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aus Münster

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Summary

In this thesis, it is shown that combining contributions of different VLBI analysis centers, a so called intra-technique combination, improves the robustness and stability of the final VLBI results. For this purpose, a refined combination method has been developed which is in many theoretical and practical aspects superior to combination approaches currently used for comparable geodetic combination tasks. For example, datum-free normal equation systems are used as input, which ensure that the contributions are not deformed by any constraints at all, and the same underlying terrestrial reference frame can be applied during the combination process. Furthermore, a statistically rigorous variance component estimation approach for the relative weighting of the contributions is used. The combination process implies detailed comparisons and analyses of the individual ACs' contributions. From these, as one of the outcomes of this thesis, several systematic differences between the individual contributions were detected and eliminated. The adherence to standards was considerably improved. The combination process itself reduces the "analyst's noise" and damps the impact of outliers. Validations with independent results of other space-geodetic techniques confirm a benefit of up to 15% more accurate results than from individual solutions.

Another aspect of this thesis is the general problem of any intra-technique combination, the correlations between the individual contributions. So far, the contributions of different ACs are always treated as independent data sets, although they have been derived from virtually the same set of original observations. It is shown that correlations between the individual ACs' contributions can be determined and rigorously taken in account during the combination process if the combination is performed directly on the level of the observation equations, instead on the level of normal equation systems. The main effect of considering these correlations is that the formal errors of the estimated combined parameters are considerably more realistic, but the parameters as such remain unchanged within their formal errors.

Zusammenfassung

In der vorliegenden Arbeit wird gezeigt, dass eine Kombination von Beiträgen verschiedener VLBI Analysezentren, eine so genannte Intra-Technik Kombination, die Robustheit und Stabilität der endgültigen VLBI Ergebnisse verbessert. Dazu wird eine verfeinerte Kombinationsmethode entwickelt, die in vielen theoretischen und praktischen Aspekten besser ist bisher existierende Realisierungen. Zum Beispiel werden als Eingangsdaten datumsfreie Normalgleichungen genutzt, durch die gewährleitest wird, dass keiner der Beiträge vor der Kombination durch Bedingungen deformiert ist. Darüber hinaus bieten sie den Vorteil, dass derselbe zugrunde liegende terrestrische Referenzrahmen verwendet werden kann. Ferner erfolgt die relative Gewichtung der einzelnen Beiträge über eine statistisch strenge Varianz-Komponenten Schätzung. Der Kombinationsprozess impliziert detaillierte Vergleiche und Analysen der einzelnen Beiträge. Dadurch werden systematische Unterschiede zwischen den Einzelbeiträgen aufgedeckt und beseitigt sowie erhebliche Verbesserungen in der Einhaltung von Standards erzielt. Durch den Kombinationsprozess selbst wird das sog. "Analysten-Rauschen" reduziert. Validierungen mit unabhängigen Ergebnissen anderer Weltraumverfahren können einen Genauigkeitsgewinn von bis zu 15% gegenüber den Einzellösungen bestätigen.

Darüber hinaus wird in dieser Arbeit das allgemeine Problem einer jeden Intra-Technik Kombination untersucht, das in der Abhängigkeit der einzelnen Beiträge voneinander besteht. Bisher wurden diese als unabhängig voneinander betrachtet, obwohl sie nahezu den gleichen Satz an originären Beobachtungsdaten verwenden. Es wird gezeigt, dass Korrelationen zwischen den einzelnen Beiträgen bestimmt und streng im Kombinationsprozess berücksichtigt werden können, wenn die Kombination direkt auf der Ebene der Beobachtungsgleichungen anstatt auf der bisher verwendeten Normalgleichungsebene durchgeführt wird. Die Berücksichtigung dieser Korrelationen führt in erster Linie zu realistischeren Standardabweichungen der geschätzten kombinierten Parameter, die Parameter als solche bleiben innerhalb ihrer formalen Fehler unverändert.

Contents

Preface

This thesis includes the following papers, ordered chronologically and referred to as Paper A–G in the text:

Paper A:

VENNEBUSCH, M., S. BÖCKMANN, A. NOTHNAGEL (2007) *The contribution of Very Long Baseline Interferometry to ITRF2005.* J Geod 81(6):553-564, DOI 10.1007/s00190-006-0117-x.

Paper B:

BÖCKMANN, S., T. ARTZ, A. NOTHNAGEL, V. TESMER (2007) *Comparison and combination of consistent VLBI solutions.* In: Boehm, J., A. Pany, H. Schuh (eds) Proceedings of the 18th European VLBI for Geodesy and Astrometry Working Meeting, 12-13 April 2007, Geowissenschaftliche Mitteilungen, Heft Nr. 79, Schriftenreihe der Studienrichtung Vermessung und Geoinformation, Technische Universität Wien, ISSN 1811-8380, pp 82-87, (available electronically at http://mars.hg.tuwien.ac.at/evga/proceedings/).

Paper C:

BÖCKMANN, S., A. NOTHNAGEL (2008) *The Variance Component Approach in the IVS Combination.* In: Finkelstein, A., D. Behrend (eds) Measuring the Future, Proceedings of the Fifth IVS General Meeting, pp 329-334, (available electronically at http://ivscc.gsfc.nasa.gov/publications/gm2008/).

Paper D:

BÖCKMANN, S., A. NOTHNAGEL, T. ARTZ, V. TESMER (2010A) *International VLBI Service for Geodesy and Astrometry: Earth orientation parameter combination methodology and quality of the combined products.* J Geophys Res, 115, B04404, DOI 10.1029/2009JB006465.

Paper E:

BÖCKMANN, S., T. ARTZ, A. NOTHNAGEL (2009) *IVS' contribution to ITRF2008 - Status & Results.* In: Bourda, G., P. Charlot, A. Collioud (eds) Proceedings of the 19th European VLBI for Geodesy and Astrometry Working Meeting, Université Bordeaux 1 - CNRS - Laboratoire d'Astrophysique de Bordeaux, pp 102-106, (available electronically at http://www.u-bordeaux1.fr/vlbi2009/proceedgs/).

Paper F:

BÖCKMANN, S., T. ARTZ, A. NOTHNAGEL (2010B) *VLBI terrestrial reference frame contributions to ITRF2008.* J Geod 84:201-219, DOI 10.1007/s00190-009-0357-7.

Paper G:

BÖCKMANN, S., T. ARTZ, A. NOTHNAGEL (2010C) *Correlations between the contributions of individual IVS analysis centers.* In: Behrend, D., K.D. Baver (eds) IVS 2010 General Meeting Proceedings, NASA/CP-2010-xxxxxx, in press

1. Introduction

During the last decades space-geodetic techniques have contributed significantly to the understanding of the kinematics and dynamics of the Earth. Each of the space-geodetic techniques Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Luna Laser Ranging (LLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) can contribute in a complementary way: the VLBI technique, e.g., uniquely provides the parameters for the celestial reference frame (CRF) and is, thus, the only technique to determine the celestial pole and the Earth rotation angle. In order to benefit from the advantages of the individual techniques and to overcome technique-specific weaknesses, the relevant contributions of the individual techniques are combined (called “inter-technique combination”, see, e.g., Altamimi et al. 2007, Gambis 2004).

For the individual techniques, it is widely accepted today that the combination of the contributions from different analysis centers (ACs) using data of the same technique can improve the robustness and stability of the technique-specific products (“intra-technique combination”). It is common practice for the ACs to use different software packages and approaches to estimate the unknown parameters from the original observations. Generally, highly precise space-geodetic contributions from different ACs can differ in the rejection of outliers, in the usage of analysis options without conventions, and even due to small logical or coding errors. Therefore, the contributions of the different ACs are not identical even if they use the same observations or software packages.

The approach to combine the contributions of different ACs to one official, final product yields two positive effects compared to using only one individual solution:

1. The combination process implies detailed comparisons and analyses of the differences between the contributions. This helps to uncover problems, systematic effects and to understand their different stochastic properties, and in the end yields better reflected, clearly documented, and more homogeneous contributions.
2. After such a thorough scrutiny of the contributions, the “analyst’s noise” (influence of still hidden smaller errors or of effects for which a conventional treatment is not yet defined or desired) will be reduced which leads to an improved stability of the final combined product.

One might consider such a combination approach to have the disadvantage that the final solution is a mixture of several analysis strategies with several different unknown shortcomings mixed up which cannot be discovered nor be removed later. However, the approach to declare a single contribution to be the final product implies that this contribution should be clearly "better" than all others. In order to assess one contribution to be the best, appropriate external high quality data sets for validation, or clear, objective and correct criteria are required. Both of these are not available at present.

The goal of this thesis is to further improve the robustness and stability of the results of the VLBI intra-technique combination by using a new combination method for the intra-technique combination. This endeavor is embedded in and contributes to the product generation of the International VLBI Service for Geodesy and Astrometry (IVS). In order to fulfill this task, a refined combination method has been developed which is in many theoretical and practical aspects superior (e.g., using datum-free normal equation systems and a variance component estimation approach) to other existing combination approaches. Detailed analyses of the individual ACs’ contributions have been carried out in order to uncover and eliminate remaining systematic differences between them. Finally, the results have been validated with the results of other space-geodetic techniques in order to show the benefit of the new combination.

Moreover, a general problem of any intra-technique combination is investigated which has up to now been completely disregarded: So far the contributions of different ACs are being treated as independent data sets although they have been derived from virtually the same set of original observations. Theoretically, the interdependency of the contributions can be expressed by correlations, but in practice, the determination of the level of correlation and a rigorous consideration of these correlations in presently used combination methods are a delicate problem.

This thesis includes seven recently published papers which document (a) the IVS method to combine different VLBI contributions and (b) the quality of the combined products such as time series (a sequence of data points, measured at successive times) of long-term Earth orientation parameters (EOP) and station positions as well as terrestrial reference frames (TRFs).

The general structure of this thesis is as follows:

- Chapter 2 "Scientific context" describes the background, in order to make the motivation of the thesis clearer and gives a general overview of different combination methods.
- Chapter 3 "Geodetic Very Long Baseline Interferometry", gives a very short overview of the VLBI principles. Furthermore, it describes the basic methods to determine the parameters usually estimated from VLBI observations.
- The fourth chapter "Relevant Analysis Options" provides an overview of the analysis options at the disposal of the analyst and describes how differences in the analysis options can affect the combined results.
- Chapter 5 "Short description of the included papers" briefly introduces the seven papers included in this thesis.
- The most important results of this thesis are summarized in chapter 6.
- Chapter 7 provides an outlook on possible further research.
- In chapter 8, a list of publications on related work is given to which I have contributed. These publications are not included in this thesis, but are meant to document the relevance of this work for the scientific community.

2. Scientific context

The three fundamental pillars of space geodesy consist of: the geometry and kinematics of the Earth's surface, the Earth orientation and rotation, and the Earth's gravity field and its variability (www.ggos.org). The International Earth Rotation and Reference Systems Service (IERS) with its core products IERS Conventions, International Terrestrial Reference Frame (ITRF), International Celestial Reference Frame (ICRF) and EOPs is directly involved in two of these fields, namely geometry and Earth rotation (Rothacher 2003). Virtually all of the geo-scientific efforts which use highly precise global point positions or Earth rotation data are based on these products.

Today, almost all products of the IERS are determined by combining relevant contributions of different space-geodetic techniques. According to the IERS Terms of Reference[1] the official contribution of an individual technique shall be provided by the technique-specific services in the IERS, i.e., the International GNSS Service (IGS, Dow et al. 2005), the IVS (Schlüter and Behrend 2007), the International Laser Ranging Service (ILRS, Pearlman et al. 2002), and the International DORIS Service (IDS, Tavernier et al. 2006), because the individual services have the best knowledge of their own technique and technique-specific problems. These official contributions should be the result of an intra-technique combination done by the corresponding technique service (Altamimi et al. 2007, Rothacher 2003).

Already in the 1990s, Beutler et al. (1995) and Kouba and Mireault (1996) showed that a combination of the individual GPS (Global Positioning System) solutions stabilizes the results of the various IGS products. Furthermore, Pearlman et al. (2005) demonstrated that the ILRS combined station coordinates and EOPs gave improved results measured by the scatter of Helmert parameters with respect to ITRF2000 of successive weekly ILRS solutions for 2004. For the DORIS observations, Gambis (2006) showed that the combination process significantly improves both polar motion components by 1.1 and 0.7 mas in terms of root mean squared (RMS) with respect to the IERS 05 C04 EOP series[2] for, respectively, X-pole and Y-pole.

For a long time, combination at the level of results ("averaging individual numbers") has been the method of choice. However, this method implicates several disadvantages. E.g., combining EOP time series independently from the corresponding station position information neglects the direct interaction between EOP and the underlying TRF. As different ACs often use different TRFs to determine their EOP, the EOP series then could have been systematically different from each other depending on the constellation of the network (Nothnagel et al. 2006).

