogeneous as possible, the local tie vectors are used without the variance-covariance matrices within the combination. The advantages of doing so are:

- The impact of the local ties on the combined solution is more homogeneous. Considering the covariances provided for some of the ties means, that these ties have a smaller impact on the combined solution (as the components are not completely independent) than the other ties, for which no covariance information is available. This is further emphasized by the fact that the covariances are missing mainly for the older ties, that often do not fit as well to the space geodetic techniques as the more recent ones.
- For co-location sites with more than two stations, the vectors linking the different stations are handled individually within the combination, which cannot be done in the case of using the covariance matrices as they are given in the SINEX files.

Nevertheless, it is pointed out, that the availability of a homogeneous set of precise local ties with variance-covariance information is important for the computation of high-quality ITRF solutions in the future. In that case standard deviations derived from local network adjustments as well as correlations between the vector components could be considered correctly in the combination process.

In this context, the role of the local ties in ITRS realizations has to be discussed. At many co-location sites, local tie vectors and difference vectors derived from the space geodetic technique solutions differ by millimetres up to centimetres. Significant systematic differences can be caused by many reasons, e.g. systematic differences between the space geodetic techniques, induced for example by deficiencies of the applied reduction models. Alternatively, they can be measurement errors in case of the local ties themselves. Introducing the local ties with their estimated (or a posteriori assumed) standard deviations lead to a deformation of the combined network, affecting the station positions with the largest standard deviations mostly.

For example, for the VLBI-SLR co-location at site Monument Peak the absolute discrepancy between local ties and coordinate differences derived from space geodetic techniques is 93 mm; the standard deviation per local tie component is about 1.8 mm, the standard deviation of SLR station positions is below one millimetre per component and that of the VLBI station position is 10 to 20 mm per component. Introducing the local tie with the given standard deviation lead to a significant deformation of the VLBI network.

Consequently, a selection of local ties is necessary and appropriate standard deviations of the local ties must be found requiring that the change of the network geometry (deformation of the network) due to the combination shall be minimized. However, also a high consistency of the four network parts (GPS, SLR, VLBI and DORIS) of the combined frame w.r.t. the realization of origin, scale and orientation has to be ensured.

The pole coordinates as the only common parameters of all four techniques are a very reliable "measure" of the consistency of the combined frame, because of their one-to-one correlation to the orientation of the frame. Fig. 10 illustrates the relation between pole offset and local ties, which arises from the fact, that the orientation of two frames w.r.t. x- and y-axis can be combined twice: by the combination of the pole coordinates and by the combination of the station coordinates. Both links must be consistent. Consequently, when combining the station networks, but not the EOP, the mean offset between the estimated pole series shall become a minimum. The mean pole offset is computed by $\sqrt{\overline{\Delta x_{pole}}^2 + \overline{\Delta y_{pole}}^2}$. Summarizing the requirements, two criteria are formulated, based on which the most suitable set of local ties along with the corresponding standard deviations, applied for the local ties in the combination, are identified:

(1) the deformation shall be minimized by introducing a reasonable number of well distributed local ties and
(2) the consistency shall be maximized (equivalent to a minimized pole offset).

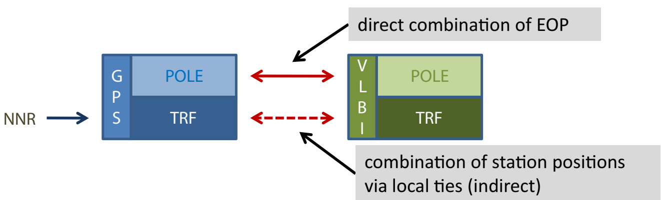

Fig. 10 Relation between combination of terrestrial networks and terrestrial pole coordinates for the example of combination of GPS and VLBI. The orientation of the GPS and VLBI frames w.r.t. x- and y-axis is combined twice: by the combination of the pole coordinates and by the combination of the frames. Both links must be consistent.

Fig.2 shows the global distribution of the station networks. It can be seen, that the station networks themselves as well as the co-location sites show a rather inhomogeneous distribution. Especially, in the southern hemisphere large regions with a sparse distribution of stations and/or co-location sites exist. Moreover, it becomes obvious from the figure, that GPS contributes to most (72%) of the co-locations and is therefore essential for the combination of the station networks of the different techniques. Fig. 11 shows a histogram of the number of the co-location sites per co-location type. Since most co-locations of SLR, VLBI and DORIS are to GPS stations, it is effective to start with the analysis of local ties for GPS-VLBI, GPS-SLR and GPS-DORIS combinations. In order to save CPU time and disk space, the analysis is done separately.

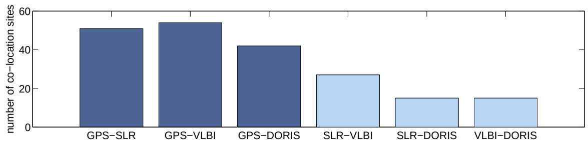

Fig. 11 Number of co-location sites for the different co-location types. Dark blue: co-locations with GPS, light blue: co-locations without GPS.

For each of the combination types about 70 test combinations are performed introducing different sets of local ties with different standard deviations. For this purpose, the EOP parameters are not combined. The deformation of the network caused by the combination was derived from seven parameter similarity transformations of the combined w.r.t. the single technique solutions: The obtained root mean square (RMS) of the station position residuals (after reducing the effect of transformation parameters) is a measure for the mean network deformation. The deformation of the GPS network is very small compared to the networks of the other techniques because of its large number of observations and the high station density. Thus, only the deformations of the VLBI, SLR and DORIS network are analysed.

Fig. 12 shows the deformation of the VLBI network and the pole offsets for the test GPS-VLBI combinations. Groups of local ties are defined according to the level of their discrepancy from the coordinate differences obtained from the comparison of single technique solutions. These groups of categories are shown in Tab. A.1 in the Appendix, and span discrepancy levels from below 6 mm to 44 mm, with several levels in between.

As discussed above the determination of the standard deviations applied for the local ties in the combination is also part of the local tie selection process. The local ties are introduced using standard deviations between 0.01 and 2.0 mm. From Fig. 12 it can be seen clearly, that there is a relation between the standard deviations of the local ties and the deformation of the network. Additionally, the deformation increases with the number of local ties included as it is expected. The pole offset also depend on the type of test solution: using only a few local ties on the one hand and a large number of local ties - fitting the coordinate differences of the space techniques only by several centimetres - on the other hand, results in an increase of the pole offsets by about 50 μas to more than 100 μas (∼3 mm). It is not possible to identify exactly one solution in Fig. 12 for which the deformation and the pole offset is a minimum, but small values are obtained for discrepancy levels of 28 mm up to 36 mm (max. 35 sites) and standard deviations for the local ties of 0.5-1.0 mm. It is decided to use the set of local ties selected with a discrepancy level of 32 mm (33 sites) adopting a standard deviation for the tie vectors of 0.5 mm. The pole offset is about 60 μas (1.8 mm) and the deformation is smaller than 0.2 mm. The test solution computed with a discrepancy limit of 14 mm (28 sites) shows also a comparable deformation and offset. However, five more co-location sites contribute to the selected solution (see Tab. A.1), which provides a more stable integration of the networks.

The analysis of local ties is performed for GPS-SLR and GPS-DORIS in the same way as for GPS-VLBI. The results are summarized in Tab. 5. It shows that a common discrepancy limit of 30 mm and a standard deviation of 0.5-1.0 mm are identified for all co-location types. A first combination of all techniques was done introducing the identified local ties with a standard deviation of 0.5 mm. Based on this solution, local ties between SLR, VLBI and DORIS stations were selected using also a discrepancy limit of 30 mm.

Fig. 13 gives the global distribution of co-locations sites used in DTRF2008. Most of them are located in Europe and North America, while only a few are available in other regions. The current situation is insufficient as the inhomogeneity might limit the consistency and accuracy of the combined frame. A more homogeneous distribution of local ties would be an important requirement for future ITRS realizations.

Besides the situation of co-location site distribution, there are existing co-locations for which local measurements are not or not completely performed. In Tab. 6 the numbers of missing ties per co-location type and per continent/region are given. The number of sites, where no alternative local tie of the same co-location type exists, provides the number of co-locations, where local tie measurements are most important. Tab. A.2 in the Appendix lists the relevant co-locations and gives information about the observation time spans of the installed instruments. Most of the stations provide long observation time series and thus a corresponding new local tie would contribute significantly to stabilize the terrestrial reference frame.

5.2 Combination of station velocities

The combination of station velocities of different techniques at co-location sites is a central task, as the evolution of the consistency of the combined frame depends on how carefully the velocities are combined. The velocities of co-located stations are in principle identical parameters. However, different observation time spans, a different temporal distribution of observations and possible local or instrumental effects might lead to differences in the velocities. Similar as for the selection of local ties a criterion is, that the deformation of the individual station networks due to the combination shall be minimal. In order to avoid deformations, only station velocities, which do not differ significantly, are combined. The velocities are combined using a constraint of the form $v_{\mathrm{tec1}}=v_{\mathrm{tec2}}$ (see also paragraph 4.1) which is introduced with a standard deviation of 0.1 mm/yr. Tab. 7 gives an overview of the number of co-locations for which velocities are combined. The classification in co-location types reveals that for co-locations of GPS, SLR and VLBI about 40% to 45% of the velocities can be combined. DORIS velocities agree best for co-locations with GPS: 33.3% of the velocities do not differ significantly. The deformation of the networks caused by the combination of the velocities is quantified by the RMS of station velocity residuals resulting from the transformation between the combined and the single-technique solutions. The values reach from 0.09 mm/yr for GPS up to 0.83 mm/yr for DORIS (see Tab. 8).

