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Symposium 134: Geodetic Reference Frames
Geodetic Reference Frames

IAG Symposium
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9-14 October 2006

Edited by

Hermann Drewes
President IAG Commission 1 “Reference Frames”
Geodetic reference frames are the basis for three-dimensional, time dependent positioning in all global, regional and national networks, in cadastre, engineering, precise navigation, geo-information systems, geodynamics, sea level studies, and other geosciences. They are necessary to consistently estimate unknown parameters using geodetic observations, e.g., station coordinates, Earth orientation and rotation parameters. Commission 1 “Reference Frames” of the International Association of Geodesy (IAG) was established within the new structure of IAG in 2003 with the mission to study the fundamental scientific problems for the establishment of reference frames. The principal objective of the scientific work of the Commission is basic research on:
- Definition, establishment, maintenance, and improvement of geodetic reference frames.
- Advanced development of terrestrial and space observation techniques for this purpose.
- Analysis and processing methods for parameter estimation related to reference frames.
- Theory and coordination of astrometric observations for reference frame purposes.

Additional objectives of the Commission are the international collaboration:
- For the definition and deployment of networks of observatories.
- With related scientific organizations, institutions, agencies, and IAG Services.

In order to review the status of the scientific work and to discuss the plans for future investigations, the Commission organized the IAG Symposium “Geodetic Reference Frames” (GRF2006). It was held in Munich, Germany, from October 9-14, 2006.

The programme of the Symposium was divided according to the Sub-commissions, Projects and Study Groups of Commission 1 into eight general themes:

1. Combination of space techniques
2. Global reference frames and Earth rotation
3. Regional reference frames
4. Interaction of terrestrial and celestial frames
5. Vertical reference frames
6. Ionosphere modelling and analysis
7. Satellite altimetry
8. Use of GNSS for reference frames

One day of the Symposium was dedicated to a joint meeting with the International Congress of Federación Internacional des Géomètres (FIG) and the INTERGEO congress of the German Association of Surveying, Geo-information and Land Management. The contributions presented at this meeting are integrated into these proceedings.

More than 160 scientists from 31 countries assisted the sessions. There were 74 oral presentations given and 40 posters shown during the five days of the Symposium. 49 of these papers were accepted for the proceedings. They shall resume the principal scientific outcome of the Symposium and give guidelines for the future.

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Session 1
Combination of Space Techniques
Convenor: M. Rothacher
Combination of Earth Orientation Parameters and Terrestrial Frame at the Observation Level


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Abstract. A rigorous approach to simultaneously determine both a terrestrial reference frame (TRF) materialized by station coordinates and Earth Orientation Parameters (EOP) is now currently applied on a routine basis in a coordinated project of the Groupe de Recherches de Géodésie Spatiale (GRGS). To date, various techniques allow the determination of all or a part of the Earth Orientation Parameters: Laser Ranging to the Moon (LLR) and to dedicated artificial satellites (SLR), Very Large Baseline Interferometry on extragalactic sources (VLBI), Global Positioning System (GPS) and more recently DORIS introduced in the IERS activities in 1995. Observations of the different astro-geodetic techniques are separately processed at different analysis centres using unique software package GINS DYNAMO, developed and maintained at GRGS. The datum-free normal equation matrices weekly derived from the analyses of the different techniques are then stacked to derive solutions of station coordinates and Earth Orientation Parameters (EOP). Two approaches are made: the first one consists to accumulate normal equations (NEQs) derived from intra-technique single run solution in a single run combined solution; the second one leads to weekly combinations of NEQs. Results are made available at the IERS site (ftp iers1.bkg.bund.de) in the form of SINEX files. The strength of the method is the use of a set of identical up-to-date models and standards in unique software for all techniques. In addition the solution benefits from mutual constraints brought by the various techniques; in particular UT1 and nutation offsets series derived from VLBI are densified and complemented by respectively LOD and nutation rates estimated by GPS. The analyses we have performed over the first four months of the year 2006 are still preliminary; they show that the accuracy and stability of the EOP solution are very sensitive to a number of critical parameters mostly linked to the terrestrial reference frame realization, the way that minimum constraints are applied and the quality of local ties. We present thereafter the procedures which were applied, recent analyses and the latest results obtained.

Keywords. Earth rotation, terrestrial reference frames, robust combination

1 Introduction

The reference EOP series computed at the Earth Orientation Centre at Paris Observatory provide the transformation between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). They are obtained from the combination of individual EOP time series derived from the various astro-geodetic techniques. Although the current determination of reference frames and EOP temporal series are both derived from the same observation processing, products are separately computed. The main consequence is that inconsistencies arise and increase with time. Since a few years, researches have been carried out to develop a more satisfying approach allowing a simultaneous determination of both station coordinates and EOP in order to ensure a global consistency between the EOP and both reference frames. Different approaches are now applied within the IERS. The first one is based on the combination of SINEX matrices derived from the intra-technique combinations provided by the international services, IGS, IVS, ILRS (Altamimi et al, 2002; Altamimi et al., 2005). An alternative approach is the combination at the observation equation level. Various investigations have been carried out (Andersen, 2000, Thaller et al., 2006). Our project is in the continuity of previous studies within the GRGS (Yaya, 2002; Gambis et al., 2006; Gambis et al., 2007, Coulot et al., 2007).
Observations of the different techniques are processed separately by the unique software package GINS/DYNAMO. The normal matrices derived from the analyses of individual techniques are stacked to give both the terrestrial frame materialized by station positions and Earth Orientation Parameters (EOP). In order to ensure both matrices invertibility and stability of solutions different types of constraints have to be taken into account.

2 Constraints

When solving for parameters, i.e. EOP and station coordinates, the normal equation matrices might not be invertible; it is then necessary to apply constraints. Two kinds of constraints can be applied in the procedure:

2.1 Minimum constraints

Minimum constraints concern transformation parameters: translation, rotation parameters and a scale factor. Their application allows to inverse normal equations matrices suffering from rank deficiencies and therefore is initially not invertible. The minimum constraints applied in the present analyses are translations and rotations in X, Y, Z for the VLBI, translation in Z and rotation in X, Y, Z for GPS and DORIS and three rotations for SLR. For more details about minimum constraints, see Sillard and Boucher (2001).

2.2 Local ties constraints

The combination of EOP and station coordinates derived from the various techniques requires a link between the terrestrial reference frames. This link is brought by local surveys at co-location sites where two or more techniques are simultaneously observing. Classical surveys are usually direction angles, distances, and levelling measurements between reference points of the instruments or geodetic markers. This is commonly referred to as local ties (3D coordinate differences between the reference points). Local surveys between the collocated instruments are performed by national geodetic agencies operating space geodesy instruments to provide local ties. An accuracy level of 1-2 mm is required for reference frames combination; however in reality estimates can reach several centimetres (Ray and Altamimi, 2005). A local tie file thus is derived from the computation of the ITRF (Altamimi et al, 2002). DYNAMO allows generating a normal equation matrix from such a local ties file. 23 selected “good” local ties constraints (associated to ITRF2000) were used in the present analyses. The co-location ties play an essential role within the inter-technique combination. Several studies emphasized the significant discrepancies between terrestrial geodetic surveys and those derived from space technique observations (Angermann et al. 2004, Ray and Altamimi 2005). The errors brought by the inaccuracy of ties propagate into the reference system and EOPs affecting their stability. In addition, errors are largely unpredictable since different subsets of ties are involved in the successive weekly solutions. In the present analyses, the limited number of local ties might not be helpful.