The IGS was the first service which started to combine EOPs in a more rigorous way by considering the direct relation between the TRF and EOPs in the combination process. Since mid 1999 (GPS week 1013) weekly station coordinates, apparent geocenter positions and daily Earth rotation parameters, namely pole position and rate, calibrated length of day (LOD), are rigorously combined on an operational basis (Mireault et al. 1999, Ferland and Piraszewski 2009). Since January 2004, the ILRS performs EOP combinations using the full variance-covariance information of the individual solutions (Bianco et al. 2006). Within the IVS, the rigorous EOP combination is in operation since January 1, 2007 (Böckmann et al. 2010a) using datum-free normal equations. The IERS began using rigorous combination methods for EOPs and TRF with the ITRF2005 products (Altamimi et al. 2007, Angermann et al. 2009).

In general, a rigorous combination can be carried out in three different ways:

1. at the level of observation equations,
2. at the level of normal equations,
3. at the level of solutions with their full variance-covariance matrices.

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[1] http://www.iers.org

[2] http://data.iers.org/products/176/11165/orig/eopc04.62-now

Theoretically, all three methods can be made equivalent if the observations can be regarded as statistically independent and all models used in the data analysis as well as the unknown parameters to be combined are identical. A combination at the level of observations requires software packages and IT-infrastructure suitable for a huge number of observations. This would make the distributed processing, as it is done within the international services, very difficult. Even most combination efforts, claiming to be at the observation level, are in fact done at the normal equation level for practical reasons. So, this is an idealized case which has not been used on an operational basis so far.

If datum-free normal equations are used, it is ensured that all contributions are not deformed at all by any constraints before combination. By using this procedure, the same underlying TRF can be applied during the combination process and, thus, guarantees that literally an identical TRF is applied for all input series and, thus, the input information is completely undistorted. The drawback of the current realization is, that at the moment only three different VLBI software packages are able to produce datum-free normal equations.

If the covariance option is chosen for the submission and combination, a proper inversion is needed requiring some sort of datum definition beforehand by the analyst. In this case, the only way to freely dispose of the datum is either to set up additional similarity transformation parameters or to remove the datum definition prior to the combination process. Both of these approaches can bring about several difficulties which do not persist if datum-free normal equations are used. E.g., removing the datum definition requires that the constraints applied to the individual solutions are known exactly. Setting up similarity transformation parameters, especially setting up scale parameters for each 24h session, could be critical, as VLBI equation systems are normally much weaker than those of global GPS networks. DREWES and ANGERMANN (2003) mention that the necessary inversion may cause loss of precision by numerical effects. FERLAND et al. (2000) state, however, that the rounding/truncation problems by unconstraining the covariances used within the IGS combination are minor.

In order to avoid potential problems with the weak VLBI equation systems, the IVS decided to use datum-free normal equations. In addition to IGS, also the ILRS (BIANCO et al. 2003) and IDS (TAVERNIER et al. 2006) favor the combination at the level of solutions with full variance-covariance matrices. In order to avoid the possibility of distortions, only loosely constrained solutions are used. However, even loose constraints may affect the combination results if they are applied repeatedly (DREWES and ANGERMANN 2003).

3. Geodetic Very Long Baseline Interferometry

3.1 Basic principles

The basic principle of VLBI consists in simultaneous observations of an extra-galactic radio source by two or more radio telescopes. During a standard VLBI observing session of 24 hours, three to eight globally distributed radio telescopes observe 15 (in the early years) to 60 (today) extra-galactic radio sources. As the extra-galactic radio sources used for geodetic VLBI are very distant (2 to 12 billion light-years), the broadband microwave signals emitted by these sources seen by different telescopes on the Earth can be considered as a plane wave front (parallel). The signal of an extra-galactic radio source arrives at two telescopes with a time delay τ, the fundamental geodetic VLBI observable.

The time delay τ_{geom} only derived from the geometry can be mathematically described by:

$$\tau_{geom} = t_1 - t_2 = -\frac{1}{c}\mathbf{b} \cdot \mathbf{k} \tag{3.1}$$

with the VLBI vector baseline $\mathbf{b} = \mathbf{r}_1 - \mathbf{r}_2$ computed from the position vectors of two VLBI telescopes $\mathbf{r}_i$ and the unit vector in the direction of the radio source $\mathbf{k}$. t_1 and t_2 are the arrival times at the two telescopes, respectively, and c denotes the velocity of light.

Since Eq. (3.1) only describes the geometrical delay, a more sophisticated model has to be used to model the real VLBI observations. Therefore, the observed delay τ_{obs} has to be expressed in the barycentric system, a quasi-inertial system:

$$\tau_{obs} = t_1 - t_2 = -\frac{\mathbf{k}}{c} \cdot (\mathbf{R}_2(t_2) - \mathbf{R}_1(t_1)) \tag{3.2}$$

where $\mathbf{R}_i(t_i)$ denotes the position vectors in the barycentric frame. For the computation of the vector baseline $\mathbf{B}$ in the barycentric frame, the position vectors $\mathbf{R}_i(t_i)$ both have to be used at the arrival time t_1.

Because the actual measurements are made on the moving Earth, the vector baseline $\mathbf{B}$ has to be transformed from the barycentric system into the geocentric system. This conversion takes place via the so-called Lorenz-transformation. Hereby, diurnal and annual aberration effects arise, because of the rotation of the Earth and the movement of the Earth around the sun.

The geocentric vector baseline $\mathbf{b}$ can be computed from the geocentric position vectors $\mathbf{r}_i$. Since the position vectors are expected to be in the geocentric earth-fixed system, they have to be transformed accordingly. Generally, this transformation can be carried out with three time-dependent Eulerian rotation angles. For historical reasons and a better physical interpretation, the three necessary rotations are decomposed into five independent rotations represented by four rotation matrices:

$$\mathbf{r}_{i,e} = \mathbf{W} \cdot \mathbf{S} \cdot \mathbf{N} \cdot \mathbf{P} \cdot \mathbf{r}_i \tag{3.3}$$

with:

$\mathbf{W}$	rotation matrix for polar motion (coordinates of the intersection points of the Earth's rotation axis and the Earth crust, x_p and y_p)
$\mathbf{S}$	rotation matrix for the Earth rotation phase (the orientation of the Earth's rotation axis in the celestial space, $dUT1$)
$\mathbf{P}, \mathbf{N}$	rotation matrices for precession (z, ξ_A, Θ_A) and nutation ($d\phi$, $d\varepsilon$)
$\mathbf{r}_{i,e}$	geocentric earth-fixed position vectors of the observation sites.

The unit vector in the direction of the radio source **k** can be computed from the right ascension and declination of the source given in the celestial frame:

$$\mathbf{k} = \begin{pmatrix} cos\alpha \cdot cos\delta \\ sin\alpha \cdot cos\delta \\ sin\delta \end{pmatrix} \tag{3.4}$$

In addition to the aberration effects, several other effects occurring on the way through the Solar System, and the Earth's atmosphere as well as geophysical phenomena have to be accounted for in order to exploit the high accuracy of the VLBI measurements. Detailed descriptions of the various effects are given, e.g., in Schuh (1987) or Tesmer (2004). According to, e.g., Haas (1996), Cannon (1999) the basic geometrical delay has to be extended to:

$$\begin{aligned} \tau_{obs} &= \tau_{geom} && (3.5) \\ &+ \tau_{j-aber} + \tau_{t-aber} + \tau_{rel} + \tau_{load} + \tau_{tid} && (3.6) \\ &+ \tau_{clock} + \tau_{instr} + \tau_{tropo} + \tau_{ionos} \cdots \end{aligned}$$

where:

τ_{j-aber}	annual aberration because of the motion of the Earth around the solar system barycenter,
τ_{t-aber}	diurnal aberration because of the rotation of the Earth,
τ_{rel}	relativistic corrections to the geometric delay τ_{geom},
τ_{load}	deformation of the Earth surface because of loading effects (e.g. due to ocean tides and atmospheric pressure changes),
τ_{tid}	deformation of the Earth because of tides and changes of the angular momentum due to ocean tides,
τ_{clock}	mis-synchronization of the reference clocks at each observatory,
τ_{instr}	propagation delays through on-site cable runs and other instruments,
τ_{tropo}	propagation delays through the non-ionized portions of the Earth's atmosphere,
τ_{ionos}	propagation delays through the ionized portions of the Earth's atmosphere.

The general principle of VLBI has been described by many authors. For more details see, e.g., Thomas (1972), Campbell (1987), Sovers et al. (1998), Ma and MacMillan (2000) or, Takahashi et al. (2000).

3.2 Parameter estimation in VLBI data analysis

Theoretically, all elements contained in the VLBI observation equation can be estimated from VLBI observations. However, some of them can be highly correlated with each other (like tropospheric zenith delay, station clock, and height estimates). For others, observations from a longer time span are needed to obtain stable estimates. Generally, the parameters estimated from VLBI observations can be separated into primary geodetic and astronomical target parameters and auxiliary parameters (Tesmer 2004). The primary geodetic and astronomical target parameters comprise the source and station positions as well as the EOPs together with their time derivatives. The EOPs give the full transformation between a TRF and a CRF and describe the irregularities of the Earth's rotation with respect to a non-rotating reference frame. Two parameters ($d\psi$, $d\varepsilon$) correct the precession-nutation model of the celestial pole, one parameter ($dUT1$) represents the irregularities of the rotation angle, and two (x_p, y_p) describe polar motion with respect to the crust. Besides these primary target parameters, auxiliary parameters are estimated which represent the influence of the atmosphere, i.e., the tropospheric horizontal gradients and zenith wet delays (ZWDs), and the mis-synchronization of the reference clocks at each but one observatory. One clock is used as reference clock and cannot be estimated.

The selection of parameters to be estimated can vary with the primary goal of the solution, can depend on the number of participating stations, as well as on the duration of the session. For example, the reference frame parameters (i.e, the CRF and TRF) are normally determined from a huge number of sessions and, therefore, are representative for a long time span. EOPs, in general, are determined once per 24-hour session. However, the $dUT1$ and polar motion parameters can also be estimated with a higher resolution of, e.g., one hour in order to determine the sub-daily variations of Earth rotation. If station positions are to be estimated session-wise, non-deforming datum definition constraints are necessary in order to transform the relative positions into “geocentric” ones. The choice of a particular parameterization for the auxiliary parameters is subject to ongoing research and may vary from analyst to analyst (Vennebusch 2008). Details concerning these analysis options are given in Ch. 4.

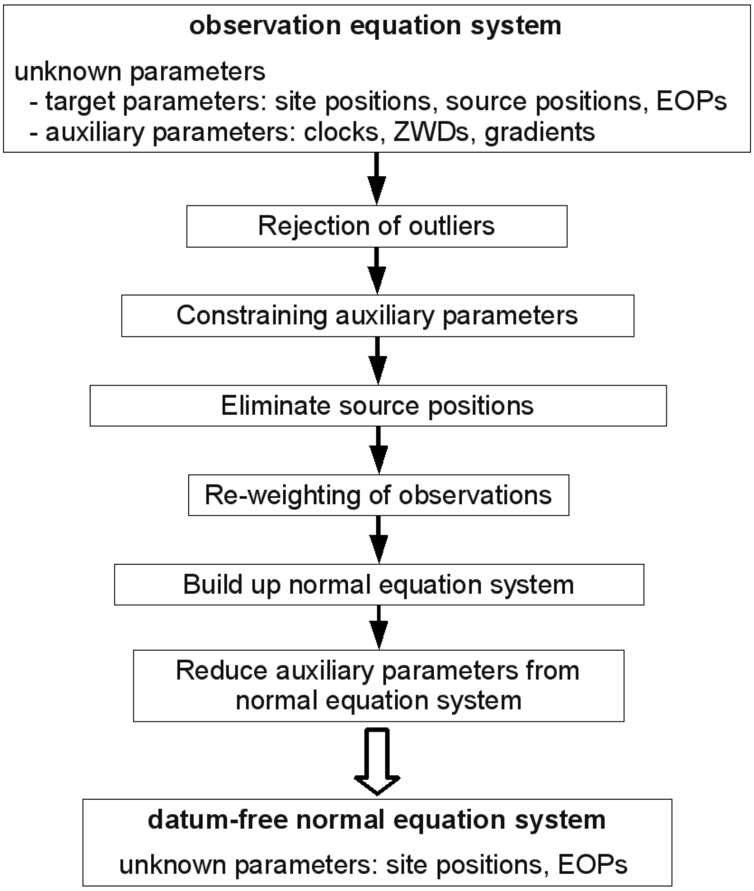

Figure 3.1: Flow chart of the generation of datum-free normal equation systems by the IVS ACs.