Table 7 Number of co-location sites for which velocities are combined.

techniques	number of canditates	combined	in percent [%]
GPS-VLBI	54	24	44.4
GPS-SLR	51	23	45.1
GPS-DORIS	42	14	33.3
VLBI-SLR	27	11	40.7
VLBI-DORIS	15	2	13.3
SLR-DORIS	15	4	26.7

5.3 Combination of the EOP

Since ITRF2005, EOP were included in the ITRF computations (*Altamimi et al.*, 2007). This provides clear

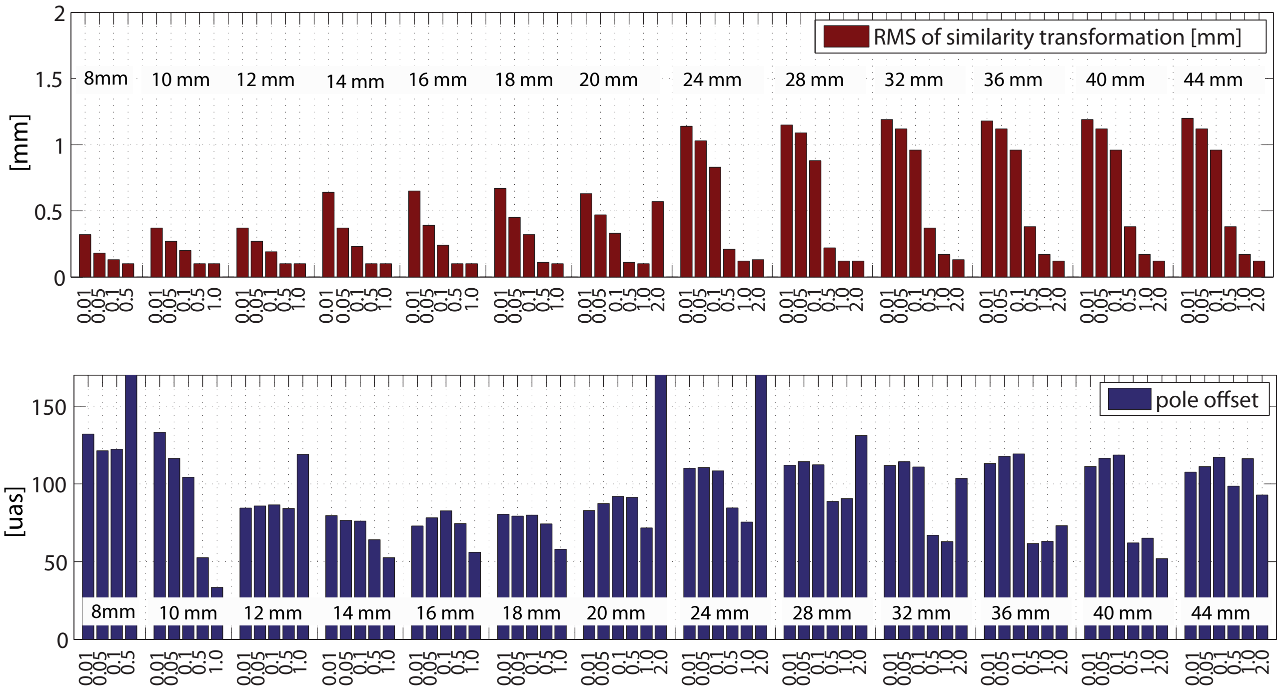

Fig. 12 Deformation of the VLBI network quantified by the RMS of the station position residuals resulting from the transformation between the combined and VLBI-only solution (upper plot) and mean offset of terrestrial pole (lower plot) for GPS-VLBI combinations using different sets of local ties and vary the standard deviations for the local tie vectors.

Table 5 Discrepancy limits and standard deviations used for local ties.

Techniques	limit of discrepancy [mm]	standard deviation for local tie vector [mm]	number of co-locations at which ties are introduced	number of ties
GPS-VLBI	32	0.5 - 1.0	33	97
GPS-SLR	30	0.5 - 1.0	30	117
GPS-DORIS	30	0.5 - 1.0	34	137
VLBI-SLR-DORIS	30		28	93

Table 6 Overview of missing local ties per co-location type. The numbers a/b/c are: a) number of missing ties, b) number of sites where ties are missing, c) number of sites where this type of tie does not already exist.

Continent/Region	GPS-DORIS	GPS-VLBI	GPS-SLR	VLBI-SLR	VLBI-DORIS	SLR-DORIS
Europe	6/3/0	7/4/2	13/8/2	7/3/2	4/2/2	/
Asia	/	9/7/5	9/8/4	4/3/3	/	1/1/1
Africa	4/2/0	/	2/2/2	/	1/1/0	1/1/0
North America	1/1/0	17/8/5	21/2/1	5/4/2	4/4/2	6/2/1
South America	5/4/0	/	1/1/0	/	/	2/2/0
Australia	/	1/1/1	2/1/0	/	/	3/1/0
Antarctica	/	1/1/0	/	/	/	/
Oceania	13/3/0	/	3/1/0	/	/	/

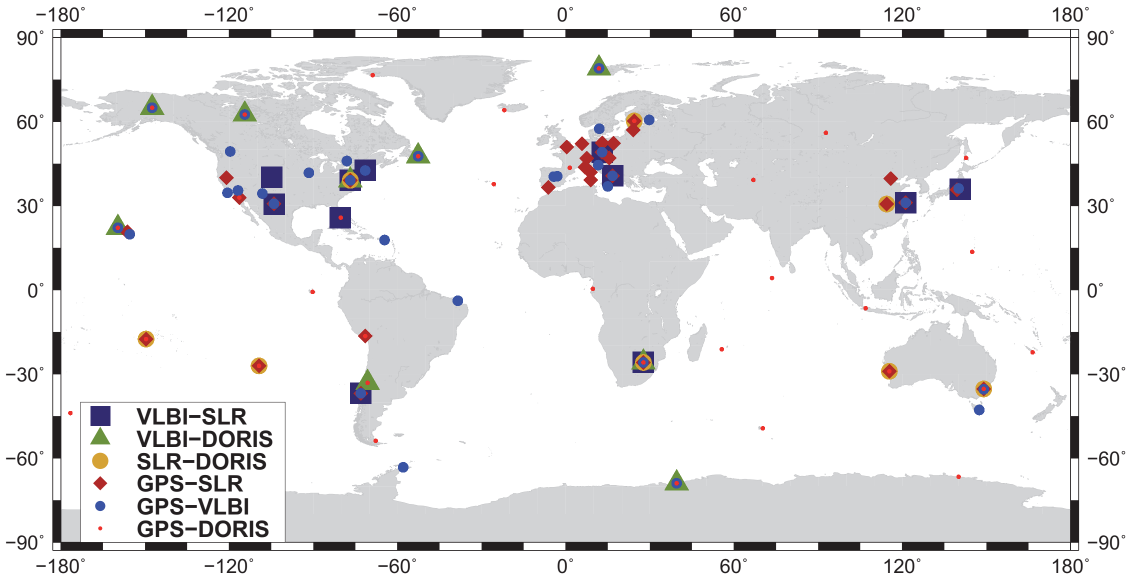

Fig. 13 Global distribution of the co-location sites used in DTRF2008.

Table 8 Mean deformation of the networks due to the combination of velocities. The deformation is quantified by the RMS values of the velocity residuals resulting from the transformation between the combined and the single-technique solution.

technique	mean deformation [mm/yr]
GPS	0.09
VLBI	0.02
SLR	0.40
DORIS	0.83

advantages in the development of the ITRF. As described above, the coordinates of the terrestrial pole are very reliable in order to verify the consistency of the combined frame. Furthermore, the combination of terrestrial pole coordinates can be considered as a "global tie". If the complete time series of pole coordinates are combined, this global tie is introduced at all epochs for which pole coordinates are available. The combination of LOD can be described as the combination of a global daily rotation w.r.t. z-axis of the ITRF. Finally, the common adjustment of the reference frame and a full set of EOP guarantees the consistency between all parameters.

The EOP available for the computation of ITRF2008 are listed in Tab. 4. In theory, UT1-UTC and nutation parameters can – in an absolute sense – only be provided by VLBI, the only technique which is directly linked to the inertial frame. The satellite techniques contribute to UT1-UTC and the nutation parameters only by their first derivatives in time (i.e. LOD and the nutation rates). The coordinates of the terrestrial pole as well as their rates can be estimated from the observations of all techniques.

Whereas the pole coordinates of the terrestrial pole are provided from all the technique input data contributing to ITRF2008, the corresponding pole rates are only provided by GPS and VLBI data. In case of LOD, only GPS, VLBI and SLR contribute. Different parameterizations are used for the techniques, that may also affect the combined EOP solution, so that systematics can occur between the techniques.