2.3 EOP continuity constraints

In addition, in order to stabilize the EOP time series and remove the short-term noise, continuity constraints on EOP have to be applied between successive weekly solutions. This leads to smooth the corresponding time series. EOP constraints values have been fixed to 1mm for all parameters according to different tests performed.

3 Data processing of the various techniques

We present thereafter the main characteristics and recent improvements of the processing concerning the different techniques involved in the combinations. The data processing is performed using the GINS DYNAMO package. The a priori dynamical and geometrical models used in the GINS DYNAMO include GRIM5-C1 gravity field model and the three body point mass attraction from the Sun, the Moon (in addition J2 Earth’s indirect effect) and planets. A priori models include: Earth tides, FES-2004 ocean tide, 6h-ECMWF atmospheric pressure fields, DTM94bis thermosphere model, albedo and infra-red grids from ECMWF, station coordinates derived from ITRF 2000, EOP from IERS C04 series.

In a first step GINS computes the residuals between the model and the measurements. An elimination procedure is firstly applied on outliers and then the partial derivatives of the estimated parameters are computed for the remaining measurements. Individual normal equations are then handled by the DYNAMO package allowing permutation, reduction, stacking, solving with
additional constraints on the chosen parameters. We give thereafter the basic characteristics of the study: the time span extends over the first four months of the year 2006. The parameters estimated are station coordinates and all EOP, i.e. polar motion, UT1 and nutation offsets. Polar motion is common to all techniques, UT1 and pole offsets are mainly determined by VLBI, whereas GPS contributes in the rates of these quantities. The estimation of tropospheric parameters is being gradually implemented in the processing of the various techniques.

3.1 Satellite Laser Ranging (SLR)

Observations of LAGEOS 1 and 2 satellites have been processed over 9-day arcs with 2-day overlaps. The network comprises about 30 observing stations. The final RMS values are in the range of 1 cm for both satellites. Weekly normal equations are derived relative to a range bias per week, per station and per satellite, station coordinates and EOP at 6-hour intervals. Final results are obtained with a two week delay. Two modifications were recently implemented: the use of the difference between the centre of reflection and the centre of mass as dependant of the type and power of the laser and the use of the tropospheric correction derived from ECMWF meteorological models. SLR observations are currently processed at GEMINI/ CERGA in Grasse, France.

3.2 DOPPLER Orbit determination (DORIS)

Satellites processed are SPOT2, SPOT4 and SPOT5. Recently the upgrade of the GINS software has permitted processing of ENVISAT and Jason observations with the right centre of phase correction. The effect of the South-Atlantic Anomaly was introduced as a model. Residuals are in the range of 0.4 mm/s. Fitted parameters include orbital elements, drag and solar pressure coefficients, tropospheric zenithal bias, frequency bias and Hill parameters. The application of the tropospheric correction derived from ECMWF meteorological models has lead recently to the suppression of the abnormal scaling factor in the network. DORIS observations are currently processed at CLS in Toulouse.

3.3 Global Positioning System (GPS)

Non differenced iono-free GPS data are processed over 2-day arcs with one day overlaps using elevation and azimuth depending on antenna patterns. Convergence residuals are about 5 mm for phase and 40 cm for range measurements. Orbits comparison with IGS gives a mean difference of 1 cm 3D-RMS; Note that the best IGS centers give an estimate smaller than 3 cm. The satellites or stations that exhibits large residuals are removed (main problems occurs during eclipsing satellites). GPS parameters, i.e. receiver and satellites clocks biases, real-valued ambiguities or satellite dynamical parameters such as initial state vector, solar drag scale factor Y-bias are reduced from datum-free normal equations before delivering. Future improvements (not in the present study) are to be implemented in the processing such as dynamical modelling of the solar radiation pressure force and double differences mode taking into account integer ambiguities (recent orbits comparisons indicate 6-7 cm 3D-RMS differences with IGS orbits). The GPS normal equations are today obtained with a delay between 3 and 9 weeks after the measurements. GPS data are currently processed at CLS in Toulouse.

3.4 Very Long Baseline Interferometry (VLBI)

VLBI data acquired on a regular basis by the International VLBI Service for Geodesy and Astrometry (IVS) are processed using the GINS software in order to estimate the Earth orientation Parameters (EOP) and station positions. These include both IVS intensive sessions (i.e. daily one-hour long experiments) and the so-called IVS-R1 and IVS-R4 sessions (i.e. two 24-hour experiments per week). The fact that intensive sessions are included in the data processing is for the sake of improving the global combination of all techniques and not in particular results concerning the VLBI technique. The free parameters include station positions and the five EOP along with clock and troposphere parameters. The clocks are modelled using piecewise continuous linear functions with breaks every two hours. The tropospheric zenith delays are modelled in a similar way except that breaks are applied every hour. The a priori terrestrial reference frame used is VTRF2005 (Nothnagel 2005) while the celestial frame is fixed to the ICRF (Ma et al. 1998, Fey et al. 2004). Overall, a total of 20 stations have been used in such sessions. The final post-fit weighted RMS residuals for the VLBI time delay is of the order of 30 picoseconds for the R1 and R4 sessions, and less for the intensive ones.
4 Combination

4.1 Strategy

The NEQ derived from the various analyses were handled using DYNAMO. In the first step parameters to be estimated, station coordinates and EOP are kept whereas “external parameters” like orbit elements tropospheric parameters, clock offsets, etc so far not combined are removed from NEQ. In the following analyses station velocities are held fixed to their ITRF values. We assume that this procedure is acceptable for such a short analysis time interval. NEQ are then stacked according to different following strategies. The first one considers intra-technique long term solutions stacked into a global combination; the second approach leads to a weekly resolution of the different techniques.

4.2 Single run solution

This solution is performed in two steps: the first one is the intra-technique single run stacking of NEQ. The four resulting intra-technique NEQ are then stacked into the single run NEQ combined solution.

4.2.1 First step: intra-technique solution

Weekly NEQ derived by the dedicated analysis centres are stacked for each technique to derive a single run solution. The mean measurement residuals lead to the determination of the weight of each technique in the global combination. The weighting procedure is based on the variance component estimation method as suggested by Helmert and described in Sahin et al. (1992). The weights determined in these analyses have been fixed in the operational combinations. The relative weights are used in the matrices combinations. They should be carefully considered since contributions to EOP and station coordinates are different according to techniques. For instance, VLBI is the only technique to determine both UT1 and nutation offsets where as satellite techniques can only bring some information on their respective rates. GPS-derived polar motion is more accurate. SLR brings a constraint in the long-term stability of the latter components. In addition, changes in the weights of the respective techniques can have significant effects on the final estimation quality.

4.2.2 Second step: inter-technique combination

The four intra technique NEQs derived over the four months are then accumulated into a single NEQ containing EOP at six-hour intervals. In this process local ties associated with ITRF2000 were considered. A global reference frame consistent with ITRF2000 is obtained, station positions rates being fixed to ITRF values in the process.