The IVS ACs’ contributions used for the combination are made available as datum-free normal equation systems. These normal equations are set up for each single 24-hour session either via the least squares collocation method (see e.g., Moritz 1980) or the classical least squares method (according to the Gauss-Markoff-Model, see e.g., Koch 1999). A simplified representation of the generation of these normal equation systems from the observation equation as given in Eq. (3.7) is displayed in Fig. 3.1. Unknown parameters contained in the observation equation system are site positions, source positions and daily EOPs ($dUT1$ and polar motion offsets together with their time derivatives as well as nutation offsets) as well as the auxiliary parameters tropospheric horizontal gradients, ZWDs and clock parameters. In the first step, outliers are rejected by each analyst. Constraints are added to the auxiliary parameters to stabilize occasional weaknesses in the equation system in a second step. Source positions are eliminated by deleting the corresponding row of the observation equation system. In doing so, each AC keeps the source positions fixed to its own CRF solution, however each with the orientation of the axes defined by the ICRF (Ma et al. 1998). In the fourth step, the observations are re-weighted. This means that the stochastic model is refined, which basically consists of the variances obtained from the correlator output. Finally, the normal equation system is build up from the modified observation equation system. In the last step, the auxiliary parameters (tropospheric horizontal gradients, ZWDs and clock parameters) are reduced from the normal equation systems without affecting the estimates of the target parameters. Unknown parameters remaining explicitly in the equation system are site positions and daily EOPs.

4. Relevant analysis options

When analyzing geodetic VLBI observations, an analyst may choose between many analysis options. Basically, there are two types of analysis options: those options which are obviously preferable to others or subject to conventions, and those options which cannot be judged objectively to be superior or inferior to others. These two types of analysis options are described in the following. Especially the second type can lead to systematic differences between the individual ACs' contributions (see Ch. 1).

The IVS ACs contributing to the IVS-combined products are listed in Tab. 4.1. Table 4.2 shows the common standards which have been used by the ACs contributing to the IVS input to ITRF2008. The most important analysis options for modeling and parameterization used differently by the IVS ACs at the moment are summarized in Tab. 4.3.

Table 4.1: IVS ACs contributing to the IVS-combined products

Analysis Center	**Country**	**Abbreviation**	**Software**
Geoscience Australia	Canberra, Australia	AUS	OCCAM(LSC)
Federal Agency for Cartography and Geodesy	Leipzig, Germany	BKG	CALC/SOLVE
German Geodetic Research Institute	Munich, Germany	DGFI	OCCAM(LSM)
Goddard Space Flight Center	Washington DC, USA	GSFC	CALC/SOLVE
Institute of Applied Astronomy	St. Petersburg, Russia	IAA	QUASAR
Institute of Geodesy and Geoinformation	Bonn, Germany	IGG	CALC/SOLVE
Paris Observatory	Paris, France	OPA	CALC/SOLVE
Shanghai Observatory	Shanghai, China	SHAO	CALC/SOLVE
US Naval Observatory	Washington DC, USA	USNO	CALC/SOLVE

4.1 Analysis options subject to conventions

In order to ensure maximum consistency, accuracy, and interpretability of the combined solution, all individual IVS ACs' contributions must be generated using common standards. These common standards are based on the recommendations of the IERS Conventions 2003 (McCarthy and Petit 2004) and the IVS Analysis Conventions (Nothnagel 2009). The IERS Conventions describe the mathematical modeling of physical processes (e.g., solid Earth tides, pole tides, mapping function). They are accepted by a broad majority of the geodetic community and are relevant for several space-geodetic techniques. The IVS Analysis Conventions are set up by the IVS Analysis Coordinator and are relevant for the VLBI technique-specific effects only. For example, these conventions provide values for antenna axis offsets, station eccentricities and coefficients for thermal expansion of the different radio telescopes.

4.2 Analysis options without conventions for modeling and parameterization

Besides the analysis options which are clearly defined by conventions or recommendations and, thus, should be used by all analysts, many options can be chosen which cannot be judged objectively superior or inferior to others or are still scientifically open questions. At this point only a few examples of the long list of options are given, in order to emphasize the complexity of VLBI data analysis.

Table 4.2: Common standards used by all contributing IVS ACs

Station coordinates	
Solid Earth tides	IERS Conventions 2003
Permanent tide	'conventional tide free'[a]
Pole tides	IERS Conventions 2003
Ocean tides	FES2004 (Finite Element Solution 2004, Letellier 2004)
Ocean loading	FES2004 without correction for the geocenter motion[b]
Atmospheric loading	not applied
Earth Orientation Parameters	
Sub-daily EOP model	IERS Conventions 2003
Precession/Nutation model	IAU2000A[c], excl. Free Core Nutation (Mathews et al. 2002)
Troposphere modeling	
Zenith hydrostatic delay	Modified Saastamoinen model (Davis et al. 1985) with surface pressure measured at the site
Hydr./wet mapping function	Hydrostatic / Wet Vienna Mapping Function 1 (VMF1, Boehm et al. 2006)
Gradients	MacMillan (1995) with wet VMF1
Technique-specific effects	
Thermal expansion	IVS Analysis Conventions (Nothnagel 2009)
Antenna axes offsets	IVS Analysis Conventions
Station eccentricities	official IVS table[d]

[a] the positions are computed on a surface used by all techniques for the position definition which is called 'conventional tide free' in chapter 7.1.3 in the conventions (the step 3. 'uncorrection for the permanent tide', in the official IERS-Code 'dehanttideinel.f' is not applied)

[b] http://www.oso.chalmers.se/loading/

[c] IAU = International Astronomical Union

[d] http://gemini.gsfc.nasa.gov/solve_save/ECCDAT.ecc

- For the calibration of the signal delay arising from the propagation through the Earth's atmosphere, meteorological data is needed. One could argue that that data should be used which is recorded at the station during the observations. But, it can be subject to biases or drifts, or even worse, the recording drops out due to various reasons. Global meteorological data sets, e.g., from numerical weather models, on the other hand, do not come along with a measure of quality and might not fit the local conditions well. Still, they are available as one homogeneous, global data set.

- In order to describe the behavior of the clock and the atmospheric delay mathematically in the observation equations, a second order polynomial approach together with continuous piece-wise linear functions to account for faster variations are chosen. To stabilize occasional weaknesses in the equation systems, e.g., in time intervals with only a small number of observations, constraints have to be added. The handling of these constraints as well as the optimal interval length for the piece-wise linear functions are still open questions and their handling change from analyst to analyst. On the one hand, the interval length should be as short as possible to represent the physical behavior of the atmosphere best. On the other hand, from a mathematical point of view, the interval length should be as long as possible to obtain the most stable equation system. Another approach used by VLBI analysts is to describe the atmosphere and clock behavior stochastically. The constraints of ZWDs and horizontal tropospheric gradients as used by the IVS ACs are given in Tab. 4.3 expressed as path delay of the radio signals.

- Daily a priori values for EOPs have to be interpolated for each observation epoch. Some analysts use a linear interpolation scheme, others prefer cubic splines. This does not only affect the smoothness of the a priori values, but also the way such a prioris can be transformed to other values later.

- Because the frequency standards ("clocks") at each of the two antennas are normally independent of each other, one clock has to be chosen as the reference clock for the entire network. The reference clock should provide high-frequency stability, as the estimation of the remaining clocks depends on the reference clock. Moreover, the constraints added to the piece-wise linear functions affect the whole solution differently, if such clock estimates are highly variable. Nevertheless, there is no official view, and the decision is left to each analyst which clock is chosen as reference. Some analysts even prefer to apply constraints that sum the clock offsets of all stations to be zero instead of fixing one reference clock.

- Basically, the stochastic VLBI model consists of the variances obtained from the correlation process. Due to various reasons (see, e.g., SCHUH 1987, NOTHNAGEL 1991), these variances are not fully realistic. Therefore, additive baseline-dependent or station-dependent corrections to the variances as proposed by PETROV (1998) are applied by some analysts. TESMER (2004) developed a refined stochastic model with elevation and station-dependent re-weighting.

- Some geodetic VLBI sessions show larger baseline-dependent clock offsets. PETROV (1999) gives four possible causes for baseline-dependent clock offsets: Non-modeled source structure effects, systematic clock misclosure introduced by correlation and post-correlation procedures, presence of strong outliers, and errors while resolving group delay ambiguities which may result in the appearance of permanent clock misclosures. It is questionable whether baseline-dependent clocks should be estimated if they are caused by one of the first three points.

- Clocks often exhibit "jumps" and instabilities at a level that would greatly degrade the interferometer accuracy if left unmodeled (HEINKELMANN 2008). To account for these effects, analysts introduce so-called clock breaks in the adjustment. Some of these "jumps" can be detected very clearly in the post-fit residual delays, others are not so clear. Thus, the individual solutions can differ in the clock breaks introduced. Figure 4.2 shows as an example the residuals of the baseline GILCREEK–KOKEE of the session 02OCT29XA. On the left hand side the residuals are shown as green dots before parameterizing the clock break, on the right hand side afterwards.

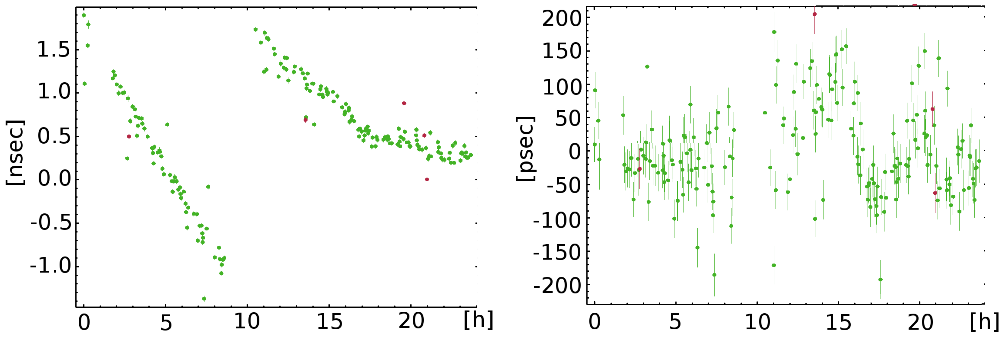

Figure 4.1: Residuals of the baseline GILCREEK–KOKEE of the session 02OCT29XA, left: residuals (green dots) before parameterizing the clock break, right: after the clock break was introduced. N.B.: the scale of the left and right graphic is not the same.

- The detection and rejection of outliers is realized differently by each analyst. The exact number of outliers varies from session to session and depends on the outlier test used by the analysts. On average, between 1% and 3% of the original observations are rejected.

Differences in the usage of such analysis options can yield

1. obvious systematics (offsets, drifts, periodicities etc.) which can easily be identified,

2. superimposed systematics through multiple effects of similar magnitude which seem to have quasi-random appearance,
3. statistical (white) noise.

Of critical nature are all systematic discrepancies in the individual solutions. If such solutions are combined, the combined solution will be less useful for high-precision purposes, since the interpretability of the combined solution is no longer ensured. Systematic differences in the models can affect observations of stations in different ways, depending on their geographic location etc. Multiple model effects can create noise-like variations, e.g., in the station positions and, due to the small number of observatories participating in each VLBI session, they affect the estimated EOPs noticeably. The reasons for such variations can then only be identified by detailed studies of the individual models and analysis options. Several authors have analyzed the effect of such type of options in varying depths, (see, e.g., MacMillan and Ma 1997, Tesmer et al. 2006, Tesmer et al. 2007, Tesmer 2007, Heinkelmann et al. 2009).

According to these investigations, several of the analysis options not defined by conventions just yield different noise floors and, thus, are acceptable in a combination effort. These options are, e.g., the parameterization and handling of constraints of clock and atmosphere parameters, the chosen reference clock, the parameterization of baseline-dependent clock offsets, as well as the introduction of clock breaks in the equation system. All of them are implicitly contained in the pre-reduced datum-free normal equation matrix. In contrast to this, systematic effects from this second type of options are to be expected due to the choice of zero or non-zero a priori values for the horizontal tropospheric gradients and the constraints used for them (Tesmer et al. 2006), by different interpolation schemes to map the daily a priori EOPs to the observation epoch and by different weighting strategies. All other analysis options that can yield systematic effects are subject to conventions.

Table 4.3: Different analysis options for modeling and parametrization used by the IVS ACs.