In order to decide, whether the EOP common to at least two techniques can be combined, they are investigated w.r.t. systematic differences. Fig. 14 shows for example the difference time series GPS-VLBI, GPS-SLR and GPS-DORIS for the x-component of the terrestrial pole. The WRMS values of all three difference time series are comparable and from a visual analysis no systematic effects can be identified, except of sawtooth-like features during the years 2001-2003 in the GPS-SLR plot and a sine-wave-like signal in the GPS-DORIS series between 2000 and 2003.5. For both effects the reasons are unknown. However, w.r.t. the WRMS values the systematics are not significant.

Fast Fourier analyses were performed for the difference time series. Amplitudes of up to 0.062 mas are found. The estimated amplitudes are significant and show, that systematic differences between the techniques in the order of 0.06 mas ($\sim$ 1.9 mm at the Earth's surface) do exist. As the differences are quite small, the pole coordinates are combined for all four techniques. However, the identification of the causing sources, e.g. different models or parameterizations used

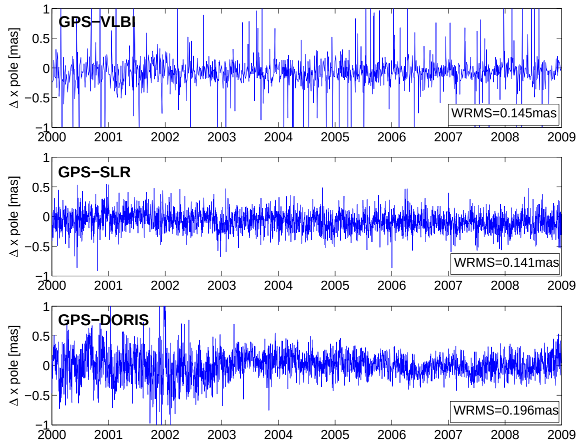

Fig. 14 Difference time series GPS-VLBI (upper plot), GPS-SLR (middle plot) and GPS-DORIS (lower plot) for the x-component of the terrestrial pole (2000.0-2009.0).

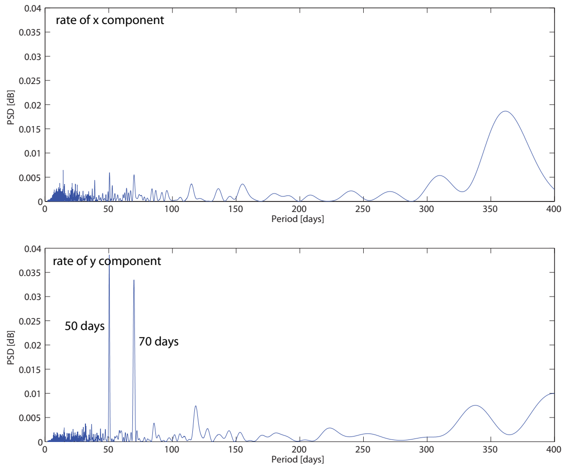

Fig. 15 Power spectra of the difference time series GPS-VLBI for the rates of the x- and y-component of the terrestrial pole.

for the techniques or effects related to orbit modelling, will be an important task in the future. So, e.g., the observed 120 day period of the GPS-DORIS series, clearly visible in the power spectrum given in Fig. A.1 in the appendix, might be related to deficiencies in solar radiation pressure modelling of the DORIS satellites (*Zelensky et al.*, 2010).

Rates of the terrestrial pole are only provided by GPS and VLBI. Fig. 15 shows the power spectrum of the difference time series. Whereas for the x-component a near annual signal with an amplitude of 0.06 ± 0.002 mas/d is dominant, the time series of differences of the y-pole shows clear periods of 50 and 70 days, related to GPS orbit characteristics (*Rodriguez-Solano et al.*, 2011). The amplitudes are 0.085 mas/d $\pm$ 0.006 and 0.078 mas/d $\pm$ 0.004 for 50 days and 70 days periods, respectively. Because of the significance of these signals, pole rates of GPS and VLBI are not combined in DTRF2008 solution, but reduced from the normal equation system by partial reduction (*Angermann et al.*, 2004).

LOD difference time series are analysed for differences between GPS, VLBI and SLR. Whereas for GPS-VLBI amplitudes of maximal 0.0083 ms ($\sim$3.6 mm at the Earth's surface) occur, the GPS-SLR and VLBI-SLR difference time series are affected by frequencies with amplitudes of up to 0.02 ms ($\sim$9.2 mm). Some of the frequencies found for the latter two difference series, are very close to tidal frequencies. So, the 13.653 days period might be related to O_1, 14.772 d to τ_1 and 9.127 d to Q_1. An additional comparison w.r.t. IERS 05 C04 (*Bizouard and Gambis*, 2009) gives the same results. It can be concluded, that LOD derived from SLR is affected by systematic signals. The correlation to some tidal frequencies is astonishing and has to be analysed in more detail. Because of the large amplitudes of the SLR difference time series, only the GPS and VLBI LOD are combined for the DTRF2008 solution, the LOD parameters from SLR are reduced.

5.4 Estimation of variance factors

For the combination of heterogeneous observation data of different space geodetic techniques, variance components have to be estimated in order to consider differences in the variance levels of the techniques. One approach is to estimate variance components directly within the combination adjustment by variance component estimation (VCE) (*Koch*, 1999). This approach, however, is problematic in terms of the available common parameters. Only the EOP and velocities at co-location sites (which do not differ significantly) can be combined directly and thus are considered as real common parameters. The number of combined EOP and velocities, however, is very different for each of the techniques. The contribution of the station positions to the variance components is very small, as they are combined indirectly via local ties, those residuals and a priori standard deviations play an important role and can dominate the variance factors. The main problem, however, is that errors in the stochastic models of each of the observation techniques cannot be considered by the classical VCE. Neglecting correlations between GPS observations lead to quite optimistic standard deviations of the GPS derived parameters. This is a well known problem (*Schön and Kutterer*, 2006), which cannot be compensated by the VCE.

In order to overcome this problem, variance components are estimated using an empirical approach based on the variation of the station position time series. The requirement is, that the formal errors σ_{est} derived for the station positions from the network adjustment per technique are the same as the standard deviations σ_{TS} of mean station positions derived from station position time series. The σ_{TS} for one station is computed by

$$\sigma_{\text{TS}} = \frac{\text{RMS}}{\sqrt{n}}, \tag{9}$$

wherein, RMS is the root mean square of the station position residual time series and n is the number of epochs. For the computation of the variance components, average values from subsets of good stations with long time series are used for σ_{est} and σ_{TS} in order to compute the variance components. Tab. 9 provides the results of the empirical variance component estimation.

Table 9 Computation of variance components.

technique	σ_{est} [mm]	σ_{TS} [mm]	VC=$\left(\frac{\sigma_{\text{est}}}{\sigma_{\text{TS}}}\right)^2$
GPS	0.17	0.29	0.34
VLBI	0.20	0.17	1.38
SLR	0.68	0.60	1.28
DORIS	1.19	1.17	1.03

While, the variance components of VLBI, SLR and DORIS are close to 1.0, GPS is down-weighted by a factor of 3. This is expected, because of the afore mentioned fact, that existing correlations between the GPS observations are not yet considered, as the computation of the correlations is very difficult (*Schön and Brunner*, 2008).

5.5 Datum definition - Analysis of datum parameters

The definition of the geodetic datum of ITRF follows the IERS Conventions (*Petit and Luzum*, 2010), see section 4.2. The origin of the frame is realized from SLR observations. The time series for SLR and VLBI derived scale are constant in time except for an annual signal and noise (see Fig. 9). However, the agreement of the scale information provided by SLR and VLBI has to be analysed. The limited number and sparse distribution of co-located SLR and VLBI stations, together with the local tie misfits, leads to an instability in a direct 14-parameter similarity transformation.

In order to overcome this problem, two approaches, labelled in the following as approach $\mathcal{A}$ and $\mathcal{B}$, are used in order to assess the agreement w.r.t. the realized scale. For approach $\mathcal{A}$ a GPS-VLBI and a GPS-SLR combined solution are computed, realizing the scale of the combined frame from the VLBI and the SLR observations, respectively. Then a transformation between the two solutions is performed estimating translation, rotation, scale parameters and their corresponding rates. The transformation was performed using a set of good and well distributed GPS stations. Thus, the loss of accuracy within the transformation step is very small. In order to assess the influence of the local ties – used for computation of the GPS-VLBI and GPS-SLR combined solutions – on the results, the scale parameter estimation was done three times, using three different standard deviations (2.0, 1.0 and 0.1 mm) for the local ties. The results are summarized in Tab. 10.

Table 10 Estimated scale differences between SLR and VLBI (approach $\mathcal{A}$) and the RMS values of the station position residuals resulting from similarity transformation between the combined and the technique only solutions.