4.3 Assessment of the EOP solutions derived

EOP are computed with respect to the IERS EOP C04 (Gambis, 2004) used as the reference and corrected by the diurnal and sub diurnal model (Ray et al., 1994). Station position corrections are computed with respect to ITRF2000 positions (Altamimi et al., 2002) corrected with models from the IERS conventions (McCarthy and Petit, 2004). As previously mentioned, station velocity rates are held fixed to ITRF2000 values. Polar motion and UT1 are derived at 6-hour intervals whereas pole offsets are derived on a 12-hour basis. For the sake of comparisons, EOP sub-diurnal values are modelled by a piecewise linear fit to yield values at 0:00 hour. Table 1 shows for all EOP, statistics, biases and RMS relative to differences between intra-technique solutions and the combined single run solution “GRGS” derived from the stacking of individual intra technique NEQs with C04 used as the reference. EOP continuity constraints with values of 1mm are applied. The effect of the EOP continuity constraints leads to constrain the successive EOP determinations to remove the jumps due to instability in the weekly realizations of the terrestrial frames. Except for DORIS which presents high uncertainties, results are reflecting the accuracy currently reached by the different techniques. The combination process brings some slight improvement with respect to intra-technique results for all EOP. RMS values are still not at the level of accuracy of the best intra-technique estimates provided by international services and given in the last column of the table. This comes mainly from the fact our processing of the individual techniques observations need to be separately improved to match the best products given by GPS for polar motion and VLBI for UT1. Another reason is that the official IGS and IVS EOP series are combinations of several individual analysis centers contributions. Therefore, the
“analysis noise” is reduced and consequently the time-series becomes smoother.

Table 1. Bias (first line) and RMS (second line) of the differences between single run of individual techniques solutions on one hand and long term combined inter-technique solution on the second hand with IERS C04 over the four first months of 2006. Pole components are expressed in \( \mu \text{as} \), UT1 in \( \mu \text{s} \).

<table>
<thead>
<tr>
<th></th>
<th>DORIS</th>
<th>VLBI</th>
<th>SLR</th>
<th>GPS</th>
<th>COMB</th>
<th>GRGS</th>
<th>Best solution</th>
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<td>10</td>
<td>8</td>
<td>35</td>
<td>(IERS)</td>
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</tr>
</tbody>
</table>

4.4 Inter-technique weekly solution

Another strategy is to stack the NEQ derived per technique into a global multi-technique solution. In the process local ties are applied. This is assumed to ensure the continuity between the successive weeks. In order to inverse and solve the system, constraints on EOP continuity and minimum constraints on station positions have also to be applied. Daily EOPs at 0:00 h and weekly station positions are obtained using a linear piecewise fit.

Table 2 gives the statistics concerning the two approaches, single run and weekly solutions for polar motion and UT1 differenced with C04 used as the reference. Analyses were performed applying or not EOP continuity constraints. We can note the progressive improvement of the different solutions. The weekly solution with no constraints presents significant weekly jumps which are reduced when EOP constraints are applied. The significant bias in y-pole of about 200 \( \mu \text{as} \) proves that the solution is expressed in a system close to ITRF, this value being the present discrepancy between ITRF and the current C04 (Gambis, 2004). The alternative procedure based on single run intra-technique combination followed by the stacking of the different NEQ is performed as well with and without applying EOP constraints. The improvement is significant. Results obtained when EOP constraints are applied are comparable to the best solutions available. It appears that local ties always applied play a different role in the two procedures since in the case of weekly solutions, only a variable sub-set of ties is applied whose inaccuracies leads to propagate instabilities. Due to mis-modelling in the longitude of node or satellites orbits, it is well known that LOD values estimated from space satellite techniques are biased; this leads to single run errors in the integrated Universal Time UT1. The situation is similar for nutation. When calibrated by VLBI, LOD and nutation rates derived by GPS can be valuable in the combination (Gambis et al., 1993; Rothacher et al., 1999). This is apparently a difficulty in the UT1 and nutation combination as it was recently discussed by Ray et al. (2005). Still, the results we obtained show than the potential of VLBI is not degraded by the single run errors brought by GPS but it benefits from the stability of UT rates. Let us recall that VLBI intensive sessions are involved in the processing. Situation is similar for nutation. The same conclusion was given by Thaller et al. (2006).

Table 2. Statistics, bias (first line) and RMS (second line) of the differences of combined weekly and long term combined inter-technique solution with and without EOP continuity constraints with IERS C04 over January-April 2006. Pole components are expressed in \( \mu \text{as} \), UT1 in \( \mu \text{s} \).

<table>
<thead>
<tr>
<th></th>
<th>Weekly</th>
<th>Weekly</th>
<th>Single run</th>
<th>Single run</th>
<th>Best solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EOP cont</td>
<td>Single run</td>
<td>EOP cont</td>
<td>Single run</td>
<td></td>
</tr>
<tr>
<td>X-Pole</td>
<td>1</td>
<td>-6</td>
<td>-23</td>
<td>-23</td>
<td>(IGS)</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>87</td>
<td>114</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Y-Pole</td>
<td>214</td>
<td>209</td>
<td>213</td>
<td>203</td>
<td>(IGS)</td>
</tr>
<tr>
<td></td>
<td>123</td>
<td>99</td>
<td>119</td>
<td>74</td>
<td>40</td>
</tr>
<tr>
<td>UT1</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>(IERS)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

4.5 Assessment of the quality of the global reference frame derived

Weekly sets of station coordinates are expressed in a frame consistent with the ITRF2000 used as the reference. The quality of the multi-technique combined terrestrial reference frame (GRGS) depends on the relative qualities of the contributing solutions per technique as well as on the combination strategy which is applied. The overall quality indexes of the individual solutions included in the GRGS combination is given via the transformation components. Table 3 represents the transformation between these reference frames expressed in the form of mean translation, rotation and scale factor parameters of the single run solution. It gives the accuracy of the origin and scale. We can note the significant Tx value of about 2 cm with respect to ITRF2000 which is present in
all solutions. Large translations found in the results of VLBI may result from the fact that the a-priori TRF is VTRF2005 and not ITRF2000 on contrary to other techniques. Rotation angles are negligible as it could be expected. It appears that results concerning SLR and VLBI for the scale are significantly different from the other techniques.

Table 3. Reference frame. Mean values of the 7-parameter transformation with respect to ITRF2000 over the first four months of 2006. UNIT is cm. Standard deviations are given on second line.

<table>
<thead>
<tr>
<th></th>
<th>Tx std</th>
<th>Ty std</th>
<th>Tz std</th>
<th>Scale std</th>
<th>Rx std</th>
<th>Ry std</th>
<th>Rz std</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORIS</td>
<td>2.3</td>
<td>0.4</td>
<td>-3.6</td>
<td>-1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>GPS</td>
<td>0.3</td>
<td>0.5</td>
<td>2.1</td>
<td>0.17</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SLR</td>
<td>2.6</td>
<td>-1.3</td>
<td>1.7</td>
<td>-1.5</td>
<td>1.2</td>
<td>-0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>VLBI</td>
<td>0.2</td>
<td>0.4</td>
<td>2.0</td>
<td>0.7</td>
<td>0.9</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>COMBINED</td>
<td>1.5</td>
<td>-2.6</td>
<td>-3.6</td>
<td>1.1</td>
<td>0.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.7</td>
<td>2.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

5 Conclusions

The combination process based on datum-free NEQ is now done on a routine basis since the beginning of 2005 in a coordinated project within the frame of GRGS. The project is still in a research phase for the processing of individual techniques as well as for the final combination. We already demonstrated the good quality of the results for EOP as well as for station coordinates. The global combined solution benefits from the mutual constraints brought by the different techniques. Better results are expected after the improvement in the processing of the individual techniques. The strength of the method is the use of a set of identical up-to-date models and standards in unique software. In addition the solution benefits from mutual constraints brought by the various techniques; UT1 and nutation offsets derived from VLBI are constrained and complemented by respectively LOD and nutation rates estimated by GPS. Before EOP and station coordinates be derived on an operational basis with an optimal accuracy different problems have to be studied and solved. EOP and station coordinate solutions are sensitive to a number of critical parameters linked to the terrestrial reference frame realization mostly local ties whose errors propagate in an unpredictable way in the station coordinates and EOP series. We are here in a context of service oriented researches. This implies that we have to find and apply the optimal values for the critical parameters involved, minimum constraints for stations, EOP continuity constraints and techniques weights. This “tuning” is essential to provide consistent, accurate and stable products.