Modeling	**Realization**	**ACs**
a priori ZWDs	from num. weather model	GSFC, IGG, OPA, SHAO, USNO
	zero	AUS, BKG, DGFI, IAA
a priori tropospheric gradients	from num. weather model (MacMillan and Ma 1997)	BKG, GSFC, IGG, OPA, SHAO, USNO
	zero	AUS, DGFI, IAA
Time resolution and constraints of ZWDs	20 min, rates constrained to 0 ± 15 mm/hr (= 50 ps/hr)	GSFC, OPA, SHAO, USNO
	60 min, rates constrained to 0 ± 15 mm/hr (= 50 ps/hr)	BKG, DGFI, IGG
	stochastic model	AUS, IAA
Time resolution and constraints of tropospheric gradients	6 hr, offsets constrained to a priori value ±0.5 mm, rates constrained to 0 ± 2.0 mm/d	GSFC, SHAO, USNO
	8 hr, offsets constrained to a priori value ±0.5 mm, rates constrained to 0 ± 2.0 mm/d	OPA
	12 hr, offsets constrained to a priori value ±0.5 mm, rates constrained to 0 ± 2.0 mm/d	IGG
	24 hr, offsets constrained to a priori value ±0.5 mm, rates constrained to 0 ± 2.0 mm/d	AUS, BKG, DGFI, IAA
Interpolation schemes to map daily a priori EOPs	cubic spline	BKG, GSFC, IGG, OPA, SHAO, USNO
	linear	AUS, DGFI, IAA
Weighting	weights from correlator	AUS, IAA, OPA
	baseline-dependent re-weighting (Petrov 1998)	BKG, GSFC, IGG, SHAO, USNO
	refined stochastic model (Tesmer 2003)	DGFI
Baseline clock parameters	yes	BKG, GSFC, IGG, OPA, SHAO, USNO
	no	AUS, DGFI, IAA

5. Short description of the included papers

Since the Analysis Coordinator of the IVS is responsible for the dissemination of the official IVS products, the IVS Combination Center has been established at the Analysis Coordinator's office at the IGG, University of Bonn. Here, on an operational basis, the official IVS EOP time series are computed. Furthermore, the official IVS contributions to the last two realizations of the most important TRFs, the ITRF2005 (Altamimi et al. 2007, Angermann et al. 2009) and the ITRF2008, have been computed by the IVS Combination Center. The center was also involved in the work for the second realization of the ICRF (ICRF2, Fey et al. 2009). All seven papers of this thesis have been prepared in this context, three of them as reviewed papers (two in Journal of Geodesy, one in Journal of Geophysical Research - Solid Earth), four of them as summaries of research work, presented during international VLBI working meetings (number of pages strictly limited to five or six).

In the following my own and the (co-)authors' contributions to the papers are briefly described.
Axel Nothnagel is the supervisor of this thesis and, consequently, of the whole work contributing to prepare the papers. Furthermore, he improved the text of the papers by organizational, linguistic and grammatical corrections.
Thomas Artz and Volker Tesmer provided data sets used as input to the IVS combination as well as a huge amount of test data sets which helped to understand and eliminate systematic effects between the individual contributions to the combination. In addition, they contributed with their long experience in the analysis of VLBI data and their detailed knowledge about the two VLBI software packages, OCCAM and CALC/SOLVE. In addition they helped to improve the text of the respective sections.
Markus Vennebusch, the first author of Paper A, started to build up the VLBI intra-technique combination based on normal equation systems used at IGG. He wrote the first sections of Paper A: *1 Introduction* and *2.1 Basics of the IVS combination at the normal equation level.*
My own contribution to all papers consists of the preparation of the provided data sets, of the further development of the combination methodology as well as of the analysis the data. Moreover, I did all the computations, elaborated the presentation of the results, and wrote the text (except for the two sections of Paper A as stated above).

5.1 Main Points of Paper A

Vennebusch, M., S. Böckmann, A. Nothnagel (2007) The contribution of Very Long Baseline Interferometry to ITRF2005. *J Geod* 81(6-8):553-564, doi: 10.1007/s00190-006-0117-x.

This paper documents the IVS contribution to the ITRF2005. Before and up to the realization of the ITRF2000, individual ACs were invited to submit their results directly to the ITRF Product Center of the IERS. These inputs consisted of consolidated TRF solutions, some with full variance/covariance matrix. For the ITRF2005, however, the strategy was changed fundamentally from several points of view: The combination approach was changed to a rigorous combination based on weekly / session-wise contributions. Another change was that only one input per technique was requested from the services of the International Association of Geodesy (IAG), which should be the result of a pre-combination of the individual contributions provided by their ACs. In this context, a rigorous combination of VLBI normal equation systems from different ACs was carried out for the first time. Therefore, this paper mainly focuses on the combination methodology and on the basic mathematical principles, to a lesser extent on the quality assessment.

5.2 Main Points of Paper B

Böckmann, S., T. Artz, A. Nothnagel, V. Tesmer (2007) Comparison and combination of consistent VLBI solutions. In: Boehm, J., A. Pany, H. Schuh (eds) *Proceedings of the 18th European VLBI for Geodesy and Astrometry Working Meeting, 12-13 April 2007*, Geowissenschaftliche Mitteilungen, Heft Nr. 79, Schriftenreihe der Studienrichtung Vermessung und Geoinformation, Technische Universität Wien, ISSN 1811-8380, pp 82-87, (available electronically at http://mars.hg.tuwien.ac.at/evga/proceedings/).

Based on the experience gathered during the combination efforts for ITRF2005, some discrepancies between the individual series were discovered. Since a combination can only stabilize the results, if the individual contributions are consistent, in this paper, the results from two VLBI analysis software packages, OCCAM and CALC/SOLVE, have been compared in detail to detect remaining systematic differences. The comparisons have been carried out with station position time series and EOP time series calculated from standard solutions as used for the official IVS combination. The biggest systematic differences have been detected in the station height components and could be attributed to differences in the pole tide model.

5.3 Main Points of Paper C

Böckmann, S., A. Nothnagel (2008) The Variance Component Approach in the IVS Combination. In: Finkelstein, A., D. Behrend (eds) *Measuring the Future, Proceedings of the Fifth IVS General Meeting*, pp 329-334, (available electronically at http://ivscc.gsfc.nasa.gov/publications/gm2008/).

In order to account for the different qualities of the individual contributions to the combination process, weighting factors have to be determined. The variance component estimation (VCE) is used as a tool to determine the relative weighting factors for the individual contributions. The basic idea of the VCE is to compute individual variance factors for groups of observations instead of one common a posteriori variance factor. Here, a group of observations consists of all observations of a contribution by one individual AC. The reciprocal values of the estimated variance factors can, thus, be used as weights for each contribution. In this paper, the VCE as introduced in the IVS combination approach is explained and the computed variance factors for each contribution are discussed. Furthermore, comparisons are presented showing the benefit of the variance component approach.

5.4 Main Points of Paper D

Böckmann, S., A. Nothnagel, T. Artz, V. Tesmer (2010a) International VLBI Service for Geodesy and Astrometry: Earth orientation parameter combination methodology and quality of the combined products. *J Geophys Res*, 115, B04404, doi: 10.1029/2009JB006465.

After two years of operational EOP combination based on datum-free normal equations, this paper gives a critical review of the combination method and the IVS EOP products. We document the improvements and enhancements in the combination strategy achieved in the two years, discuss critical issues like different a priori models used by different ACs, and report on the quality of the IVS-combined products measured by comparisons with independently derived EOP series. These comparisons yield a significantly better agreement for the IVS-combined EOP solution of 10 % - 15 % than for the individual VLBI EOP solutions. This is the case for almost all EOP components. The only exception is the Y-pole component where the DGFI solution fits better to the independently derived EOP series than the combined solution. The results clearly show that a combination reduces the analyst's noise and, therefore, provides a more stable solution.

5.5 Main Points of Papers E and F

In late 2008, the IERS ITRF product center issued a call for contributions to the next realization of the International Terrestrial Reference System (ITRS), the ITRF2008. In this context two papers originated:

Böckmann, S., T. Artz, A. Nothnagel (2009) IVS' contribution to ITRF2008 - Status & Results. In: Bourda, G., P. Charlot, A. Collioud (eds) *Proceedings of the 19th European VLBI for Geodesy and Astrometry Working Meeting*, Université Bordeaux 1 - CNRS - Laboratoire d'Astrophysique de Bordeaux, pp 102-106, (available electronically at http://www.u-bordeaux1.fr/vlbi2009/proceedgs/).

Böckmann, S., T. Artz, A. Nothnagel (2010b) VLBI terrestrial reference frame contributions to ITRF2008. *J Geod* 84(3):201-219, doi: 10.1007/s00190-009-0357-7.

The first one was presented during an international VLBI working meeting. It documents the status reached in March 2009 and presents some preliminary results. At this stage, for some stations, significant height offsets were detected because different ACs did not use consistent antenna axis offsets in the original VLBI data analysis. The comparisons of the EOP have shown that the use of different high-frequency EOP models resulted in significant systematic variations in the LOD component of up to 10 μs/d. For the final contribution to the ITRF2008 all VLBI input solutions had to be reprocessed with the official IVS table for antenna axis offsets and the same high-frequency EOP model according to the IERS Conventions 2003.

The final IVS contribution to the ITRF2008 is presented in the second paper. In this paper, the quality of the IVS pre-combined input is documented by assessing the consistency of the individual contributions provided by the IVS ACs and by comparing the pre-combined input with the ITRF2005, analyzing linear and non-linear site motion. Altogether, nine IVS ACs analyzed the full history of VLBI observations. Due to several shortcomings in the contributions of two ACs, these had to be excluded from the combination process. Thus, the official IVS input to ITRF2008 was generated combining contributions of seven IVS ACs. It consists of session-wise datum-free normal equations of altogether 4539 daily VLBI sessions from 1979.7 to 2009.0 including data of 115 different VLBI sites. Since the computation of ITRF2005, two new sites, Zelenchukskaya (West-Russia) and Badary (Central-Russia), were added to the VLBI network and three more years of data are available. Furthermore, some discrepancies between the analysis options used by the IVS ACs discovered after the release of ITRF2005 have been overcome. The whole set of original VLBI data used in each AC's analysis was reprocessed homogeneously with the latest models, like the VMF1, (Boehm et al. 2006) for atmospheric delays and corrections for thermal expansion of the radio telescopes (Nothnagel 2009).

5.6 Main Points of Paper G

Böckmann, S., T. Artz, A. Nothnagel (2010c) Correlations between the contributions of individual IVS analysis centers. In: Behrend, D., K.D. Baver (eds) *IVS 2010 General Meeting Proceedings*, NASA/CP-2010-xxxxxx, in press

This paper focuses on the general problem of intra-technique combinations: The contributions of different ACs are treated as being independent, although having been derived from almost the same set of original observations. In this work, the level of correlation between the contributions to the IVS combination is quantified, the effects of neglecting these correlations on the estimated parameters and their formal errors discussed, and the findings are applied to the IVS combination process.

6. Summary of the most important results

6.1 Combination algorithm to derive the IVS products

One of the goals of this thesis is to find out if a combination of the contributions from different IVS ACs using almost the same set of original VLBI observations can improve the robustness and stability of the final products. First of all, this requires a high-quality combination algorithm. Figure 6.1 shows a flow chart of the algorithm developed for the IVS combination. The combination strategy is based on datum-free pre-reduced normal equation systems which takes into account the direct interaction between the EOPs and the underlying TRF rigorously. As a mechanism for exchanging the contributions of the individual ACs, the Solution INdepenend EXchange format (SINEX, Blewitt et al. 1994) is used. A discussion of the different possibilities for a rigorous combination is given in Ch. 2.

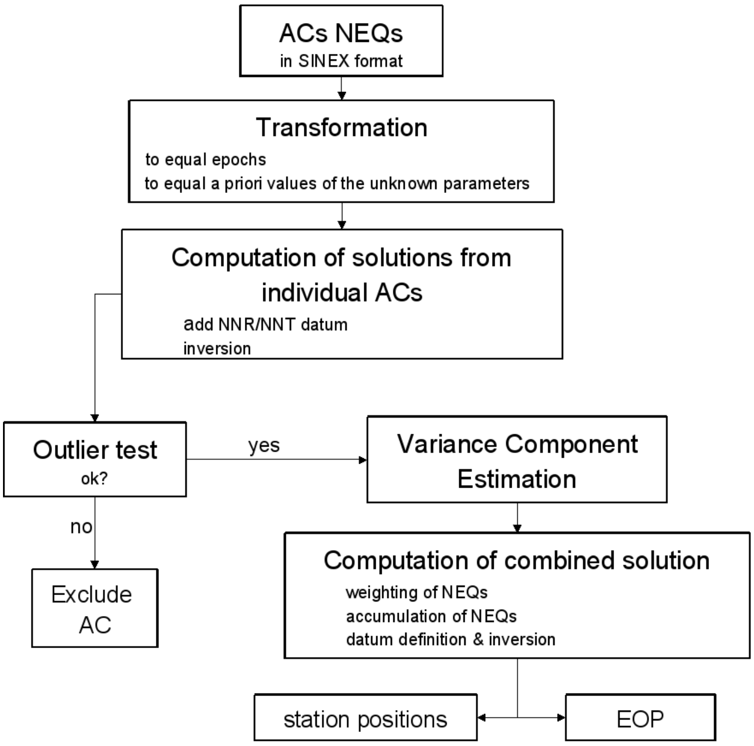

Figure 6.1: Flow chart of the IVS intra-technique combination

The strategy of the VLBI intra-technique combination mainly consists of five steps. First of all, various checks are performed to ensure that all SINEX files contain the mandatory blocks to be able to calculate a solution, that the eccentricities are equal for all contributions, that the normal equation system includes the necessary parameters, and that the system of normal equations is datum-free. One of the basic requirements for the combination is that the systems have to be based on the same a priori values. Therefore, in a second step, transformations are carried out to refer all parameters to the same reference epoch as well as to an equal set of a priori parameter values. Afterwards, outlier tests are performed in order to check the suitability of each individual contribution for the combination. Therefore, session-wise solutions are computed from the individual ACs' contributions. In the fourth step, all normal equations are rescaled by a variance factor, determined in a variance component estimation, in order to account for the differences inherent in the individual contributions. The variance component estimation is carried out for each single session. The advantage of this session-wise weighting is the flexibility that an ACs' contribution of each single sessions can be down weighted, if, e.g., a clock break at a station was not found by one AC. A disadvantage can be that this method is less robust in order to determine a weighting that represents the different analysis strategies of each AC. Finally, a combined datum-free normal equation system is calculated by adding the weighted normal equations of each contribution. For details about the weighting algorithm see Böckmann and Nothnagel (2008) (Paper C). On the one hand, this combined datum-free normal equation system is published for further combination efforts with other space-geodetic techniques. On the other hand, three different products are generated in the routine combination process by adding an appropriate datum: a combined TRF, a combined long-term EOP time series, and a set of combined station position time series.