	$\sigma_{tie} = 2$ mm	$\sigma_{tie} = 1$ mm	$\sigma_{tie} = 0.1$ mm
pos[ppb]	0.09 ± 0.02	0.31 ± 0.02	0.55 ± 0.02
vel[ppb/yr]	0.03 ± 0.001	0.03 ± 0.001	0.01 ± 0.001
RMS VLBI			
pos[ppb]	0.16	0.2	1.2
vel[ppb/yr]	0.04	0.04	0.22
RMS SLR			
pos[mm]	0.20	2.5	4.9
vel[mm/yr]	0.40	0.44	0.84

A second approach (approach $\mathcal{B}$) for estimating the scale difference is, to set up scale parameters within DTRF2008 for SLR, and realize the scale of the reference frame only from VLBI observations. The estimated SLR scale parameter gives the difference between the VLBI and the SLR scale. The same can be done vice versa, realizing the scale by SLR and estimating a VLBI scale parameter. The results must be the same, but with different signs. The results for this approach are given in Tab. 11. The standard deviation used for the local ties is 0.5 mm.

From approach $\mathcal{A}$ a scale difference between 0.09 and 0.55 ppb is estimated depending on the standard deviations used for the local ties. Applying a large standard deviation (that means, the station networks are deformed only slightly) the scale difference is small and increases if smaller standard deviations are used. The conclusion is, that the local ties contribute in part to

Table 11 Estimated scale differences between SLR and VLBI (approach $\mathcal{B}$). The standard deviation used for local ties is 0.5 mm as it is used for the DTRF2008 computation.

	VLBI w.r.t. SLR	SLR w.r.t. VLBI
pos[ppb]	0.54 ± 0.03	-0.55 ± 0.03
vel[ppb/yr]	0.000 ± 0.002	0.000 ± 0.008

the scale difference. Estimating the scale difference using approach $\mathcal{B}$, gives comparable results as the third solution type of approach $\mathcal{A}$ do. This is understandable as the standard deviations used for the local ties are small for both solutions.

As a conclusion, the scale difference between SLR and VLBI is between 0.09 ppb and 0.55 ppb. The uncertainty arises from the sensitivity of the scale realization w.r.t. the handling of the local ties and it is thus not fully reflected by the estimated standard deviations. Nevertheless, despite the high uncertainty, the scale difference of about 1.0 ppb found by *Altamimi et al.* (2011) is not confirmed by the results of the two approaches. The scale rate difference does not exceed 0.03 ppb/yr. As the mean difference derived from approach $\mathcal{A}$ is small (it corresponds to 2 mm at the Earth's surface), we conclude, that both techniques shall contribute to the realization of the DTRF2008 scale.

The orientation of DTRF2008 and its linear time evolution are realized by applying no-net-rotation conditions w.r.t. ITRF2005 using a subset of IGS05 stations.

The horizontal velocity field of DTRF2008 has a final net rotation of 0.06 ms/yr, which is obtained from an APKIM model computation based on the station velocities of DTRF2008. The same net rotation was estimated for ITRF2005, which was aligned to ITRF2000 (*Altamimi et al.*, 2002). The latter one was related to the plate kinematic model NNR-NUVEL-1A showing a net rotation of 0.01 ms/yr.

While NNR-NUVEL-1A is a geophysical plate model reflecting plate motions averaged over millions of years and considering only 12 rigid plates, the Actual Plate Kinematic Models (APKIM) provided by *Drewes* (2009b) are based on the velocities of geodetic observation stations. APKIM considers 17 rigid plates and additional deformation zones (e.g. Andes, Mediterranean, California, Asia) of the Earth's crust. The alignment of DTRF2008 to APKIM model would provide an reference frame without a net rotation integrated over the entire Earth surface (*Drewes*, 2009b). The DTRF2008 solution provided by the ITRS Combination Centre at DGFI for ITRF validation purposes was however aligned to ITRF2005 in order to ensure consistency with respect to the linear time evolution of orientation and hence of the EOP for DTRF2008 and ITRF2008.

6 Results

The DTRF2008 solution comprises station positions, station velocities, coordinates of the terrestrial and the celestial pole (nutation parameters), UT1-UTC and LOD. The reference epoch of the station positions is 2005.0. The results are available at the anonymous ftp server ftp.dgfi.badw.de/pub/DTRF2008 in different file formats. A short description of the solution files is also given there. In Fig. 16, as one example, the estimated horizontal station velocities are displayed.

In order to analyse the results w.r.t. consistency and accuracy, internal as well as external comparisons are performed for the station coordinates and the EOP.

6.1 Station coordinates and datum realization

One of the important criteria within the combination process is to minimize the deformation of the technique's individual station networks and to ensure a consistent datum realization. In order to investigate the final DTRF2008 solution w.r.t. both criteria, similarity transformations between DTRF2008 and the technique-specific TRF solutions are performed. Tab. 12, 13 and 14 summarize the results of the transformations.

Table 12 Translation parameters of DTRF2008 w.r.t. the SLR-only TRF solution.

technique		tx	ty	tz
SLR	pos [mm]	0.1 ± 0.21	-0.3 ± 0.21	0.2 ± 0.21
	vel [mm/yr]	0.1 ± 0.05	0.1 ± 0.05	0.1 ± 0.05

Table 13 Scale parameters of DTRF2008 w.r.t. the technique-specific SLR and VLBI TRF solutions.

technique		scale
SLR	pos [mm]	0.6 ± 0.21
	vel [mm/yr]	-0.1 ± 0.05
VLBI	pos [mm]	-0.1 ± 0.06
	vel [mm/yr]	0.0 ± 0.01

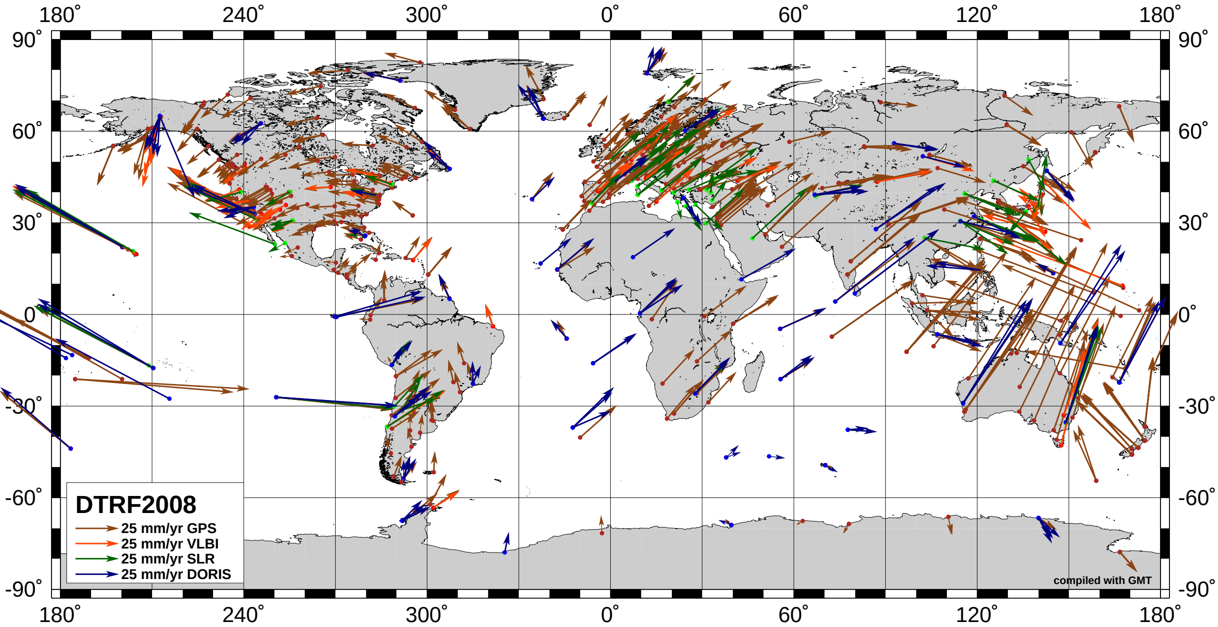

Fig. 16 Station velocities of DTRF2008.

Table 14 RMS values of all transformations of DTRF2008 to the technique-specific TRF solutions.

technique		RMS
SLR	pos [mm]	1.73
	vel [mm/yr]	0.39
VLBI	pos [mm]	0.32
	vel [mm/yr]	0.05
GPS	pos [mm]	0.60
	vel [mm/yr]	0.09
DORIS	pos [mm]	3.31
	vel [mm/yr]	0.83

Since SLR is defined to realize the origin of the frame, no translation parameters should be estimated for SLR. The translation parameters given in Tab. 12 are very small and not significant. The largest translation occurs with -0.3 mm for the y-component. The translation rates do not exceed 0.1 mm/yr and are also not significant. The scale parameters estimated for SLR and VLBI are given in Tab. 13). Whereas the scale difference in case of VLBI is very small and not significant, a small but significant scale factor for SLR of 0.6 *mm* is estimated. On the one hand, the scale parameters confirm the results of the scale analysis in paragraph 5.5, showing that no significant scale difference between SLR and VLBI exist, that affects the DTRF2008 strongly. However, the small scale change of SLR can be caused, either by small scale differences between SLR and VLBI or by the introduced local ties, as also discussed in paragraph 5.5.

The RMS values of station position residuals resulting from the transformations, given in Tab. 14, are a measure of the network deformations and reflect at the same time the internal accuracy of the DTRF2008. Whereas the geometry of the GPS and VLBI networks changes marginally, the SLR and DORIS are affected more. The reason is the lower precision of the SLR and DORIS station coordinates (see Tab. 9).