References


DGFI Combination Methodology for ITRF2005 Computation

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Abstract. In its function as an ITRS Combination Centre DGFI has computed a solution of the International Terrestrial Reference Frame 2005 (ITRF2005). It is based on the combination of epoch normal equations (weekly or session data sets, respectively) of station positions and Earth Orientation Parameters (EOPs) from the geodetic space techniques VLBI, SLR, GPS and DORIS. The procedure includes the datum free accumulation of technique-specific normal equations, the inter-technique combination using local tie measurements at co-location sites, and the computation of the ITRF2005 solution.

Key words: Terrestrial Reference Frame, combination methodology, ITRF2005

1 Introduction

The International Earth Rotation and Reference Systems Service (IERS) released in December 2004 a call to the international geodetic services for providing time series of solutions (or normal equations) of station positions and Earth Orientation Parameters (EOPs) for a new realization of the International Terrestrial Reference Frame 2005 (ITRF2005). The data should be epoch solutions (satellite observations weekly, VLBI session-wise) to allow detailed analyses, e.g., the detection of non-linear motions or discontinuities in the station coordinate series, and a rigorous combination. The common processing of time-dependent station positions and EOPs shall ensure the consistency of the terrestrial reference frame and the orientation of the Earth in space. The International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), and the International DORIS Service (IDS) provided corresponding data sets of the observations of the Global Positioning System (GPS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

Within the re-organized IERS structure, the Product Centre for the International Terrestrial Reference System (ITRS) hosted at the Institute Géographique National (IGN, France), is supplemented by ITRF Combination Centres, which have been established at Deutsches Geodätisches Forschungsinstitut (DGFI), IGN and National Resources Canada (NRCan). The ITRS Product Centre at IGN is coordinating the processing. DGFI and IGN computed one solution each for ITRF2005. Both used their own software and applied their preferred methodology. This guarantees independent results and allows a decisive validation and quality control of the results. A detailed description of the combination methodology of the ITRS Combination Centre at DGFI is provided in various publications (e.g., Angermann et al., 2004 and 2007; Meisel et al., 2005; Drewes et al., 2006).

2 Input data sets for ITRF2005

Table 1 summarizes the major characteristics of the ITRF2005 input data. For GPS, SLR and VLBI official single-technique combined solutions were submitted by the Technique Centres (TCs), namely NRCan for the IGS, the Institute for Geodesy and Geoinformation (IGG), University Bonn for the IVS, and the Agenzia Spaziale Italiana (ASI) for the ILRS. These solutions were obtained by combining the results of the services’ individual Analysis Centres (ACs). No combined DORIS solution was available by the IDS. Two solutions were submitted instead, computed by two ACs, namely the IGN in cooperation with the Jet Propulsion Laboratory (JPL) and the Laboratoire d’Études en Geophysique et Oceanographie Spatiale (LEGOS) in cooperation with Collecte Localisation par Satellite (CLS), designed hereafter by LCA.

Accompanied with the solutions the TCs/ACs
Table 1: Input data sets for ITRF2005 (NNT = no net translation, NNR = no net rotation, NNS = no net scale, NEQ = normal equations)

<table>
<thead>
<tr>
<th>Techn.</th>
<th>Service AC</th>
<th>Data</th>
<th>Time period</th>
<th>Parameters</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>IGS</td>
<td>Weekly solutions</td>
<td>1996 – 2005 since June 1999 since March 1999</td>
<td>Station positions EOP (pole rates, LOD) geocenter</td>
<td>NNT: 0.1 mm NNR: 0.3 mm NNS: 0.02 ppb</td>
</tr>
<tr>
<td></td>
<td>NRCan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLBI</td>
<td>IVS</td>
<td>Daily sessions free NEQ</td>
<td>1981 – 2005</td>
<td>Station positions EOP (pole, UT1 + rates)</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>GIUB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLR</td>
<td>ILRS</td>
<td>Weekly sol.</td>
<td>1993 – 2005</td>
<td>Station positions EOP (pole – LOD)</td>
<td>Loose</td>
</tr>
<tr>
<td></td>
<td>ASI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DORIS</td>
<td>IGN</td>
<td>Weekly sol.</td>
<td>1993 – 2005</td>
<td>Station positions EOP (pole, UT1 + rates)</td>
<td>Loose</td>
</tr>
<tr>
<td></td>
<td>LCA</td>
<td>Weekly sol.</td>
<td>1993 – 2005</td>
<td>Station positions EOP (pole)</td>
<td>Loose</td>
</tr>
</tbody>
</table>

provided a list with information about discontinuities (e.g., equipment changes, earthquakes) in station positions, which are used as input by the ITRS Combination Centres. Furthermore the ITRF2005 input data comprise the local tie information which was provided by the ITRS Product Centre.

3 Combination methodology

The general concept of the ITRS Combination Centre at DGFI is based on the combination of normal equations and the common adjustment of station positions, velocities and EOP using the DGFI Orbit and Geodetic Parameter Estimation Software (DOGS). The data flow and combination procedure is shown in Figure 1.

3.1 Accumulation of technique-specific time series

After a detailed analysis of the input time series data we generated epoch normal equations for each technique. As the resulting GPS normal equations were not singular, we reduced the a priori datum information by setting up seven Helmert-transformation parameters for each week since GPS should not contribute to the datum definition. For VLBI the free normal equations were used as they were provided by the IVS. In the case of SLR and DORIS normal equations were generated from the loosely constrained solutions. For each of the techniques we reduced stations with too few observations, which do not allow for a reliable estimation of station positions and velocities. The criteria for the reduction were: GPS and DORIS < 26 weeks, SLR < 13 weeks, VLBI < 4 sessions.

In the epoch normal equations velocity parameters were set up and then they were accumulated separately for each technique. Minimum datum parameters were added to generate technique-specific multi-year solutions with station positions, velocities and EOP. In the case of discontinuities reported by the Technique Centres new position and velocity parameters were set up for the corresponding stations. Time series solutions were computed by transforming them to the multi-year solutions. The resulting time series of station positions and datum parameters were analysed w.r.t. further discontinuities and non-linear effects. A few additional discontinuities were identified during the iterations and considered in the final accumulation.