More details are given in Vennebusch et al. (2007) (Paper A) which focuses on the basic mathematical principles of the combination based on normal equation systems, in Böckmann et al. (2010a) (Paper D) and in Böckmann et al. (2010b) (Paper F) in which improvements and enhancements in the combination strategy are documented.

6.2 Adaption of analysis options in the IVS

Besides the high-quality combination algorithm, consistency between the individual IVS ACs' contributions (i.e., only differences in the stochastic properties remaining) is essential for a good quality of the combined product. If series with systematic differences are combined, the influence of such systematics would be damped, but the combined products would not have a clear reference and, thus, would be less useful for high-precision purposes. Therefore, much effort has been undertaken to define and implement common standards in the community. These are based on the recommendations of the IERS Conventions 2003 and the IVS Analysis Conventions. Table 4.2 in Sec. 4.1 lists the most important ones. Although the conventional models should be the same in all software packages used, discrepancies in these type of analysis options were indeed discovered. However, differences may also originate from a different treatment of effects, for which no objectively best models exist at present or for which no widely accepted convention has been defined.

In order to find out whether the estimated parameters of the individual ACs yield systematic differences, detailed internal comparisons have been carried out. In the following, some typical examples are shown, where systematic differences have been uncovered and possible reasons are discussed. It should be mentioned here, that the graphical representation of the resulting time series in its session-wise form is not suitable because of the high noise level. For a better interpretation and detection of systematic differences, the time series are smoothed either with a weighted mean or a median of a moving 90-day window which is calculated each seventh day. This helps to uncover residual systematics in the individual solutions as they are expected to be at the same or even a lower order of magnitude than the high-frequency noise level itself. The 90-day window was chosen as a good compromise between suppressing the high-frequency noise in a robust way and having minimal damping of signals in the lower frequency domain. The formal errors of the weighted means are derived using rigorous error propagation. However, this approach has the disadvantage that possible periodic signals with periods smaller than 90 days will not be detected.

The first example, displayed in Fig. 6.2, originates from Böckmann et al. (2009) (Paper E). Clear systematic annual variations appear in the differences between the individual solutions and a preliminary combined solution. In this figure, only the LOD component is shown, but the same systematic variations are visible in the polar motion rates. Detailed studies of the individual models and analysis options have been carried out in order to identify the reasons for these variations. It turned out that they were mainly caused by different a priori high-frequency EOP models used in the individual contributions. While the contributions of DGFI and GSFC are computed with the model as recommended in the IERS conventions, the contributions of BKG and OPA used a high-frequency EOP model called "hf1102a" (Gipson 1996). The remaining differences between the DGFI and GSFC solutions, which are detectable in the EOP rates, can be attributed to different interpolation schemes to map the daily a priori EOP to the observation epoch.

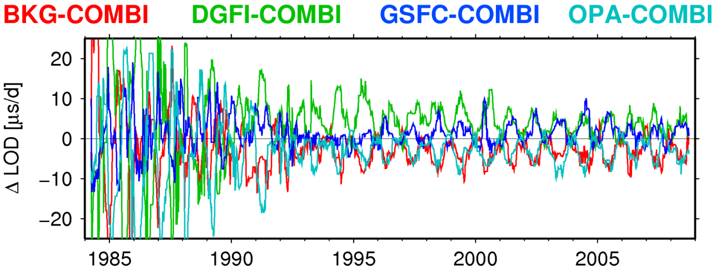

Figure 6.2: Daily LOD estimates of each individual solution compared to the preliminary combined solution. Different a priori sub-daily EOP models cause systematic annual variations. The time series are smoothed with a weighted mean of a moving 90-day window.

Another example is given in Fig. 6.3, published in Böckmann et al. (2007) (Paper B). Here the estimated height position time series of two individual solutions, DGFI and IGG, computed with different VLBI software packages (OCCAM and CALC/SOLVE), are compared. Only those sites participating in more than 30 sessions are shown. The arrows illustrate the mean offsets of the session-wise differences. The green and red arrows show the situation before and after the adaption of the analysis options, respectively. On average, the height offsets reach up to 5 mm with a clear systematic behavior of the signs in the individual quadrants of the Earth.

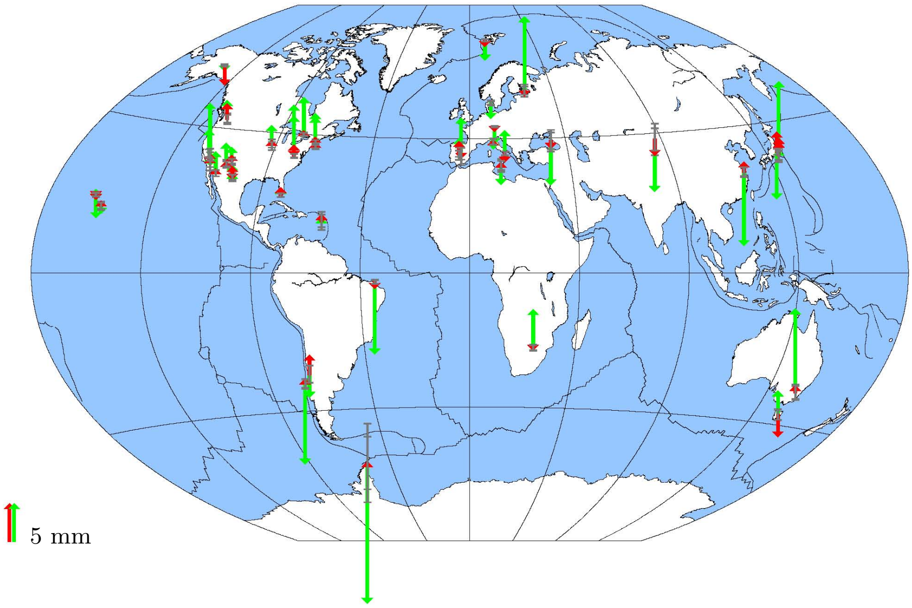

Figure 6.3: Offsets of the mean session-wise differences, in green the situation before the adaption of the analysis options, in red afterwards. Only those site participating in more than 30 sessions are shown.

Various geophysical phenomena can cause site displacements of a couple of centimeters, primarily in the height component. The IERS Conventions provide models describing the displacement due to ocean tidal loading, due to the solid Earth tides arising from the direct effect of the external tide generating potential, due to pole tides caused by Earth rotation variations as well as due to atmospheric loading. Furthermore, the reference points of the VLBI antenna can be affected by thermal deformations. All these models have been compared in detail. The main reason for these systematic differences are differences in the pole tide corrections. For the solution of IGG the pole tide corrections are referenced to a mean pole ($X_0 = Y_0 = 0$) instead of a linear pole path as recommended by the IERS Conventions 2003 which was used in the DGFI solution. After using the same pole tide model in both software packages, almost all offsets became smaller than 1 mm with random signs (red arrows).

The last example, published in Böckmann et al. (2010b) (Paper F), shows session-wise scale estimates for nine individual ACs' VLBI solutions derived from a seven-parameter similarity transformation of the session-wise station positions w.r.t. a common TRF. The IAA solution in gray shows a clear offset of about 1.5 ppb. Since the relativistic modeling has a direct impact on the scale, the implementation of the general relativistic models for space-time coordinates in the QUASAR software used by IAA, have been reviewed. We found out that this model used in this analysis software was coded according to the model recommended in the IERS Conventions 1996 instead of the Conventions 2003. The scale estimated for the AUS contribution is neither similar to the IAA scale nor to the other contributions. We identified, that the solutions computed from the normal equation systems provided by the AUS AC yielded unreliable results for all estimated parameters. However, the direct results from the OCCAM(LSC) software used by this AC are quite reasonable. Thus, most likely errors occurred in the analysis chain, i.e., in the extraction of the normal equations.

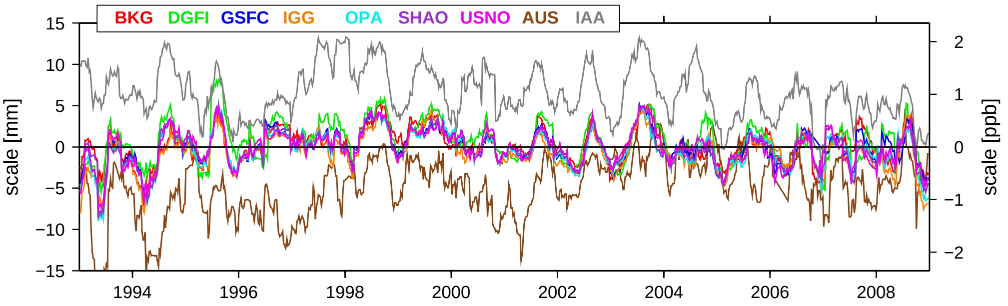

Figure 6.4: Session-wise scale estimates for nine individual VLBI solutions derived from a seven-parameter similarity transformation of the session-wise station positions w.r.t. a common TRF. The scale time series are smoothed with a weighted mean of a moving 90-day window.

6.3 Consistency of the individual contributions to the IVS combination

As described in Sec. 6.2, detailed comparisons of the individual contributions were carried out, and uncovered systematic deviations were removed to the largest extent possible by the IVS ACs by recommendations of the author. The aim of this section is to illustrate the level of homogeneity achieved, and to quantify the level of analyst noise that is left. Furthermore, signals in the time series are discussed. The results presented in this section as well as in the next one (Sec. 6.4) are published in Böckmann et al. (2010a) (Paper D) and Böckmann et al. (2010b) (Paper F).

In order to give an impression of the quality and consistency of the individual series, station position time series computed from each individual contribution with respect to a combined TRF solution are calculated. As an example, the time series of station WETTZELL (Germany) from each AC's contribution is illustrated in Fig. 6.5. For a better presentation and interpretability, the graph is provided twofold, (a) for the whole observation period of WETTZELL (1984-2008) and (b) for only part of the time series (2000 - 2005) together with the formal errors. The consistency of the individual time series shown here for WETTZELL is typical

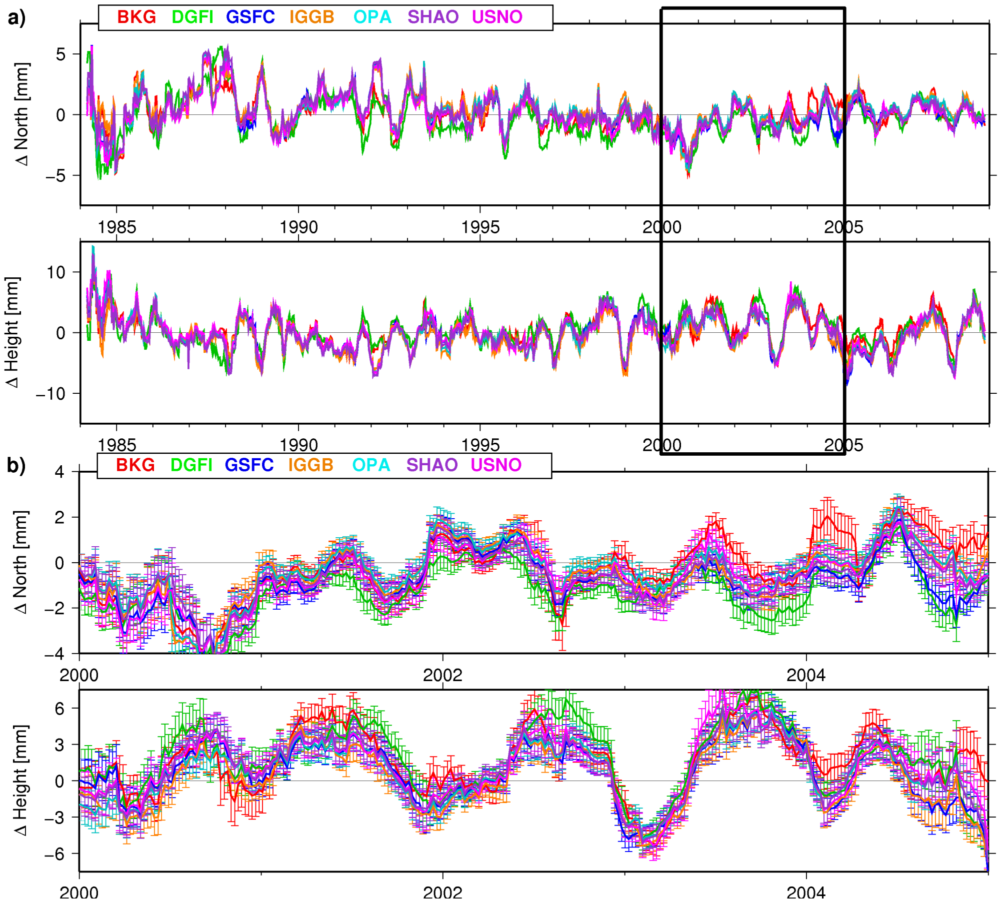

Figure 6.5: Weighted mean smoothed time series of the north and height component (estimates with respect to the combined TRF) of the individual ACs solution of the station WETTZELL (Germany). The east component looks similar to the north component. a) The time series for the whole observation period. Errors bars are not shown. b) A detail (2000-2005) of a) with zoomed scale. The error bars denote the 1σ formal errors of the smoothed time series.

for sites observing frequently. The time series of the ACs GSFC, SHAO and USNO are nearly identical. This is not surprising, since they all use the same software and a very similar solution setup (see Tab. 4.3 in Sec. 4.2). Thus, these contributions almost only differ in the way of identifying outliers. As expected, a slightly different temporal behavior is visible for the time series of BKG and DGFI. However, the differences are still within their 1σ formal errors. The BKG contribution is computed with the same software package, but many analysis options, that are not subject to conventions, are different from the GSFC/SHAO/USNO solution setup. The DGFI contribution is computed with a different software and a different solution setup.