The consistency of the DTRF2008 network could be validated by precise orbit determination for satellites co-locating GPS, SLR and DORIS (e.g. Jason-2), or at least two of the techniques. In the next years, the IERS will focus on the development of appropriate validation procedures taking advantage of the potential of co-location satellites.

6.2 Earth Rotation Parameters

The temporal resolution of the estimated EOP time series is given in Tab. 15. It varies in time, according to the availability and the resolutions of the input data (see Tab. 4).

Fig. 17 shows the DTRF2008 as well as the technique-specific EOP time series w.r.t. IERS 05 C04. The corresponding WRMS values are given in Tab. 16. For the components of the terrestrial pole the combined solution shows a smaller scatter w.r.t. IERS 05

Table 15 Temporal resolution of DTRF2008 EOP time series.

parameter	time span	temporal resolution	contributing techniques
coordinates of the terrestrial pole and LOD	1980.0 - 1983.0	session-wise	VLBI
coordinates of the terrestrial pole and LOD	1983.0 - 1993.0	3-daily, additional session-wise	SLR and VLBI
	1993.0 - 2009.0	daily	GPS, SLR, VLBI and DORIS
UT1-UTC and nutation parameters	1983.0 - 2009.0	session-wise	VLBI

C04 as VLBI, SLR and DORIS do. In contrast, GPS shows a smaller variation w.r.t. IERS 05 C04 than the combined series. The scatter of the DTRF2008 series is about twice of the GPS one. This could result from the fact, that the terrestrial pole coordinates of IERS 05 C04 series are dominated by the contribution of the GPS solutions, whereas the GPS contribution was down-weigthed in DTRF2008 as described in paragraph 5.4. In case of UT1-UTC and LOD the DTRF2008 shows a marginally smaller scatter w.r.t. IERS 05 C04 than the technique-specific solutions. The UT1-UTC parameters, which are derived from VLBI observations only, benefit from the LOD combination. For the nutation parameters marginally larger variations for the DTRF2008 solution exist.

The offsets of the DTRF2008 EOP w.r.t. IERS 05 C04 are small (see Tab. 17). That proves the high consistency of DTRF2008 and ITRF2005 in terms of orientation, as IERS 05 C04 is aligned to ITRF2005 (*Bizouard and Gambis*, 2009).

Attention has to been drawn to the standard deviations of the terrestrial pole coordinates and of LOD, which are significantly affected by periodic signals. The standard deviations of the contributing GPS series show the same effect, as shown in Fig. 18 for example, for the x-component of the terrestrial pole.

Table 16 Weighted RMS values of technique-specific and combined EOP time series w.r.t. IERS 05 C04.

parameter	technique	WRMS
x-component of the terrestrial pole [mas]	GPS	0.0630
	VLBI	0.1630
	SLR	0.2051
	DORIS	0.2336
	DTRF2008	0.1225
y-component of the terrestrial pole [mas]	GPS	0.0549
	VLBI	0.2316
	SLR	0.2040
	DORIS	0.3569
	DTRF2008	0.1215
LOD [ms]	GPS	0.0224
	VLBI	0.0274
	DTRF2008	0.0215
UT1-UTC [ms]	VLBI	0.0127
	DTRF2008	0.0120
X-component of the nutation [mas]	VLBI	0.0624
	DTRF2008	0.0645
Y-component of the nutation [mas]	VLBI	0.0738
	DTRF2008	0.0769

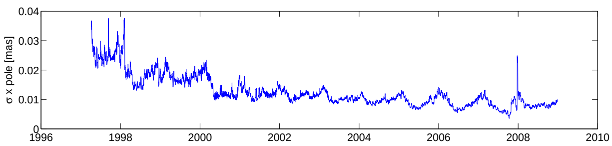

Fig. 18 Standard deviations of the x-component of the terrestrial pole derived from GPS.

In order to investigate the periodic signals, the variance factors applied for the Analysis Centres (AC) contributions within the IGS weekly combination are analysed. They are extracted from the summary files of the weekly IGS combination, provided together with the weekly combination products of IGS (ftp://cddis.gsfc.nasa.gov/gps/products/$week/). The variance factors are displayed in Fig. 19. For nearly all the contributions also for those with small variance factors (corresponding to a high weight in the combined solution) periodic signals are found. It is remarkable, that the signals of the different AC are more or less in phase. That means, the agreement of the AC solutions have a periodic variation. In order to investigate the frequencies in more detail, a fast Fourier transform of the standard deviations of the x-component of the terrestrial pole (see Fig. 18) is performed. The amplitude spectrum is given in Fig. 20. The dominant periods are close to one year, half a year and 7 days. Signals with periods of 50 and 70 days, which could be expected from the known deficiencies in GPS orbit modelling (*Rodriguez-Solano et al.*, 2011) are also detected. However, the amplitudes are small compared to the annual and semi-

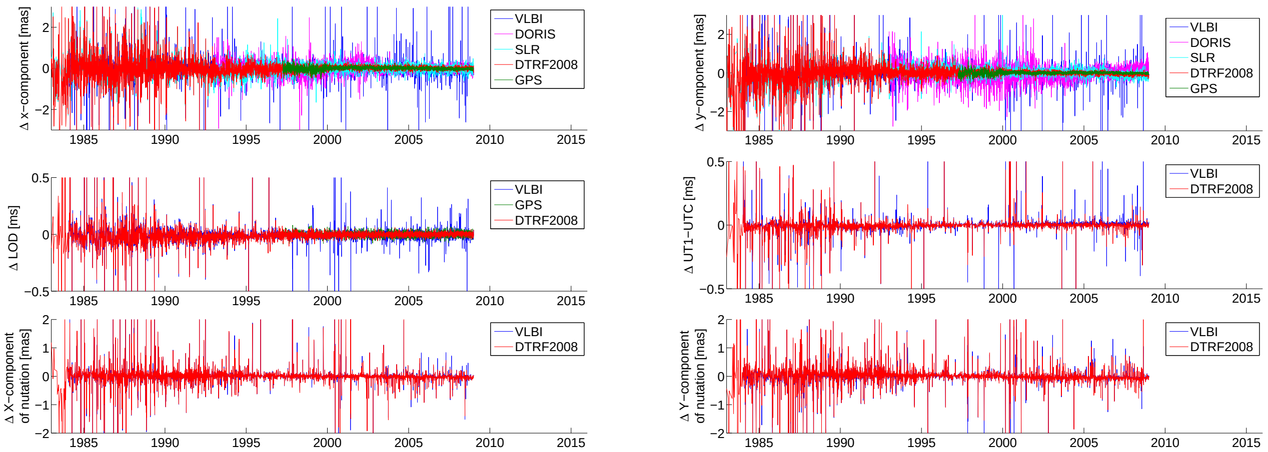

Fig. 17 Time series of EOP derived from technique-specific solutions as well as from DTRF2008 w.r.t. IERS 05 C04. Time series are plotted starting at 1983.0; the very noisy part of the series from 1980.0 to 1983.0 is ignored.

Table 17 Mean offsets of DTRF2008 EOP time series w.r.t. IERS 05 C04

parameter	offset
x-component of the terr. pole [mas]	-0.0265
y-component of the terr. pole [mas]	-0.0644
LOD [ms]	-0.0001
UT1-UTC [ms]	-0.0023
X-component of the cel. pole [mas]	-0.0091
Y-component of the cel. pole [mas]	-0.0047

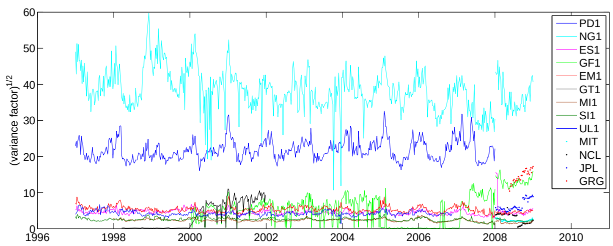

Fig. 19 Variance factors applied for the IGS AC solutions within weekly IGS combination (source: summary files of weekly IGS combination at ftp://cddis.gsfc.nasa.gov/gps/products).

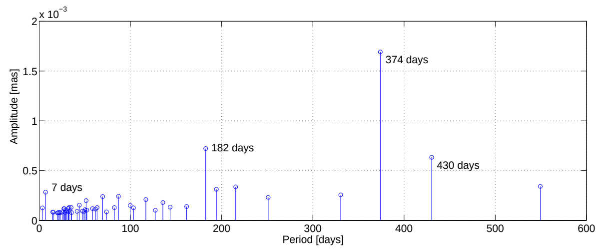

Fig. 20 Amplitude spectrum of the 50 dominant frequencies with periods up to 600 days.

annual signal. Besides the periodic signals also changes in the analysis and combination strategy are reflected in the standard deviations. So, for example the set up of a new analysis strategy at 01-01-2008 can be seen clearly. An effect on the EOP parameters themselves is not visible. But, in order to ensure high accuracy and consistency of the ITRS realization, the complete series of observation data must be processed homogeneously. Additionally, the systematic signals in the standard deviations of the EOP requires further investigation, that is outside the scope of this paper.