Figure 2, as an example, shows the position time series for the height component of the GPS station HOFN, Iceland. A discontinuity in the station height of nearly 5 cm led to two different solutions on this station. As shown in Table 2 the velocity estimates of these two solutions differ by 4.2 mm/a. An important issue (also for many other stations with discontinuities) is the question, whether the estimated velocities for different solutions should be equated or not. For a decision based on statistical tests it is important that the standard deviations are realistic,
Accumulation of time series normal equations

Local ties → Inter-technique combination

ITRF 2005 solution

\[ \text{TRF}(x, v) + \text{EOP} \]

VLBI

SLR

GPS

DORIS

Multi-year NEQ

\[ \text{TRF}(x, v) + \text{EOP} \]

Figure 1: Data flow and combination procedure of the ITRS Combination Centre at DGFI.

Figure 2: Position time series for the height component of GPS station HOFN, Iceland.

which requires sophisticated weighting methods. Another problem is that for many stations the time series solutions are affected by annual signals which are also visible in Figure 2. Especially in short time intervals (e.g., < 2.5 years) annual signals may affect the estimation of positions and velocities (see Micsel et al., 2008).

The precision of repeated weekly (or session-wise) position estimates provides information to assess the internal accuracy of the solutions. The results obtained for the different space techniques using a subset of good reference stations for each space technique are summarized in Table 3.

Table 2: Vertical station velocity estimates of two solutions (before and after the jump) at GPS station HOFN, Iceland.

<table>
<thead>
<tr>
<th>Epochs JD2000</th>
<th>Velocities [mm/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sol. 1</td>
<td>-786.5 - 619.7</td>
</tr>
<tr>
<td>Sol. 2</td>
<td>627.5 - 1825.5</td>
</tr>
<tr>
<td>Sol. 2 - 1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Precision of repeated epoch station position estimates for different space techniques. Note: The epochs are daily sessions for VLBI and weekly solutions for the other space techniques.

<table>
<thead>
<tr>
<th>Techn.</th>
<th>TC/AC</th>
<th>North [mm]</th>
<th>East [mm]</th>
<th>Up [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>IGS</td>
<td>2.4</td>
<td>3.0</td>
<td>7.8</td>
</tr>
<tr>
<td>VLBI</td>
<td>IVS</td>
<td>6.7</td>
<td>6.9</td>
<td>12.5</td>
</tr>
<tr>
<td>SLR</td>
<td>ILRS</td>
<td>9.4</td>
<td>9.0</td>
<td>9.7</td>
</tr>
<tr>
<td>DORIS</td>
<td>IGN/JPL</td>
<td>24.3</td>
<td>32.3</td>
<td>22.5</td>
</tr>
</tbody>
</table>
3.2 Inter-technique combination

The input data for the combination of different techniques are the accumulated intra-technique (VLBI, SLR, GPS and DORIS) normal equations. The parameters include station positions, velocities and daily EOPs. Concerning the combination of EOPs from the different space techniques it has to be considered, that the VLBI estimates are referred to the midpoint of a daily VLBI session (from 17 h to 17 h), whereas the EOP values of the other techniques are referred to 12 h. The VLBI EOP estimates have therefore to be transformed to the reference epochs of the other techniques.

The connection of the different techniques' observations is given by local tie measurements between the instruments' reference points at co-location sites. This is a key issue within the inter-technique combination. As shown for example in Angermann et al. (2004) and (Krügel and Angermann, 2005) the selection of suitable local ties is difficult because the number and the spatial distribution of "high quality" co-location sites is not optimal. As the EOP estimates must be identical for all techniques their estimates are used to validate the selected local ties and to stabilize the inter-technique combination as additional "global ties".

Within the inter-technique combination the local tie selection and implementation as well as the equating of station velocities at co-location sites was done in an iterative procedure (see Krügel and Angermann, 2006). The quality of the selected local ties was analysed by using the following two criteria: (1) The mean offsets between the x-pole and y-pole estimates of the different techniques are a measure for the consistency of the inter-technique combination and should be minimized. (2) The deformation of the networks caused by the implementation of local ties and the equating of velocities at co-location sites should be minimized. This is expressed by the RMS of position and velocity differences between the single-technique solutions and the combined solution.

The results of this quality assessment show that the EOP estimates of the different space techniques agree well (Table 4) and that the network deformations caused by the local tie implementation are small. The RMS of the differences between the single-technique solutions and the combined solutions is 1 mm maximum for

<table>
<thead>
<tr>
<th>Technique</th>
<th>x-pole [mas]</th>
<th>y-pole [mas]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>SLR</td>
<td>-0.047</td>
<td>-0.024</td>
</tr>
<tr>
<td>VLBI</td>
<td>0.018</td>
<td>0.018</td>
</tr>
<tr>
<td>DORIS</td>
<td>0.116</td>
<td>0.142</td>
</tr>
</tbody>
</table>

Table 5: RMS of the differences for station positions and velocities between the single-technique solutions and the combined solution.

<table>
<thead>
<tr>
<th>Technique</th>
<th>positions [mm]</th>
<th>velocities [mm/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>SLR</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>VLBI</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>DORIS</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

station positions and 0.3 mm/a for velocities, respectively (Table 5).

Other problems to be solved in the combination procedure include the weighting of the different techniques and the equating of station velocities of co-located instruments. The weighting is done by estimating scaling factors for the normal equations based on the precision of repeated station positions for the different techniques. For the equating of station velocities at co-location sites, measures of the significance of estimated velocities of the different techniques were applied.

For the final inter-technique combination the pseudo-observations for the selected local ties and for the equated station velocities at co-location sites are added to the normal equations obtained from the individual techniques.

4 ITRF2005 solution of DGFI

To generate the final combined solution the datum parameters have to be added to the free normal equations and the complete normal equation system (size 27000x27000) has to be inverted. The origin (translations and their rates) is realized by the contributing SLR solutions and the scale and its time variation by SLR and VLBI.
The orientation of the ITRF2005 is realized by NNR conditions w.r.t. ITRF2000 using "good" reference stations. The time variation of the orientation is coupled with the station velocities. This kinematic datum is given by an actual plate kinematic and crustal deformation model (APKIM) derived from the observed station velocities. A new model (APKIM2005) was computed from ITRF2005 station velocities. It comprises 16 rigid plates of the PB2002 model (Bird, 2003) and 4 deformation zones (Alps, Persia-Tibet-Burma, Gorda-California, and Andes orogens). The rotation velocities of the major lithospheric plates (Africa, Australia, Eurasia, North and South America) are determined with a precision of ±0.03 mrad/Myr (see Drewes, 2008).

The primary results of the final ITRF2005 solution are station positions, linear velocities and daily EOP estimates. Epoch position residuals and variations of the network w.r.t. the geocentre are obtained by transforming the time series to the ITRF2005 datum. The reference epoch for station positions is 2000.0. The accuracy of station position and velocity estimates is in general very good, but it also reflects the rather inhomogeneous data quality and quantity of the space geodetic observations. This holds in particular for a number of SLR and VLBI stations, but also for some GPS and DORIS stations with few observations. Due to the use of weekly or session's input data with discontinuities in the coordinates' time series, many stations get various solutions. This implies that the station positions and velocities are valid only for a certain time period, which has to be known by the users. Furthermore co-location sites may have different station velocities for co-located instruments, if their estimated velocities differ significantly. Figure 3 shows the station velocities of the DGFI solution ITRF2005P.