In the lower panel of Fig. 6.5b it can be seen very clearly that the strongest remaining signals in the station position time series are almost always annually repeating patterns in the height component. They reflect the integral of all vertical deformation effects on the Earth's crust, like atmospheric and hydrological loading, as well as modeling errors of seasonal nature, for which the observations have not been corrected (Collilieux et al. 2007). Therefore, in the following comparisons, we aim at detecting possible discrepancies in terms of mean amplitude and mean phase between the individual height time series. As most of these effects are repeating annually, but not of harmonic nature, an approach as proposed by Tesmer et al. (2009) has been used to compare the height variations of the different AC's contributions. In this approach, first a weighted mean value is removed from the original session-wise height estimates for each year. Subsequently, the session-wise height estimates are stacked in a time interval of one year by removing the integer year of the decimal-year time stamps, and sorted by day-of-year. Finally, this year of data is smoothed with 90-days moving weighted means, computed each 7 days. Since the robustness of the mean annual signal depends on the amount of data available, only those 32 stations are used for this analysis, which have participated in more than 90 sessions and were analyzed by all ACs.

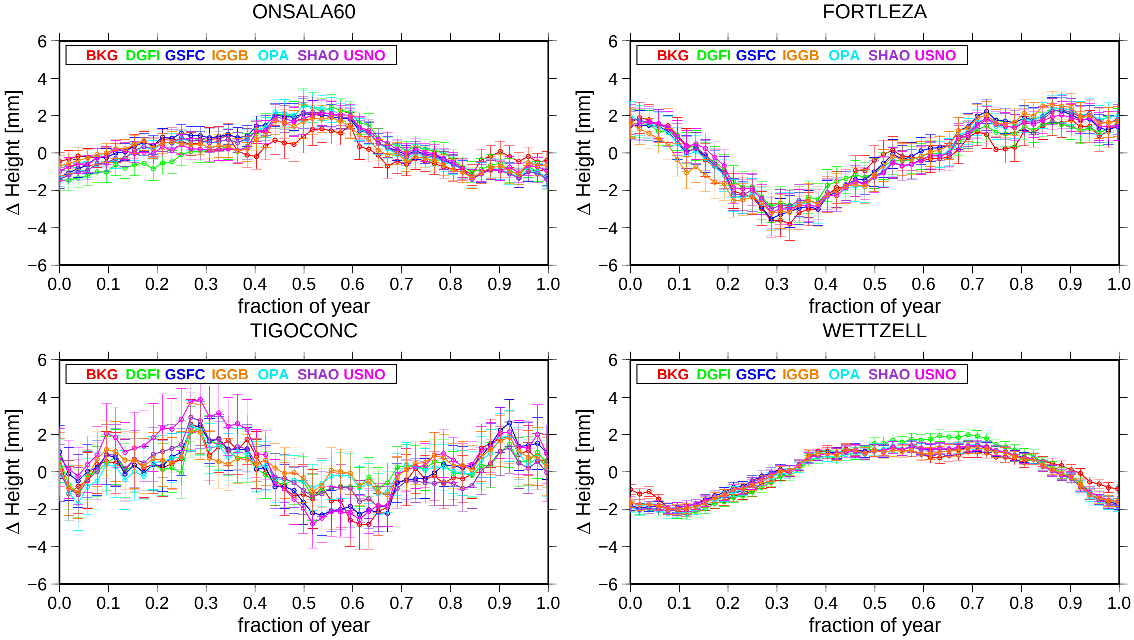

Figure 6.6: Mean annual height signals of four VLBI stations: ONSALA60, FORTLEZA, TIGOCONC and WETTZELL. The graphics illustrate 90-day moving weighted means and their formal errors, computed each 7 days from the daily height estimates with the weighted mean values removed for each year before stacking all the years.

The annual signals of the 32 stations contained in the seven ACs' contributions (BKG, DGFI, GSFC, IGG, OPA, SHAO, USNO) all agree within their formal errors. Even the results of DGFI, using the analysis software OCCAM(LSM) instead of CALC/SOLVE compare very well. Figure 6.6 illustrates the agreement for four VLBI stations: ONSALA60 (Onsala, Sweden), FORTLEZA (Fortaleza, Brazil), TIGOCONC (Concepción, Chile) and WETTZELL (Wettzell, Germany).

The different contributions agree best for WETTZELL, as it has a continuous observation time span over more than twenty years and a huge number of observations. Unlike WETTZELL, the station TIGOCONC at Concepción only started to observe in 2002 and frequently has a smaller number of delay observations per session due to its geographically remote position. Here, the consistency between the ACs is lower than for WETTZELL, but, nevertheless, most of the contributions agree within their 1σ formal errors.

The level of analyst noise that is left can be quantified by the single-session differences between each individual and the combined station position time series. Table 6.1 summarizes the differences in terms of WRMS computed as one overall value for 52 stations that have been analyzed by all ACs.

On average over all contributions, the analyst noise that is left is quite small, for the horizontal components 1.1 and 1.4 mm, for the height component 2.2 mm. The WRMS values of the solutions of OPA and SHAO show the lowest WRMS values for all three components. This might be attributed to the slightly higher weights they received in the combination process since 1993 compared to all other contributions (see Fig. 2b in Böckmann et al. (2010b), Paper F). The WRMS values of the solutions of BKG and DGFI are slightly higher than those of the other solutions. For the DGFI solution which is analyzed with the OCCAM software, this is probably due to the fact that the combined solution is dominated by six contributions using the CALC/SOLVE software. The slightly higher scatter in the BKG results (also analyzed with CALC/SOLVE)

Table 6.1: WRMS computed from the single-session station position differences between the estimates of each individual contribution and the combined series for the north, east and height component.

AC - IVS comb.	North (mm)	East (mm)	Height (mm)
BKG	1.6	2.1	3.7
DGFI	1.6	2.0	3.1
GSFC	0.9	1.1	1.9
IGG	0.9	1.2	2.1
OPA	0.7	0.9	1.5
SHAO	0.7	0.8	1.5
USNO	1.0	1.4	2.2
average	1.1	1.4	2.2

may again be attributed to the analysis options chosen by the analyst, which are in many aspects different from those used by GSFC/SHAO/USNO.

Beside the coefficients for station coordinates, the normal equation systems of each AC contain EOPs. Therefore, also the consistency of the EOP series, calculated from the normal equation systems, is analyzed by comparing each individual series with the combined series. For these comparisons, only those sessions have been used which are suitable for a reliable EOP determination[1] and which are analyzed by all ACs. The main result is that no remaining systematic differences could be detected in the individual series with respect to the combined series. As an example, Fig. 6.7 displays the differences between each individual EOP series and the combined series for the X-pole component. It is clearly visible that the consistency of all solutions improves much after 1993. This can be attributed to the generally higher quality of the VLBI results due to a better scheduling with an increased number of sources observed within one session (Eubanks et al. 1991).

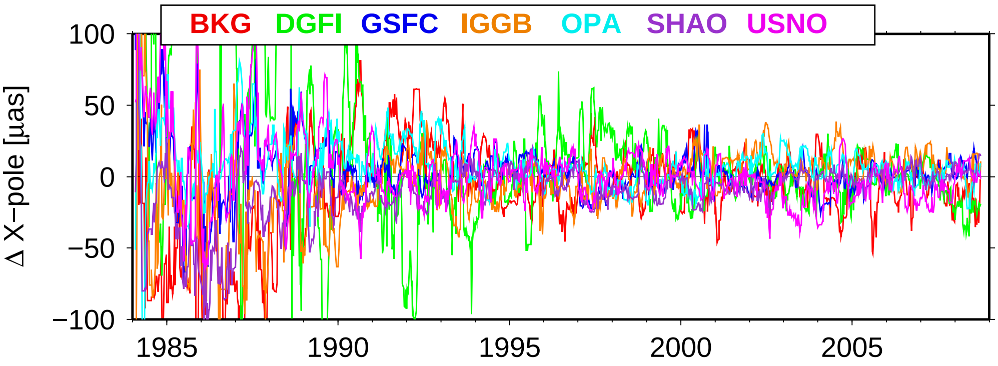

Figure 6.7: Weighted mean smoothed time series of the X-pole differences of each individual VLBI solution and the combined VLBI solution.

The offsets and rates of the differences 'individual solution minus combined solution' are almost always within three times their formal errors, as all contributions are transformed to the same TRF. The only exception is a very small rate of 3 μas/year in the nutation components (dX, dY) between the DGFI and the combined solution which corresponds to 93 μm/year on the Earth's surface. This rate could be due to the different CRF realizations which are used by the ACs. In the near future, the normal equation systems of the contributing series will be extended by including the source coordinates. Then, a common CRF can be computed in the same combination process and be used for all contributions.

WRMS values of the differences between each individual and the combined series computed over the entire observation period (1984-2008) are summarized in Tab. 6.2 for each EOP component. Generally, the seven

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[1] http://vlbi.geod.uni-bonn.de/IVS-AC/data/exclude.txt

series used as input for the IVS-combined series are very consistent, with differences between the individual and the combined series having WRMS values of about 40 μas in both polar motion offsets, and about 3 μs in dUT1. On the Earth's surface 40 μas correspond to 1.3 mm, 3 μs to 1.4 mm. These 1.3 to 1.4 mm are almost the same as the WRMS values of differences between the horizontal station positions of the individual and the combined series (see Tab. 6.1). However, as the Earth rotation offsets are in fact represented by the integral horizontal displacement of all stations, slightly better WRMS values ($\sqrt{NoStations} \sim \sqrt{6}$) for the EOPs would be expected than for the horizontal station positions. Nevertheless, the real factor also depend on the geocentric geometry of the observing networks.

Like for the station position time series, the WRMS values of the differences OPA–IVS-combined and SHAO–IVS-combined show the lowest WRMS values for almost all EOP components. The WRMS values of the differences BKG–IVS-combined and DGFI–IVS-combined are slightly higher than of the other solutions. The reason here is the same as already specified before for the station positions.

Table 6.2: WRMS values computed from the single-session EOP differences between the estimates of each individual contribution and the combined EOP series from 1984 to 2008 for polar motion, dUT1 and their first derivatives as well as nutation offsets.

AC – IVS-comb.	X-pole (μas)	Y-pole (μas)	dUT1 (μs)	LOD (μs)	X-pole rate (μas/d)	Y-pole rate (μas/d)	dX (μas)	dY (μas)
BKG	56.2	55.3	3.5	6.2	174.3	170.2	46.0	48.0
DGFI	57.8	55.2	3.4	6.5	174.9	163.6	47.8	48.9
GFSC	34.4	34.2	2.7	3.5	103.5	98.5	28.8	30.5
IGG	37.1	32.7	2.9	4.4	113.9	106.8	32.5	33.2
OPA	30.6	31.2	2.8	3.8	93.5	92.6	29.1	29.9
SHAO	27.9	28.4	2.6	2.9	86.8	80.0	24.7	26.1
USNO	41.7	37.7	3.0	4.2	122.5	111.9	34.2	36.5
average	40.8	39.2	3.0	4.5	124.2	117.7	34.7	36.2

In summary, it can be said that quite a high level of homogeneity of the individual contributions to the IVS combination is achieved. The station position time series computed from the individual contributions show all very similar signals with respect to the underlying TRF. The level of analyst noise quantified by the differences between the individual and the combined time series is quite small: below 1.5 mm for the horizontal site components and 2.2 mm for the height component. The values for the EOPs are consistent with those obtained for the horizontal site components although slightly better values are expected.