7 Comparison to ITRF2008

7.1 Station coordinates and datum parameters

The comparison of the DTRF2008 and the ITRF2008 (*Altamimi et al.*, 2011) provided by the ITRS Centre is a fundamental and important validation of the two realizations of the terrestrial reference system. Differences between both solutions allow for an investigation of the impact of differences in the computation strategies and at the same time they provide the basis for an assessment of the accuracy of the ITRF. The comparisons are done technique-wise by performing similarity transformations in order to investigate datum parameters and station coordinate residuals, separately. The results of the transformations at epoch 2005.0 are given in Tab. 18. With respect to the datum parameters, the two frames show an overall agreement of 5-6 mm. Although, the translations estimated between the SLR sub-networks of the networks are negligible, for GPS and DORIS a z-translation of -4.9 and -3 mm, respectively, exist. In case of orientation a systematic difference in y-orientation of -1.0 to -2.7 mm is found. Additionally, the orientation w.r.t. z-axis differs by 5.3 mm in case of VLBI, -3.3 mm for DORIS and 1.8 mm in case of SLR. The scale factors range from -2.9 mm (GPS) to about 3.2 mm (DORIS). Considering the time derivatives, the agreement is within 0.5 mm/yr, except of the z-translation of DORIS, which reaches 0.8 mm/yr. The agreement w.r.t. the datum parameters is quite good but millimetre accuracy is not achieved. The significant differences of up to 5 mm for translation and orientation, 3 mm for the scale and 0.5 mm/yr for the parameter rates reflect the accuracy of the ITRF2008 and DTRF2008 datum. The results show, that clear differences between the different technique-related parts of the network exist. Thus, the computation of one overall set of transformation parameters valid for all technique-related parts of the network is not allowed. For example, for SLR, which provides the origin of the frame, the translation parameters are small, in contrast to the other sub-networks (GPS, VLBI and DORIS), for which the SLR origin is adopted. The sparsely distributed co-location sites and the misfits between local ties and space geodetic techniques do not allow for a realization of the origin of a terrestrial reference frame to better than 5 mm.

The RMS values of the station position residuals after transformation, given in Tab. 18, express the agreement of the network geometries. The VLBI network shows the best agreement (0.38 mm). The largest discrepancies are obtained for DORIS (3.22 mm). In case of velocities the range is between 0.09 mm/yr for VLBI and 0.98 mm/yr for DORIS. The fact, that for station positions the agreement achieved for the network geometry is better than for the datum parameters, points out, that the datum realizations is a critical issue in the ITRF computation.

7.2 Earth Orientation Parameters

In Fig. 21 the time series of the EOP from DTRF2008 and ITRF2008 are compared. Nutation parameters are not included, as they are not provided in the ITRF2008 solution (*Altamimi et al.*, 2011). For the x- and the y-component of the terrestrial pole the agreement is quite good. The DTRF2008 series show a slightly larger noise for the time when GPS contributes (1997-2008). This might be attributed to the fact, that within DTRF2008 the GPS contribution was down-weighted by a factor of 0.34. In contrast for the ITRF2008 the GPS is weighted with a factor which is 4-5 times higher than those applied for SLR and VLBI (*Altamimi et al.*, 2011). As the IGS solution also contributes to IERS 05 C04 a good agreement is expected. The comparison of the UT1-UTC time series show mainly an offset of 0.01 ms ($\sim$4.6 mm at the Earths surface), which corresponds to the difference in orientation w.r.t. the z-axis of 5.3 mm estimated for the VLBI part of the network (see Tab. 18). The LOD time series shows a remarkable effect. The differences of ITRF2008 LOD w.r.t. IERS 05 C04 are small between the years 1995 and 2000 and increase from 1995 to 1983 and 2000 to 2009, respectively. This is not detected within the DTRF2008 series (Fig. 21).

The WRMS values of the difference time series DTRF2008-ITRF2008 are given in Tab. 19. For the x-component of the terrestrial pole and UT1-UTC the WRMS values are smaller compared to those derived for DTRF2008 - IERS 05 C04 in section 6.2 (Tab. 16). Especially for UT1-UTC, the WRMS becomes very small (0.0067 ms vs. 0.0120 ms), in case of GPS the WRMS is improved by a factor of two (0.060 mas vs. 0.123 mas). This can be attributed to the facts, that (1) the input data for both frames are the same and (2) UT1-UTC is derived only from VLBI observations (except of a small contribution of GPS via the combined LOD) and is thus not strongly influenced by the combination. The comparably large WRMS obtained for the difference series of the y-component of the terrestrial pole (WRMS=0.177 mas) seems to be caused by outliers which are not represented by correspondingly high standard deviations, as the RMS values of the x- and the y-component are of the same order of magnitude: 0.410 and 0.393 mas, respectively.

Table 19 WRMS and RMS of EOP difference time series (DTRF2008-ITRF2008).

parameter	WRMS	RMS
x-component of the terrestrial pole [mas]	0.060	0.410
y-component of the terrestrial pole [mas]	0.177	0.393
LOD [ms]	0.0421	0.1476
UT1-UTC [ms]	0.0067	0.0674

Table 18 Transformation parameters of DTRF2008 w.r.t. ITRF2008 (ITRF2008 minus DTRF2008) at the reference epoch 2005.0. Orientation and scale parameters are transformed into millimetres at the Earth's surface for reasons of comparison using a mean Earth radius of 6375 km.

technique		tx	ty	tz	rx	ry	rz	scale	σ	RMS
SLR	pos [mm]	-0.1	0.0	-0.3	0.5	-1.0	1.8	-2.0	0.33	2.02
	vel [mm/yr]	-0.2	-0.5	0.1	0.3	0.4	0.4	0.1	0.13	0.82
VLBI	pos [mm]	-1.8	1.3	-0.9	0.1	-1.3	5.3	2.1	0.08	0.38
	vel [mm/yr]	0.4	0.4	-0.1	0.0	0.0	-0.1	-0.1	0.02	0.09
GPS	pos [mm]	-1.1	0.1	-4.9	0.4	-1.3	0.1	-2.9	0.16	1.33
	vel [mm/yr]	0.1	-0.1	0.0	0.0	0.1	0.0	0.0	0.02	0.19
DORIS	pos [mm]	1.3	0.1	-3.0	0.0	-2.7	-3.3	3.2	0.49	3.22
	vel [mm/yr]	-0.1	0.4	0.8	0.0	0.0	0.0	-0.1	0.15	0.98

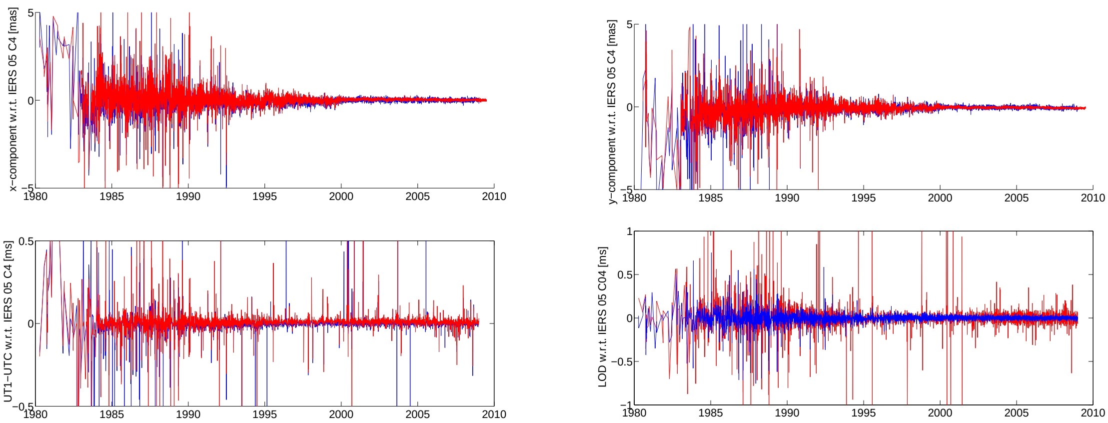

Fig. 21 Comparison of terrestrial pole coordinates, UT1-UTC and LOD of DTRF2008 (blue) and ITRF2008 (red).

8 Comparison to ITRF2005

Consistency between the subsequent ITRF solutions is required and stipulated in the IERS Conventions (*Petit and Luzum*, 2010). However, the input data used for the computation of DTRF2008 are improved compared to the ITRF2005 input data: the time series are extended by the data of the years 2006 – 2008 and several reduction models used for the analysis of the different space geodetic observations types are improved. Some of these modelling improvements are listed in Tab. 1. As a consequence, differences between DTRF2008 and ITRF2005 are expected.

Tab. 20 shows the parameters of a similarity transformation between DTRF2008 and ITRF2005 at the reference epoch of ITRF2005 (2000.0). In case of SLR the solution *ITRF2005 SLR rescaled* was used, for which the SLR network scale was adopted to the scale given by the SLR observations (http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005_SLR.php, 2011-01-18).