5 Comparison of ITRF2005 solutions of DGFI and IGN

Two independent solutions of the ITRF2005 were computed by the two ITRS Combination Centres at IGN and DGFI. The combination strategy of IGN is based on the solution level by simultaneously estimating similarity transformation parameters w.r.t. the combined frame along with the adjustment of station positions and velocities (see Altamimi et al., 2007), which is different from the combination methodology applied

Table 6: RMS differences for station positions and velocities between the IGN and DGFI solution for ITRF2005 for "good" reference stations (25 VLBI, 22 SLR, 57 GPS, 40 DORIS stations).

<table>
<thead>
<tr>
<th></th>
<th>IGN - DGFI</th>
<th>VLBI</th>
<th>SLR</th>
<th>GPS</th>
<th>DORIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positions</td>
<td>[mm]</td>
<td>0.79</td>
<td>1.82</td>
<td>0.31</td>
<td>3.32</td>
</tr>
<tr>
<td>Velocities</td>
<td>[mm/yr]</td>
<td>0.34</td>
<td>0.66</td>
<td>0.14</td>
<td>1.11</td>
</tr>
</tbody>
</table>

at DGFI.

For comparisons we performed similarity transformations between both solutions. These transformations were done separately for each space technique by using "good" reference stations. Most of the transformation parameters agree within their estimated standard deviations, except for the scale and its time variation of the SLR network. A significant difference of about 1 ppb (offset) and 0.13 ppb/yr (rate) between the DGFI and IGN solutions has been found, which accumulates to nearly 2 ppb in 2006.

The RMS differences for station positions and velocities show a very good agreement (after similarity transformations). This holds in particular for "good" stations with several years of continuous observations without discontinuities (Table 6). For weakly estimated stations (e.g., observation time less than 2.5 years, or several solutions needed due to discontinuities) larger discrepancies do exist, which however mostly reside within their standard deviations.

Thus the major problem in the ITRF2005 is the significant difference in the SLR scale. The analysis of weekly SLR solutions of the official ITRS Combination Centre A in 2006 has shown that its scale is in reasonable good agreement with the ITRF2005P solution of DGFI, whereas there is a significant scale bias of about 2 ppb w.r.t. the IGN solution, equivalent to a difference of 1.3 cm in SLR station heights.

6 Conclusions

The new approach for the terrestrial reference frame computation based on time series combination of station positions and EOP has major advantages compared to the past TRF realizations. The advanced methodology allows to account for non-linear effects in site motions and
ensures consistency between the terrestrial reference frame and the EOP.

Both, DGFI and IGN computed one solution each for the ITRF2005, which allows for the first time a decisive validation and quality control of the terrestrial reference frame results. For comparisons we performed similarity transformations between both solutions and found a very good agreement for the station positions and velocities. The problem of the significant difference in the SLR scale is subject of further analysis.

Acknowledgements. The establishment of the ITRS Combination Centre at DGFI was supported by the Federal Ministry of Education and Research (BMBF), Grant (IERS)03F0336C within the Programme GEOTECHNOLOGIEN of BMBF and DFG.

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Combining One Year of Homogeneously Processed GPS, VLBI and SLR Data

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Abstract. The parameter space that can be covered by GPS, VLBI and SLR is very broad, and many overlaps exist between the techniques. Up to now, this is not yet fully exploited in inter-technique comparisons and combinations as in most cases only station positions and Earth orientation parameters (EOP) are considered. In this contribution we include the troposphere parameters additionally, and it is demonstrated that a combined terrestrial reference frame (TRF) improves the agreement of the GPS- and VLBI-derived troposphere zenith delays (ZD). The benefit of a combination is shown for the EOP as well, although non-continuous VLBI observations complicate the situation for Universal Time (UT). Finally, the potential of connecting GPS and SLR by estimating degree one spherical harmonic coefficients of the Earth’s gravity field is analyzed.

Keywords: EOP, troposphere parameters, low-degree spherical harmonics, rigorous combination

1 Introduction

Many solutions from the space-geodetic techniques are available through the International Earth Rotation and Reference Systems Service (IERS) and its technique-specific services. However, in most cases the provided time series show systematic biases and reveal differences that result from the application of different models during the analyses of the observations. In order to give one example, Schmid et al. (2005) demonstrated that the usage of phase centre models for GPS antennas that were calibrated relatively to one reference antenna instead of absolutely calibrated models causes significant biases in the ZD of several millimetres. All differences in the a priori models that were used to generate solutions show up as discrepancies in the estimated parameters. In order to overcome this problem, GeoForschungsZentrum Potsdam, Deutsches Geodätisches Forschungsinstitut, Institute for Geodesy and Geoinformation of the University of Bonn and Bundesamt für Kartographie und Geodäsie joined forces. Within this group, a broad variety of expertise concerning the analysis of GPS, VLBI and SLR is available so that high-quality solutions for all of these techniques could be generated. The alignment of the analysis standards within the group goes considerably beyond the IERS Conventions 2003 (McCarthy and Petit 2004) and their updates, as detailed agreements were made concerning the models used for, e.g., pole tide, ocean loading, a priori ZD delay, mapping function for the troposphere delay, a priori nutation, or the method of interpolating the a priori EOP to the epochs of observation.

2 Analysis strategy

2.1 Processing procedure

The analysis can be divided into four major steps:

- analysis of the observations for the year 2004 using the pre-defined common standards to get single-technique normal equations (NEQs),
- generation of yearly single-technique solutions,
- generation of weekly combined NEQs,
- generation of a yearly solution based on the weekly combined NEQs of the preceding step.

The full reprocessing of all observations (step 1) delivers homogeneous time series for each technique. The GPS analysis was done with the Bernese GPS Software 5.0 (Dach et al. 2007), EPOS at GFZ was used for the SLR analysis, and two VLBI solutions computed with CalcSolve (Petrov 2002) and Occam (Titov et al. 2004) have been combined to an intratechnique VLBI solution according to Vennebusch et al. (2007). It must be emphasized that the application of common analysis standards in all these software packages guarantees a high level of homogeneity
between the techniques, although the homogenization can still be improved. Another important advantage of our studies is the extended parameter space. Normally, just station coordinates and EOP are provided in the solutions available via the IERS. We included additionally station-specific troposphere parameters (2D and horizontal gradients) for GPS and VLBI, geocentre coordinates for GPS, and spherical harmonic coefficients (SH) of the Earth’s gravity field for SLR (degree 1-2). Amongst others, Pavlis (2004) showed that the estimation of low-degree SH from SLR observations is reasonable. The datum-free NEQs resulting from step 1 cover one week in the case of GPS and SLR, and 24 hours in the case of VLBI, where 129 global and eight regional sessions were selected. The regional sessions do not allow a reasonable estimation of EOP, but they deliver a valuable densification for the TRF.

Yearly single-technique solutions were generated in the second step. This step is necessary to get an idea about the potential of each technique and, thus, to realistically assess the quality that can be expected for the combined solution. An internal measure for the quality of the solutions is the repeatability of station coordinates (Table 1). The quite dense network of almost 200 GPS sites reveals the best stability with a weekly repeatability of about 2 mm for the horizontal components and a factor three worse for the height. Correlations of the height with the troposphere delay and the clocks are responsible for the worse stability compared to the horizontal components. This behaviour is visible for the VLBI solution as well, but its repeatability is worse by a factor of about two compared to GPS. However, it must be kept in mind that the VLBI network is less dense and determined with 24-hour sessions. SLR, with the same amount of stations but weekly solutions, is less precise than VLBI. Considering that we have a single SLR solution and that all sites contribute to the repeatabilities, the order of magnitude agrees well within that shown by Bianco et al. (2006). Comparing with other analysis (e.g. Altamimi et al. 2007), it must be emphasized that we use an RMS instead of WRMS, and internal comparisons showed that this difference is especially important for VLBI and SLR where the formal errors are strongly varying. The 3D repeatabilities were used for a relative weighting of the technique-specific NEQs in the combination.