6.4 Quality of IVS-combined products

The quality of the IVS-combined products can be characterized on the one hand by its internal precision on the basis of station position repeatabilities, on the other hand by EOP comparisons with results from other techniques. The repeatability of a value is usually computed as the (weighted) RMS of the scatter w.r.t. the mean value. These two measures were also computed for each contributing AC's individual series.

The station position repeatabilities were computed from single-session position estimates after reducing offsets, rates and harmonic annual signals. The harmonic annual signals are removed because they are considered to consist of signal rather than noise (Petrov and Ma 2003). Offsets, rates and annual signals are estimated from each series individually. However, within their formal errors they are similar. The amplitudes are quite small with about 1 mm on average for the heights of the 52 stations that were analyzed by all ACs. The largest significant amplitude is detected for TSUKUB32 (Tsukuba, Japan) with 5.3 ± 0.6 mm which can be attributed to seasonal cyclic ground water withdrawal (Munekane et al. 2004). For the horizontal components, all annual signal amplitudes are within three times their formal errors. On average the amplitudes are 0.5 mm, with the maximum for SANTIA12 (Santiago, Chile) with 5.2 ± 2 mm probably resulting from the short observation history with data only in the early 1990s.

Table 6.3 shows the repeatabilities of the session-wise estimated station positions after removing offset, rate and harmonic annual signal from the time series. They are computed as overall values for the 52 stations that were analyzed by all ACs.

Table 6.3: Repeatabilities of the session-wise estimated station positions for the north, east and height component after removing offsets, rates and annual signal from the time series computed as overall values for the 52 stations that were analyzed by all ACs.

AC	North (mm)	East (mm)	Height (mm)
BKG	3.2	4.2	7.2
DGFI	3.0	4.0	6.6
GSFC	2.9	3.8	6.7
IGG	3.0	4.0	6.8
OPA	3.0	3.9	6.7
SHAO	2.9	3.9	6.7
USNO	3.0	3.9	6.7
average individual ACs	3.0	4.0	6.8
IVS-comb.	2.9	3.8	6.3

The repeatabilities for each of the seven series contributing to the IVS combined series are more or less at the same level. For the north and east component, they average to 3.0 mm and 4.0 mm, respectively. For the height component they reach 6.8 mm. The repeatabilities of the combined series are on average for the horizontal and vertical components only 4% and 7% smaller than those from the individual series. An interpretation of the achieved benefit is given at the end of this section.

Contrary to Tab. 6.1, which summarizes the single-session station position differences between the estimates of the individual contribution and the combined series, Tab. 6.3 shows the repeatabilities of the session-wise estimated station positions for each individual and the combined series. The values in Tab. 6.1 have to be smaller since subtraction of the combined series from the individual ones clearly reduces remaining signals.

As a second assessment of the quality of the combined results, comparisons with externally derived EOP time series from other space-geodetic techniques have been carried out. In this case, the combined GNSS time series provided by the IGS is used. The IGS polar motion and LOD combination started on June 30, 1996 and February 23, 1997, respectively. The IGS LOD combination has achieved the current level of accuracy only in the second half of 1997 (Kouba and Vondrák 2005). Therefore, for the comparisons with the IGS EOP series, 11 years of data from September 1997 to September 2008 have been used.

VLBI-derived EOPs almost always refer to the mid of the session (usually 6 h UTC) while the IGS-derived EOPs refer to the middle of the day (12 h UTC). Thus, in the following comparisons, the IGS derived polar motion offsets are linearly interpolated to the VLBI epoch of each session. Due to the high variability of LOD, a pure linear interpolation is not sufficient for this EOP component. Therefore, the IGS LOD values at the VLBI epoch were computed by (1) correcting LOD for the effect of zonal tidal deformation on the physical variations in the rotation of the Earth (LOD-R, Tab. 8.1 of McCarthy and Petit 2004), (2) interpolating linearly to the VLBI epoch, (3) adding the corrections back to the interpolated LOD-R value to obtain LOD.

Figure 6.8 shows the median smoothed differences between each individual VLBI solution and the IGS EOPs, as well as the differences between the IVS-combined VLBI solution and IGS from September 1997 onwards. Generally, the differences of all VLBI solutions w.r.t. IGS show very similar characteristics. Sometimes, the differences in polar motion and LOD exhibit moderate but clear systematics between IVS and IGS. This is by far not so clear if the raw, session-wise estimates are considered, as these values are dominated by noise.

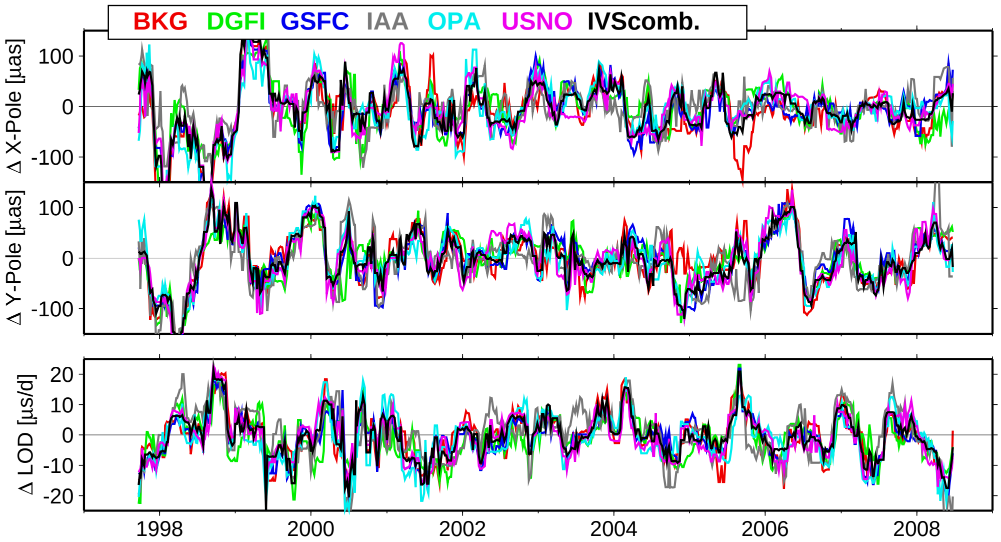

Figure 6.8: Median smoothed time series of the detrended differences of each individual VLBI solution and the combined VLBI solution w.r.t. the IGS EOP series from September 1997 till September 2008.

The discrepancies in polar motion are expected to originate from VLBI since the total GPS TRF is much more stable than that of VLBI (Artz et al. 2008, Malkin 2008). A very significant bump is visible, e.g., in the Y-pole differences in 2006. Investigations have shown that this bump results from considerable VLBI network changes which happened during that time: GILCREEK (Gilmore Creek, Alaska, USA) and ALGOPARK (Algonquin Park, Canada) stopped their operations, NYALES20 (NyÅlesund, Spitsbergen, Norway) stopped to participate for a few months, ZELENCHK (Zelenchukskaya, Russia) started to operate and MATERA (Matera, Italy) and HOBART26 (Hobart, Australia) started to participate on a more frequent and regular basis.

The situation is much less clear for the significant discrepancies in LOD:

1. VLBI measures LOD directly geometrically, while GPS LOD is affected by physical parameters of the orbit which change over the day (averaged over the whole constellation) due to a distinct linear dependency with the right ascension of the ascending node of the satellite orbits (see, e.g., Rothacher et al. 1999 or Schmid et al. 2007). Any unmodeled forces acting on the satellites, which affect the rate of change of the satellite nodes will contaminate the LOD estimates. GPS is thus not able to determine the long-term behavior of LOD. However, the VLBI results are noisier at high frequencies (due to the smaller terrestrial networks and thus less robust equation systems on the short term).

2. The IGS combined LOD values are calibrated by a moving average bias with respect to Bulletin A[2] (a rapid multi-technique combination EOP series), averaged over the latest 21 days (Mireault et al. 1999). So, it is surprising to see that IGS LOD has an anomalous long term-behavior compared to LOD from VLBI.

3. Ray et al. (2008) detected anomalous harmonics in the spectra of GPS position estimates with a period of about 351.2 days and suggested that these harmonics might be attributed to the GPS "draconic" year, i.e., the interval required for the constellation to repeat its orientation with respect to the sun. The IGS station position time series contain annual and semi-annual harmonic constituents, which is also the case for VLBI (Petrov and Ma 2003).

The WRMS values of the differences of the IVS and each single AC's VLBI solution w.r.t. IGS provide a measure of the quality. However, as discussed above, the differences still contain signals seen by each series.

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[2] http://data.iers.org/products/6/13270/orig/bulletina-xxiii-024.txt

Table 6.4 summarizes the differences of the IVS and each single AC's VLBI solution w.r.t. IGS expressed as WRMS values, computed after removing offset and rate from the series between September 1997 and September 2008. For almost each EOP component, the combined solution fits better to IGS than each individual VLBI EOP solution. For the polar motion offsets and LOD the averaged enhancement is about 10%, for the polar motion rates with 13–14% improvement even higher.

Table 6.4: WRMS of each individual VLBI series contributing to the combination and the IVS combined solution w.r.t. IGS (computed from the detrended differences between September 1997 and September 2008).

	X-Pole (μas)	Y-Pole (μas)	X-Pole rate (μas/d)	Y-Pole rate (μas/d)	LOD (μs)
BKG	140.6	125.1	347.8	338.9	20.1
DGFI	110.4	105.5	310.7	311.1	19.1
GSFC	120.9	111.0	311.5	304.6	18.6
IAA	126.8	129.5	369.0	360.8	22.5
OPA	123.4	118.1	352.6	350.7	20.1
USNO	123.1	117.6	327.9	326.7	19.6
average individual ACs	124.2	117.8	336.6	332.1	20.0
IVS comb.	110.1	106.7	290.2	289.5	18.1

The improvements in EOPs achieved by the combination are not directly comparable with the improvements in station position repeatabilities. The station position repeatabilities result from an analysis carried out for the IVS contribution to ITRF2008 (Böckmann et al. 2010b, Paper F), the EOP comparisons with IGS come from the routine IVS EOP combination (Böckmann et al. 2010a, Paper D). Not exactly the same ACs have contributed to both combinations.

As mentioned in Ch. 1, a combination of the individual ACs' contributions reduces the analyst's noise and should, thus, lead to more stable results. The comparisons of Sec. 6.3 have shown, that the smoothed individual series are very similar which makes clear that they see the same long-term signals (as most systematic differences due to non-conventional modeling effects were already found and removed in advance). The fact that the station position repeatabilities and the EOP comparisons with IGS of the IVS combined solution are not fundamentally better than those of the individual IVS series can only be interpreted in such a way that

1. the remaining analyst's noise is small compared to remaining geophysical signals or model deficiencies (see Fig. 6.5 for station positions and Fig. 6.8 for EOPs) and
2. VLBI data analysis today is already at a level of precision very close to the technical precision of the observations.

However, although the direct benefit of combining the individual contributions is quite small, due to the detailed comparisons and analyses of differences, several systematic differences between the individual IVS contributions were detected and improvements in adherence to standards achieved. Furthermore, outliers are eliminated which makes the results more robust and, thus, more reliable.

6.5 Correlations between the contributions of the individual IVS ACs

In the previous section it has been shown that the robustness and stability of the results can be improved by combining the individual contributions. However, as the contributions of each AC are derived from virtually the same set of original observations, correlations between the contributions are expected. So far this topic has been completely neglected in any intra-technique combination approach. In Böckmann et al. (2010) (Paper G) the level of the correlations between the contributions of the individual IVS ACs is investigated and the effects on the combined parameters as well as their formal errors is discussed.

In this study, the observation equations of two ACs (BKG and IGG) are used directly for the combination (in contrast to using normal equation systems). This allows to determine the level of correlations with the rigorous variance-covariance component estimation algorithm (see, e.g., Koch 1999) and to investigate the influence of neglecting the correlations on the estimated combined parameters as well as their formal errors. For the CONT02[3] data (Continuous VLBI Campaign 2002), it turned out that a realistic level of correlations between the contributions of BKG and IGG to the IVS combination lies between 0.5 and 0.7 (see Fig. 6.9). It should be noted, however, that correlations can be smaller using contributions from ACs which use different software packages or higher if more similar analysis options are chosen by the analysts than those preferred by IGG and BKG.

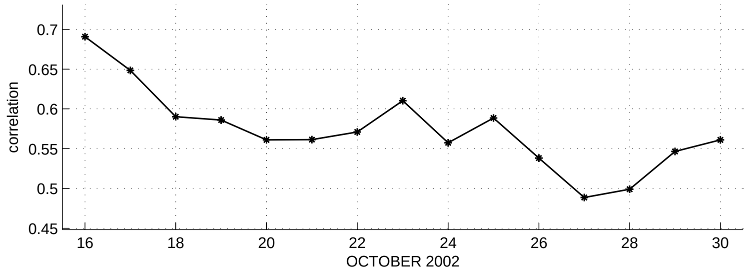

Figure 6.9: Level of correlations between the two contributions (IGG and BKG) during the two-week CONT02 campaign.