For the translations, the agreement is within 3 mm. The translation rates do not exceed 0.7 mm/yr. The orientation differs by a maximum of 3.3 mm. The rotations do not exceed 0.3 mm/yr, except for the rotations of DORIS network around the x- and y-axis. The scale factors derived from the four technique-related network parts differ strongly. For SLR no scale change is visible. The change in VLBI scale from ITRF2005 to DTRF2008 corresponds to a change in station heights of 2.6 mm. This is confirmed by the value of 2.5 mm given by *Böckmann et al.* (2010). They point out that the effect is caused by a change in the description of the mean pole within the pole tide model. Even if the model change does not induce a scale change by theory, the inhomogeneous distribution of VLBI stations causes that a scale differences is estimated applying a similarity transformation. This is strengthened by the fact, that the stations are affected by the model change very differently depending on their geographic coordinates. As the ITRF2005 scale was realized only by VLBI observations, this effect might also have an im-

Table 20 Transformation parameters of ITRF2005 w.r.t. DTRF2008 (DTRF2008 minus ITRF2005) at the reference epoch of ITRF2005: 2000.0. Orientation and scale parameters are transformed into millimetres at the Earth's surface for reasons of comparison using a mean Earth radius of 6375 km.

technique		tx	ty	tz	rx	ry	rz	scale	σ	RMS
SLR	pos [mm]	-1.0	-0.9	1.3	-0.6	1.3	3.3	0.0	0.93	3.11
	vel [mm/yr]	0.1	-0.7	0.5	0.1	-0.2	0.3	0.2	0.24	0.82
VLBI	pos [mm]	2.8	1.9	-0.4	0.1	-3.3	1.7	-2.6	0.35	1.8
	vel [mm/yr]	-0.2	0.4	-0.3	-0.2	0.2	0.1	0.3	0.06	0.33
GPS	pos [mm]	1.0	-0.2	1.8	0.0	0.0	0.0	-3.7	0.38	3.04
	vel [mm/yr]	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.04	0.34
DORIS	pos [mm]	0.4	0.8	0.3	1.7	-2.4	2.1	-4.0	0.91	6.02
	vel [mm/yr]	-0.3	1.0	0.5	1.2	-0.6	-0.3	-0.9	0.25	1.63

pact on the scale differences estimated for GPS and DORIS. It is not visible for SLR, as this was compared to *ITRF2005 SLR rescaled* . For GPS and DORIS very similar scale changes are estimated. This might be explained by the fact, that more than the double number of co-location sites of the type DORIS-GPS do exist, than of DORIS-SLR or DORIS-VLBI. Thus, the realization of scale within the DORIS part of the network is mainly based on the DORIS-GPS co-locations. In addition to the VLBI related scale change, the scale difference derived for the GPS part of terrestrial reference frame is mainly caused by the switch from relative to absolute antenna phase center corrections, which has an effect especially on the station heights (*Schmid et al.*, 2005). With respect to the datum parameters, DTRF2008 agrees with ITRF2008 in the same order of magnitude as with ITRF2005.

The RMS values of transformation residuals, reflecting the change of network geometry, range from 1.8 mm for VLBI to 6.0 mm for DORIS. The RMS values of the velocities are between 0.33 mm/yr for VLBI and 1.63 mm/yr for DORIS. These differences in the network geometry are significantly larger than for the comparison of DTRF2008 and ITRF2008 and may be mainly attributable to improvements of the reduction models since 2005 and the extension of the observation time series .

9 Discussion and Conclusions

The ITRS realization provided by DGFI, named DTRF2008, is presented in this paper. It is available in different file formats at the anonymous ftp server ftp.dgfi.badw.de. The computation strategy followed by DGFI is based on the combination of normal equation systems and differs from the methodology applied at IGN (*Altamimi et al.*, 2011), which is based on the combination of solutions. The availability of independent solutions from two ITRS Combination Centres allow a validation and an accuracy assessment of ITRF2008.

The EOP are an important parameter group within the reference frame computation. The coordinates of the terrestrial pole are parameters common to all techniques. Their combination provide an additional link between the techniques and serve as a global two dimensional tie. It is demonstrated in the paper that the pole coordinates can be used to measure the consistency of the DTRF2008. This potential of the pole coordinates is very useful in the combination process, especially for the task of the local tie selection.

In DTRF2008 computation, the global reference frame and EOP are determined in a single adjustment. This ensures consistency of the estimated parameters.

The ITRS realizations, DTRF2008 and ITRF2008, are performed using state-of-the-art solution set ups, starting with the analysis of the observation data and ending with the combination methods. It is the most accurate, consistent and long-term stable global terrestrial reference frame available. The comparison of DTRF2008 and ITRF2008 provide an accuracy of 2 – 5 mm and 0.1 – 0.8 mm/yr for the datum realization (reflected by the transformation parameters) depending on the technique. The network geometry agrees within 2 mm and 0.8 mm/yr, except of the DORIS part for which 3.2 mm and 1.0 mm/yr are estimated. The comparison of DTRF2008 and ITRF2005 provides similar values for the datum parameters. Comparable values are given for ITRF2008 by *Altamimi et al.* (2011). The network geometry agrees within 2 – 3 mm and 0.3 – 0.8 mm/yr for GPS, VLBI and SLR. For the DORIS part of the networks, an agreement of 6 mm and 1.6 mm/yr was derived. These differences may be mainly attributable to improvements of reduction models since 2005.

The internal accuracy of DTRF2008 station positions is between 0.32 mm for the VLBI and 3.3 mm for the DORIS network part. The internal accuracy of the station velocities ranges from 0.05 mm/yr for VLBI to 0.83 mm/yr for DORIS. The internal consistency of DTRF2008 w.r.t. orientation, derived from the analysis of the terrestrial pole coordinates analysed within the local tie implementation process, is estimated with 1.5 – 2.5 mm for the GPS, VLBI and SLR parts of the network. The consistency between these three and the DORIS network part is within 6.5 mm.

Despite the high accuracy of the current ITRS realizations, some deficits still exist:

- The input data of ITRF2008 are the time series of epoch solutions provided by the Technique Centres of the services IGS, IVS, ILRS and IDS. While IVS provides free normal equation systems, IGS, ILRS and IDS deliver weekly solutions. The conditions used for the computation of these weekly solutions are not provided in the SINEX files. If loose constraints are applied, they can be neglected. But if other conditions are used, the singularity w.r.t. datum parameters must be reconstructed by extending the NEQ by the parameters of a similarity transformation. Because a deformation of the solution shall be avoided, it must be guaranteed that minimum constraints are applied for the generation of the input solution series. Even, if this is done by the Technique Centres, the storage of the used conditions in the SINEX files would be useful as the original free NEQ can be reconstructed and the set up of datum parameters will become unnecessary.
- The input data of ITRF shall be consistently parameterized. The problem of inhomogeneity occurs for the EOP, which are common parameters of the techniques. However, the EOP are parameterized in different ways, so that they are, strictly speaking, not identical parameters. A homogenization of the input data by using common analysis standards would be highly desirable.
- For some of the parameters, significant signals are found which may be related to deficiencies in orbit, station position or stochastical modelling. The effects should be studied in more detail by the respective Technique Centres in order to ensure a high accuracy for future ITRF solutions.
- Seasonal signals in station positions, mainly caused by atmospherical and hydrological mass load changes, are not yet considered in ITRF computations, even if they are significant for many sites. Currently available geophysical loading models do not allow a reduction of the signal with an accuracy of 1 mm or better. Therefore, much scientific effort is undertaken to find optimal ways to evaluate the seasonal signals, e.g. by the IERS Special Bureau for Loading (SBL) (*VanDam et al.*, 2002), one of the Special Bureaus of the Global Geophysical Fluid Center (GGFC) (http://geophy.uni.lu/). The SBL is focussing on providing a consistent and accurate prediction of the deformation of the solid Earth due to loading of the atmosphere, ocean and terrestrial hydrosphere. A sophisticated and validated strategy for the reduction of seasonal signals must be developed for the improvement of the ITRS realizations.
- There is only a limited number of well distributed good co-location sites, especially in the southern hemisphere and also in Central Africa. The installation of new co-location sites linking all techniques would provide a more homogenized distribution. This would lead to an improvement of the ITRF in terms of stability, accuracy and consistency and provide the option for validating existing co-location sites.
- The local tie information currently available is rather inhomogeneous. While for about 50% of the sites the full information of the local network adjustment is available, the local tie information at other co-location sites consists of the local tie vectors only. The corresponding standard deviations are derived by empirical assessment based on the length of the tie vectors. This is inadequate for high ITRF quality and the re-measurement or re-adjustment of the local networks at the most important co-location sites (sites in sparsely covered regions with long observation time spans) is required for future improved ITRS realizations.
- A comparison of the solutions of space geodetic techniques and the local ties shows residuals of up to a few centimetres. There are several reasons for these large discrepancies. Besides the uncertainties of the local ties, modelling differences or measurement errors can also be obvious sources of discrepancies. Alleviating the discrepancies will contribute to an improvement of the ITRF.
- The rotation of the ITRF is now realized by aligning the ITRF2008 w.r.t. ITRF2005 applying a no-net-rotation condition. This ensures consistency between the subsequent frames. However, ITRF2008 velocities show a net rotation w.r.t. the entire Earth's crust. The application of a plate kinematic model which is based on the present-day velocity field of geodetic observing stations, like APKIM, would allow for the realization of a velocity field

free from net rotations, at least for the time-frame of the observation techniques.