Finally, a yearly solution based on the previously generated weekly combined NEQ was computed in order to have a homogeneous TRF as basis for the time series of EOP and troposphere parameters. The TRF datum has been defined by a sub-set of good GPS sites using a no-net-rotation and no-net-translation condition w.r.t. ITRF2000 (Altamimi et al. 2002). As we estimate the SH of degree one from SLR data, SLR itself cannot contribute to the translational datum. The SH of degree one and the geocenter coordinates from SLR and GPS, respectively, are not combined as we first want to analyze the estimates regarding any systematic differences.

The connection between the three techniques’ networks was realized by the application of local ties (LT) at co-located sites. An overview of the co-locations available for our analysis is given in Fig. 1 (at the end). Altogether there are 30 VLBI-GPS co-locations, 23 SLR-GPS co-locations and therein six stations where all three techniques are assembled. Unfortunately, no further VLBI-SLR co-locations are available so that these networks are connected mainly indirectly via GPS. After a careful selection, we applied LT for 23 VLBI-GPS and 21 SLR-GPS co-locations.

### Table 1: Repeatability of station coordinates for the single-technique solutions in [mm].

<table>
<thead>
<tr>
<th>Solution</th>
<th>#Stations</th>
<th>North</th>
<th>East</th>
<th>Up</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS (week)</td>
<td>185</td>
<td>1.91</td>
<td>1.80</td>
<td>5.66</td>
<td>3.60</td>
</tr>
<tr>
<td>VLBI (day)</td>
<td>33</td>
<td>4.65</td>
<td>4.00</td>
<td>11.09</td>
<td>7.32</td>
</tr>
<tr>
<td>SLR (week)</td>
<td>32</td>
<td>15.61</td>
<td>17.16</td>
<td>17.13</td>
<td>16.65</td>
</tr>
</tbody>
</table>

### 2.2 Combination strategy for EOP

It is essential to say some words about the parameterization and the combination strategy for EOP to understand and interpret the results. Figure 2 visualizes the basic principle. The difficulty in combining daily EOP from satellite techniques and VLBI is due to the data coverage: GPS and SLR observe continuously whereas gaps occur between two consecutive 24 h VLBI sessions so that a continuous time series at daily intervals cannot be derived. An additional problem arises because VLBI sessions typically start at 17 or 18 UTC. Thus, the balance point of all observations, where offset and drift parameters are estimated best, differs from 12 UTC. We deal with this situation in such a way that we change the parameterization in the NEQs from offset/drift per session into a linear function with two values at 0 and 24 UTC (“polygon 0h-0h”) which can then be stacked with the appropriate midnight epochs of the piece-wise linear parameterization used for the continuous time series (“continuous polygon”) derived from GPS and SLR. It is clear that a VLBI-only time series consisting of offsets given at the mid-epochs of the sessions is more stable than a time series of estimates at 0 h. Thus, if the best VLBI-only estimates are of interest, the EOP offsets at the mid-epochs of the sessions should be considered. However, if we
want to realistically assess the contribution of each technique to the combined time series, we must look at the parameterization as a polygon, especially in cases where the contribution of VLBI is essential, i.e., \( UT1-UTC \) and the nutation angles.

![Diagram](image)

**Fig. 2:** Combination strategy for time series of daily parameters derived from continuous and session-wise data.

### 3 Analyses results

#### 3.1 Earth rotation parameters

All EOP analyses presented hereafter base upon yearly solutions with station positions and EOP estimated together for the year 2004. Thus, the underlying TRF is homogeneous for the whole time series (i.e. is not changing slightly from week to week).

The daily \( x \)-pole coordinates estimated by the single-techniques are shown in Fig. 3a as differences to the IERS-C04 series (Gambis 2004), and Table 2 gives a statistical summary of this comparison. All three techniques show a bias compared to IERS-C04 at the level of a few tenths of a milli-arcsecond. The fact that the biases are quite different can be explained by slightly differing TRFs as each technique was analyzed separately here. Removing the mean biases from the residuals plotted in Fig. 3a and computing the RMS (weighted or unweighted) gives a criterion for the stability of the estimated time series. As discussed before, the EOP are set up as polygon with estimates at 0 h (except for VLBI-only), and it is clear that these estimates scatter more than estimates in the middle of each interval. Therefore, the comparisons were done for the 0 h epochs and, additionally, for the 12 h epochs (i.e., the mid of each interval) in order to have values comparable to VLBI that is analysed in the middle of each session. Furthermore, the comparison at 12 h yields values that are comparable to other studies published in the literature. Table 2 reveals a high quality of the GPS and VLBI solution whereas the SLR solution is less stable by a factor of about two compared to VLBI.

![Diagram](image)

**Fig. 3:** Estimated \( x \)-pole w.r.t. IERS-C04 series: a) single-technique solutions, b) GPS-only and combined solution.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Bias</th>
<th>WRMS 0h</th>
<th>WRMS mid</th>
<th>RMS 0h</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>-111.2</td>
<td>95.6</td>
<td>57.1</td>
<td>95.8</td>
</tr>
<tr>
<td>VLBI</td>
<td>-305.0</td>
<td>-</td>
<td>100.5</td>
<td>145.2</td>
</tr>
<tr>
<td>SLR</td>
<td>89.1</td>
<td>283.1</td>
<td>219.1</td>
<td>413.9</td>
</tr>
<tr>
<td>Comb</td>
<td>-108.4</td>
<td>90.0</td>
<td>55.9</td>
<td>91.4</td>
</tr>
</tbody>
</table>

**Table 2:** Comparison of the \( x \)-pole estimates with IERS-C04. The mean bias was removed for computing the WRMS and RMS values of the differences (values given in \( \mu \)as).

<table>
<thead>
<tr>
<th>Solution</th>
<th>Bias</th>
<th>WRMS 0h</th>
<th>WRMS mid</th>
<th>RMS 0h</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>282.6</td>
<td>83.3</td>
<td>47.9</td>
<td>88.1</td>
</tr>
<tr>
<td>VLBI</td>
<td>310.0</td>
<td>-</td>
<td>102.3</td>
<td>134.8</td>
</tr>
<tr>
<td>SLR</td>
<td>249.5</td>
<td>329.2</td>
<td>236.4</td>
<td>459.0</td>
</tr>
<tr>
<td>Comb</td>
<td>273.2</td>
<td>82.4</td>
<td>46.9</td>
<td>85.5</td>
</tr>
</tbody>
</table>

**Table 3:** Comparison of the \( y \)-pole estimates with IERS-C04. The mean bias was removed for computing the WRMS and RMS values of the differences (values given in \( \mu \)as).

As the WRMS and RMS values of the GPS solution are nearly identical, it can be concluded that all \( x \)-pole estimates have nearly identical formal errors, whereas the formal errors of the SLR- or VLBI-derived \( x \)-pole coordinates are not as homogeneous as for GPS, indicated by a larger RMS compared to
the WRMS. The scatter in the x-pole is slightly improved in the combined solution (Table 2, Fig. 3b).

The analysis of the y-pole shows similar results concerning the WRMS (Table 3). Contrary to the x-pole, the y-pole estimates of all solutions are biased similarly compared to IERS-C04 by about 0.25 to 0.3 mas. This large bias is caused by inconsistencies between ITRF2000 and the IERS-C04 series, and it clearly points out that IERS-C04 cannot be considered to be the truth.

The combination of UT1/LOD is totally different from a combination of polar motion as the contribution of the satellite techniques is limited to short-term variations in UT1-UTC. Solely VLBI can deliver long-term stability. The most stable time series derived from VLBI consists of the offsets from the parameterization “offset+drift” (Fig. 2) and shows a scatter of only 10 μs (16 μs in the unweighted case; see Table 4). However, as the combined time series is parameterized as a continuous polygon with values of UT1-UTC at the day boundaries, the corresponding VLBI-only time series (“polygon 0h-0h”) must be analyzed. As the estimates at 0 h of successive sessions were stacked, the number of epochs is not doubled. As it was supposed, the scatter increased by a factor of about 1.5 compared to the offsets given at the middle of the session (Table 4). The combination with GPS and SLR shows a clear stabilization for the time series consisting only of those 224 epochs where VLBI sessions are contributing (see Fig. 4, Table 4). This stabilization can be attributed to the valuable short-term information (LOD and polar motion) contributed by the satellite techniques and to the embedment of the sparse VLBI network into a very homogeneous and stable TRF given mainly by GPS. Looking at the whole time series consisting of all 365 epochs, it becomes clear that the extrapolation from the VLBI-given epochs to the remaining 140 epochs by using GPS- and SLR-derived LOD results, as expected, in a larger scatter (Fig. 5, Table 4). Thus, additional contributions of VLBI are needed to close the gaps and get a stable continuous time series. Thaller et al. (2007) demonstrated on the basis of the CONT02 campaign that this is possible.

### 3.2 Troposphere zenith delays

The ZD were estimated as corrections to the a priori value that was computed as the hydrostatic part of the Saastamoinen model (Saastamoinen 1973) for the height of the reference points of the VLBI or GPS site. Thus, the height difference is already taken into account when the GPS and VLBI estimates are compared, except for deviations of the true meteorological conditions from the standard atmosphere. For computing thedifference between both time series, the two-hourly GPS estimates were interpolated to hourly values, i.e., the temporal resolution for VLBI-derived ZD. The mean values for the ZD differences “GPS - VLBI” are listed in Table 5 for all colocations that have a reasonable amount of common epochs. Two comparisons were performed: first, the ZD of the single-technique solutions (“ΔZD G-V”), and second, the estimates of the weekly combined solutions (“ΔZD comb”). In the latter case, the station coordinates and the EOP were combined but the ZD were still estimated independently. As the mean ΔZD should ideally be zero we conclude that, in general, the ZD estimates for GPS and VLBI are only slightly biased. Furthermore, the combination of the TRF improves the agreement of the ZD estimates. A possible reason for remaining biases can be uncalibrated radomes on top of the antennas.

The WRMS of the ΔZD are shown in Fig. 6. If single-technique solutions are derived without any constraint on the ZD, the VLBI estimates are weakly determined for some epochs and cause a large
WRMS. This problem can be remedied if the ZD of successive epochs are slightly constrained (1 m in our case), although the constraint is not necessary for most of the stations, thus, it does not influence their ZD estimates. The positive effect of the combination can be seen in significantly reduced WRMS for those stations where the VLBI time series needs some stabilization. Thus, the stable TRF of GPS can help to stabilize the ZD for the VLBI site, although this effect is not as large as a constraint directly on the ZD, of course. However, the WRMS slightly increases in the combination compared to the single-techniques if additional constraints are applied. But in general, the scatter of the ZD biases is only a few millimetres indicating an overall good agreement. The results agree well with the comparisons done by Steigenberger et al. (2007), although their analysis covers a much longer time span.

Fig. 6: WRMS of the differences between the ZD estimates for GPS and VLBI sites. The biases (Table 5) were removed.

3.3 Geocentre coordinates

Concerning the spherical harmonic coefficients $SH_{nm}$ of degree $n$ and order $m$, the paper concentrates on the coefficients of degree 1 as they are related to the geocentre coordinates $X_{gcc}$:

$$X_{gcc} = H_{nm} \cdot R \cdot SH_{nm}$$ (1)

with the normalization factor $H_{nm}$, which is $\sqrt{3}$ in the case of $n=1$, and the radius of the Earth $R$. The SH estimated by SLR were converted into coordinates of the geocentre according to Eq. 1 and then compared to the GPS estimates (see Fig. 7). At a first glance, there are only a few similarities in the temporal behaviour of both time series and in $y$-direction there is even a bias of about 1 cm which is assumed to be caused by orbit modelling deficiencies in the GPS solution. As expected, the $z$-component is determined more stably by SLR than by GPS, so that the solution benefits from a combination. For the other components the scatter is nearly identical for both techniques, i.e., about 4 mm.

Fig. 7: Geocentre coordinates from GPS and corresponding SH of degree 1 from SLR converted to geocentre coordinates.

4 Conclusions and outlook

For the first time, homogeneous contributions of GPS, VLBI and SLR were combined for one year including station positions, EOP, troposphere parameters and low-degree SH of the geopotential.

The benefit of a combination was shown for the ZD, as a homogeneous TRF (from GPS) increases the agreement between GPS and VLBI estimates and gives stabilization for weakly determined epochs. The next step will be the combination of the troposphere parameters which was already proven to be successful by Krügel et al. (2007) for the CONT02 campaign.

It was shown that not only the pole coordinates benefit from a combination, but the time series of $UT1-UTC$ as well. However, the problem with gaps between the 24 h sessions of VLBI remains, and it has to be investigated whether the “Intensive” VLBI sessions can help as they deliver UT almost daily.

The inclusion of SH of the geopotential gives an additional link between the techniques, although the potential of a combination still has to be ascertained. Moreover, in the future, the correlations between the various parameter types will be studied in detail.

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Geotechnologien project 03F0425A and we like to thank all colleagues contributing to this project.

**References**


![Fig. 1: Network of co-located sites for the year 2004.](image)

<table>
<thead>
<tr>
<th>Station</th>
<th>hoh2</th>
<th>medi</th>
<th>onsa</th>
<th>tsk2</th>
<th>tskb</th>
<th>hrao</th>
<th>fort</th>
<th>algo</th>
<th>conz</th>
<th>wes2</th>
<th>nya1</th>
<th>kokb</th>
<th>nyal</th>
<th>fair</th>
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<tbody>
<tr>
<td>#Epochs</td>
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<td>658</td>
<td>683</td>
<td>818</td>
<td>818</td>
<td>1029</td>
<td>1260</td>
<td>1366</td>
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<td>1552</td>
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<td>1677</td>
<td>2228</td>
<td>2784</td>
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<tr>
<td>ΔZD G-V</td>
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<td>-1.5</td>
<td>-1.3</td>
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<td>13.4</td>
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<td>-1.6</td>
<td>4.2</td>
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<td>-2.2</td>
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<td>-0.6</td>
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<td>-2.3</td>
<td>0.1</td>
<td>-0.3</td>
<td>0.9</td>
<td>4.9</td>
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