The above accuracy discussion of ITRF2008 shows that the requirements of GGOS (less than 1 mm and 0.1 mm/yr for station positions and velocities, respectively) are not yet achieved. The non-linear behaviour of station positions is the main challenge for the future and therefore, the seasonal variations of station positions have to be considered in subsequent ITRS realizations.

The current situation in the central part of South America and in the Japan region (including Korea and parts of China and Russia) shows an even larger problem of the ITRF. The earthquakes occurring on February 27, 2010 in Chile and on March 11, 2011 in Japan affect the ITRF stations in these regions (for South America see http://www.sirgas.org). The co-location site Concepcion, the most important co-location site in South America, was displaced by about 3 m, as the epicenter was very close to that station. The post-seismic relaxation process now dominates the station movements in this region and it will need some years until the stations will return to a linear movement. The situation in Japan is similar. The consequence is, that ITRF2008 is not applicable in those regions for the next years. Thus, the potential of time series of weekly or monthly global reference frames (epoch reference frames), which are aligned to the ITRF, should be investigated.

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A Appendix

Table A.1 Overview of the levels of discrepancies between local ties and the coordinate differences obtained from the comparison of single technique solutions for GPS-VLBI co-locations.

Continent/ Region	site	6mm	8mm	10mm	12mm	14mm	16mm	18mm	26mm	32mm	34mm	36mm	44mm
Europe	10317	x	x	x	x	x	x	x	x	x	x	x	x
	10402		x	x	x	x	x	x	x	x	x	x	x
	12350				x	x	x	x	x	x	x	x	x
	12351										x	x	x
	12711	x	x	x	x	x	x	x	x	x	x	x	x
	12717	x	x	x	x	x	x	x	x	x	x	x	x
	12734	x	x	x	x	x	x	x	x	x	x	x	x
	13407			x	x	x	x	x	x	x	x	x	x
	13420				x	x	x	x	x	x	x	x	x
	14201	x	x	x	x	x	x	x	x	x	x	x	x
	21605	x	x	x	x	x	x	x	x	x	x	x	x
Asia	21701												
	21704												
	21730	x	x	x	x	x	x	x	x	x	x	x	x
	30302	x	x	x	x	x	x	x	x	x	x	x	x
North	40101	x	x	x	x	x	x	x	x	x	x	x	x
America	40104						x	x	x	x	x	x	x
	40105				x	x	x	x	x	x	x	x	x
	40127		x	x	x	x	x	x	x	x	x	x	x
	40400												x
	40405							x	x	x	x	x	x
	40407												
	40408		x	x	x	x	x	x	x	x	x	x	x
	40420							x	x	x	x	x	x
	40424			x	x	x	x	x	x	x	x	x	x
	40440				x	x	x	x	x	x	x	x	x
	40442		x	x	x	x	x	x	x	x	x	x	x
	40451									x	x	x	x
	40456			x	x	x	x	x	x	x	x	x	x
	40465				x	x	x	x	x	x	x	x	x
	40477					x	x	x	x	x	x	x	x
	40497												
South	41602			x	x	x	x	x	x	x	x	x	x
America	41705											x	x
	41719			x	x	x	x	x	x	x	x	x	x
Caribic	43201		x	x	x	x	x	x	x	x	x	x	x
Australia	50103								x	x	x	x	x
	50116					x	x	x	x	x	x	x	x
Antarctica	66006					x	x	x	x	x	x	x	x
	66008			x	x	x	x	x	x	x	x	x	x
	sum	9	14	19	25	28	29	31	32	33	34	35	35

Table A.2 Missing ties at co-locations, where no alternative type-specific local ties exist.

Site	Name	State	Techniques	missed ties	observation time span	obervation time	number of epochs	station
10503	Metsahovie	Finland	PRL	ties to R	R 04:343 08:177	3.5	23	
					L 83:063 96:102	13.1	31	10503S001
					L 98:063 04:337	6.8	94	10503S014
					P 98:284 08:362	10.2	389	10503M005
					P 96:364 08:362	12.0	623	10503S011
12337	Simeiz	Ukraine	PRL	all	R 94:176 08:268	14.3	67	
					L 95:158 08:346	13.5	187	12337S003
					L 98:196 08:360	10.4	157	12337S006
					P 00:114 08:152	8.1	402	
12338	Badary	Russia	DR	DR	R 07:061 09:009	1.9	54	
					D 93:005 02:219	9.6	420	12338S001
					D 04:238 05:019	0.4	22	12338S002
12356	Golosiiv - Kiew	Ukraine	PL	PL	L 01:325 08:346	7.1	26	
					P 98:053 08:362	10.8	562	
21609	Kunming	China	PL	PL	L 00:306 08:339	8.1	54	
					P 98:165 08:362	10.5	541	
21611	Changchun	China	PL	PL	L 96:066 08:360	12.8	530	
					P 04:340 08:362	4.1	188	
21612	Urumqi	China	PRL	all	R 97:233 08:268	11.1	69	
					L 03:127 03:303	0.5	24	
					P 98:102 08:362	10.7	499	21612M001
					P 02:160 08:362	6.6	341	21612M003
21702	Mizusawa	Japan	PR	PR	R 93:196 06:285	13.2	18	21702S010
					R 03:141 08:108	4.9	34	21702S012
					P 02:062 08:159	6.3	291	
21731	Shintotsukawa	Japan	PR	PR	R 95:325 08:241	12.8	39	
					P 03:271 08:362	5.2	180	
21732	Chichijima	Japan	PR	PR	R 97:238 08:241	11.0	75	
					P 96:364 08:362	12.0	586	
21736	Ishigaki Shima	Japan	RL	RL	R 06:047 08:206	2.4	17	
					L 97:253 99:315	2.2	4	21736S003
					L 97:253 99:315	2.2	4	21736S005
21742	Aira	Japan	PR	PR	R 97:238 08:206	10.9	73	
					P 98:053 08:362	10.8	496	
21749	Tanegashima Is.	Japan	PL	PL	L 04:245 08:360	4.3	50	
					P 03:348 08:362	5.0	229	
40403	Palos Verdes	USA	PR	PR	R 83:317 90:037	6.2	7	
					P 96:364 00:001	3.0	154	
40419	Kodiak	USA	PR	PR	R 84:206 90:184	5.9	15	
					P 96:364 07:195	10.5	305	40433S001
					P 01:007 06:210	5.6	212	40433S003
40433	Quincy	USA	PRL	ties to R	R 82:295 90:282	8.0	31	
					L 83:003 97:128	14.3	383	40433M002
					L 83:213 84:299	1.2	10	40433M005
					P 96:364 08:362	12.0	566	
40437	Mammoth Lakes	USA	PR	PR	R 83:180 86:295	3.3	3	
					P 98:179 05:316	7.4	136	
40439	Owens Valley	USA	RL	RL	R 80:103 88:315	8.6	111	40439S002
					R 92:241 08:248	16.0	155	40439S006
					L 88:292 90:207	1.8	5	
40451	Washington	USA	PRLD	RD	R 83:123 92:169	9.1	31	
					R 93:118 06:340	13.6	60	
					D 00:187 08:359	8.5	425	
40473	Brewster	USA	PR	PR	R 93:112 08:248	15.4	164	
					P 01:315 08:362	7.1	369	
40497	Monument Peak	USA	PRLD	LD/VD	R 82:289 90:316	8.1	35	
					L 83:048 08:346	25.8	982	40497M001
					L 83:243 83:304	0.2	5	40497M002
					D 05:348 07:346	2.0	104	40497S008
					D 07:360 08:359	1.0	54	40497S009
50108	Parkes	Australia	PR	PR	R 92:145 08:177	16.1	18	
					P 06:197 08:362	2.5	128	

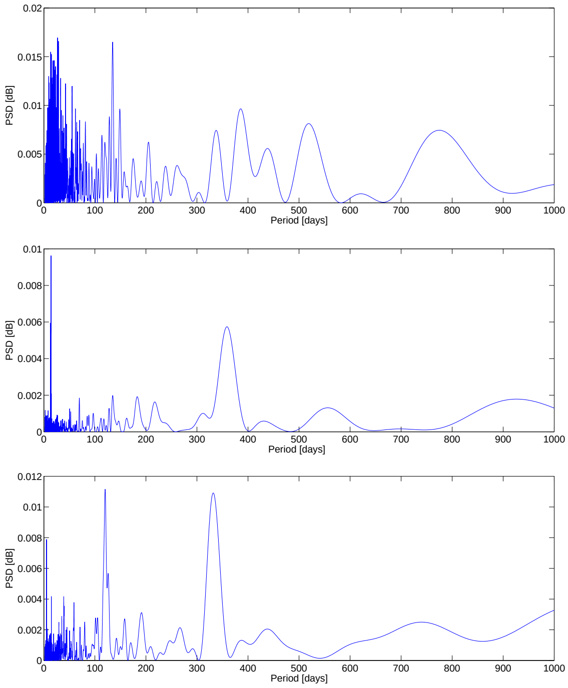

Fig. A.1 Power spectra of the difference time series GPS-VLBI (upper plot), GPS-SLR (middel plot) and GPS-DORIS (lower plot) for the x-component of the terrestrial pole.