It is shown that the negligence of correlations primarily impacts the formal errors of the estimated parameters and not the parameters themselves (a well-known fact). In the case of two contributions, formal errors are too optimistic by a factor of approximately 1.2. Since six and not only two ACs contribute to the operational IVS combination at the moment, the formal errors are expected to be even less realistic. A simplified error propagation assuming six contributions all correlated among each other with 0.6, leads to too optimistic formal errors of the combined parameters by a factor of about 2.

In order to find out if this is realistic, comparisons with independent EOP series may serve as a simple empirical approach. Here, the IGS EOP series[4] is used as a reference. The formal errors of the IGS series are assumed to be zero. If the WRMS of the differences of the two series stay within the formal errors, the formal errors can be assumed to be realistic. Therefore, the differences of all individual AC's solutions as well as of the combined solution w.r.t. IGS are computed. For the data of one month each, WRMS values and median formal errors of these differences are calculated and compared for the period 1996.0 to 2009.0.

As displayed in Fig. 6.10 for the X-pole, the ratio of the median formal errors and the WRMS, both computed for the data of one month with a 7-day sliding window, are less than one, which indicates that the formal errors are too optimistic. The same holds for the Y-pole component, LOD, and the polar motion rates. For the individual VLBI series the ratios are about 0.6, while the ratio for the combined solution (without considering correlations) is less than 0.4. However, it is not possible to attribute unambiguously the too optimistic formal errors to the IGS or to the VLBI series. In the present study, the goal is merely that the ratio of the combined series w.r.t IGS equals the level of the ratio of the individual VLBI solutions. This can be achieved by scaling the formal errors of the combined solution with 2 (see Fig. 6.10) which is exactly the number derived from a simplified error propagation.

This study has shown that correlations between the individual ACs' contributions can be determined and rigorously taken in account during the combination process if directly the observation equations are used.

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[3] http://ivscc.gsfc.nasa.gov/program/cont02/

[4] ftp://cddis.gsfc.nasa.gov/gps/products/igs00p03.erp.Z

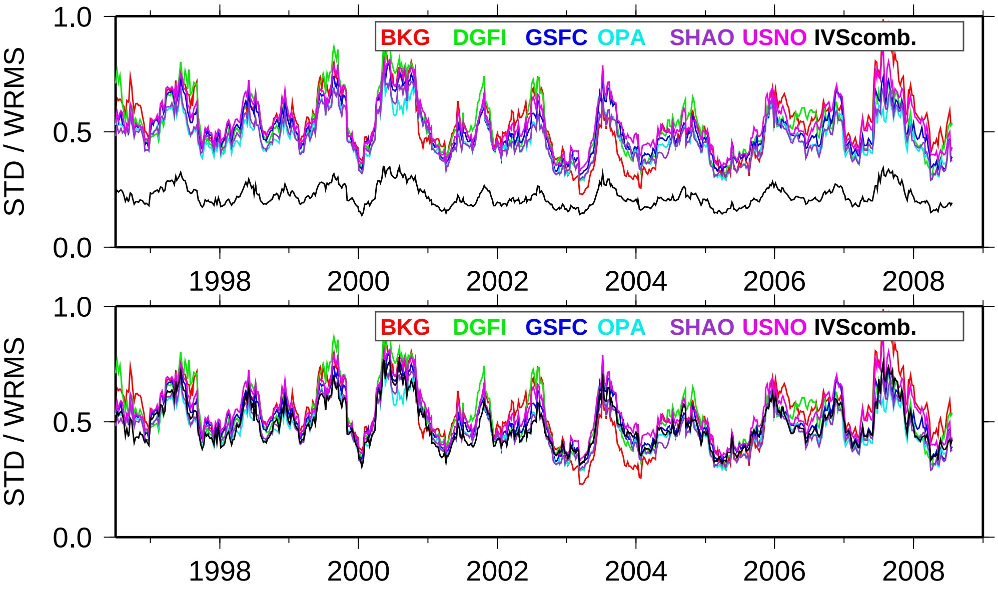

Figure 6.10: Ratio of the formal errors and the WRMS values of each individual series computed from the normal equation systems and the combined series w.r.t. IGS, (top) without scaling of the formal errors, (buttom) after scaling the formal errors of the combined solution by a factor of 2.

This leads to more realistic formal errors of the estimated combined parameters. With the current number of VLBI observations a combination at the level of observation equations is possible. However, difficulties with the software packages and IT infrastructure may occur if the future VLBI2010 concept (see, e.g., Niell et al. 2005, Behrend et al. 2008) is realized with a scheduled tenfold increase of observations (100.000 observations per session).

A validation with a longer dataset and contributions of further ACs could be useful. This would allow to investigate the variability of the correlations over a longer time span as well as the different level of correlations between the individual contributions.

7. Outlook

In this thesis, it has been shown that combining contributions of different IVS ACs to one official final product yields several positive indirect and direct effects. Due to the detailed comparisons and analyses of differences implied in the combination process, several systematic differences between the individual IVS contributions were detected and improvements in adherence to standards achieved. Furthermore, outliers can be eliminated which makes the results more robust and , thus, more reliable. The refined combination approach reduces the analyst's noise and leads to an additional benefit of up to 15% more accurate results.

Despite the satisfactory results obtained from the IVS intra-technique combination already now, there is still potential for further improvements. First of all, additional parameters like source positions and, potentially, tropospheric zenith path delays and gradients should be included explicitly in the normal equation systems. This a not a new idea, the extended parameter-space has already been suggested by Rothacher (2003) and successfully demonstrated in a German research project called *GGOS-D* (Global Geodetic-Geophysical Observing System - Deutschland, Rothacher et al. 2010). However, so far, this idea has not been adopted within the international services.

At the moment only the TRF and the EOPs are rigorously combined. But, since the EOPs are the direct link between the terrestrial and the celestial reference frame, a simultaneous estimation of the TRF, EOPs and the CRF is necessary. The VLBI technique uniquely provides the parameters for the CRF. Thus, to also add source positions to the rigorous overall combination effort, would not only improve the VLBI intra-technique combination. It would be rather important to guarantee full consistency for the IERS products ITRF, EOPs, ICRF.

More critical are the tropospheric zenith path delays and gradients. Since an objectively best parameterization for these type of parameters is still a scientifically open question, its choice changes from analyst to analyst. Thus, if these parameters should be included in the combination, an identical parameterization or at least parameterizations which can be mathematically transformed unambiguously into each other would be required. In contrast to this, a stochastic parameterization using a filter approach would be impossible. However, due to high correlations between station coordinates and troposphere parameters, the latter should not be neglected in a rigorous combination. It is expected that a combination of the troposphere parameters would lead to a stabilization of the station network. At the moment VLBI troposphere zenith delays are combined independently from all other parameters by simply averaging the results of eight IVS ACs. Using this combination method, Heinkelmann et al. (2007) found several inconsistencies between the individual ACs' results, which are due to inhomogeneous analysis options, different parameterizations, and different treatment of missing in-situ pressure records. Besides, an extension of the normal equation systems by this parameter type would allow a further combination with tropospheric parameters derived from other space-geodetic techniques. Steigenberger et al. (2007) demonstrated that troposphere parameters from VLBI and GPS show common signals at a very high level of precision. In a combination study using the 15-day CONT02 campaign, Krügel et al. (2007) showed that a combination of VLBI and GPS troposphere parameters at the normal equation level leads to an improvement of the repeatabilities of the station height components.

From a statistical point of view, intra-technique combinations suffer from the fact that the contributions of different ACs are treated independently although they are derived from the same set of original observations. As a rigorous consideration of these dependencies presents a delicate problem within today's combination methodologies, so far, this topic has been completely neglected. In Böckmann et al. (2010) this topic is investigated for the first time. A pilot study using the 15-day CONT02 campaign has been carried out, in order to determine the level of correlations between the IVS ACs contributions as well as to investigate the effect of neglecting these correlations on the combined parameters and their formal errors. It is shown that correlations at the level of 0.6 can be expected between the individual contributions. Furthermore, it is demonstrated that the formal errors of the combined parameters, determined from six contributions, are too optimistic by a factor of about 2 if these correlations are neglected. Therefore, the formal errors of the IVS combined EOPs and station positions are routinely scaled with the factor 2.

It is recommended that such studies are also carried out for the intra-technique combinations of other techniques. First of all, this would provide a general knowledge about the level of correlations between the individual contributions. Furthermore, it can be investigated how a disregard of the correlations during the combination affects the estimated combined parameters and their formal errors.

In a further development step, the possibility of using directly the observation equations instead of normal equation systems as contributions of the individual ACs should be investigated. Only a combination at the level of observation equations makes a rigorous consideration of the correlations between the individual ACs' contributions possible. In view of the number of observations per session, which today are about 5.000 per AC (35.000 for seven ACs) in a standard VLBI session, a combination at the level of observation equations would be possible. However, this will be more problematic if the future VLBI2010 concept is realized with a scheduled tenfold increase of observations. In particular, if this combination approach should also be carried over to other techniques with a much larger number of observations, like GNSS, the computer storage capacities may pose the major problem.

The intra-technique combination should also be applied to the so-called *Intensives*. So far, only the IVS ACs' contributions of regular VLBI 24h network sessions are combined. The sole objective of the Intensive sessions is the daily measurement of the Earth rotation angle UT1, as UT1 is the most variable quantity compared to all other other EOP components with significant unpredictable variations (Nothnagel and Schnell 2008). Only one large east–west baseline with about 1h of observing time is used in order to monitor the UT1 behavior and provide a basis for predictions. Due to the small number of observations these equation systems and, consequently, the estimated parameters are not very robust. Therefore, the impact of the chosen analysis options and, thus, the analyst's noise is bigger than for the the regular 24h VLBI sessions. Hence, it is expected that the Intensive sessions will strongly benefit from an intra-technique combination which will be investigated in the near future. Besides the intra-technique combination, these sessions will profit from an inter-technique combination for example with observations from GPS.

Finally it is pointed out that the detailed comparisons and standardization of models should continue on the level of the IERS services. In order not to affect the continuity and reliability of the operational products, each AC should provide two different series: an operational series with common standards for the routine combination, as well as a test series with free modeling for research on further improvements.

8. List of publications relevant to the thesis work

Below is a list of publications on related work to which I have contributed. These publications are not included in this thesis, but document the relevance of this work in the scientific community.

Kierulf, H.P., P.H. Andersen, S. Böckmann, O. Kristiansen (2010) VLBI analysis with the multi-technique software GEOSAT. In: Behrend, D., K.D. Baver (eds) *IVS 2010 General Meeting Proceedings*, NASA/CP-2010-xxxxxx, in press.

Rothacher, M., D. Angermann, T. Artz, W. Bosch, H. Drewes, S. Böckmann, M. Gerstl, R. Kelm, D. König, R. König, B. Meisel, H. Müller, A. Nothnagel, N. Panafidina, B. Richter, S. Rudenko, W. Schwegmann, M. Seitz, P. Steigenberger, V. Tesmer, D. Thaller (2010) GGOS-D: Homogeneous Reprocessing and Rigorous Combination of Space Geodetic Techniques. submitted to *J Geod.*

Steigenberger, P., T. Artz, S. Böckmann, R. Kelm, R. König, B. Meisel, H. Müller, A. Nothnagel, S. Rudenko, V. Tesmer, D. Thaller (2009a) GGOS-D Consistent, High-Accuracy Technique-Specific Solutions. In: Flechtner, F.M., M. Mandea, T. Gruber, M. Rothacher, J. Wickert, A. Güntner, T. Schöne (eds), *System Earth via Geodetic-Geophysical Space Techniques, Advanced Technologies in Earth Sciences*, Springer, ISBN 978-3-642-10227-1, in press

Nothnagel, A., T. Artz, S. Böckmann, N. Panafidina, M. Rothacher, M. Seitz, P. Steigenberger, V. Tesmer, D. Thaller (2009) GGOS-D Consistent and Combined Time Series of Geodetic/Geophysical Parameters. In: Flechtner, F.M., M. Mandea, T. Gruber, M. Rothacher, J. Wickert, A. Güntner, T. Schöne (eds), *System Earth via Geodetic-Geophysical Space Techniques, Advanced Technologies in Earth Sciences*, Springer, ISBN 978-3-642-10227-1, in press

Nothnagel. A., S. Böckmann (2009) External validation. In: *The second realization of the international celestial reference frame by very long baseline interferometry.* IERS Technical Note 35, Presented on behalf of the IERS / IVS Working Group, Fey, A., D. Gordon, C.S. Jacobs (eds), Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, (available electronically at http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn35.html), in press.

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Artz, T., S. Böckmann, A. Nothnagel and V. Tesmer (2008) Comparison and Validation of VLBI Derived Polar Motion Estimates. In: Finkelstein, A. and D. Behrend (Eds.), *Measuring the Future, Proceedings of the Fifth IVS General Meeting*, 324–328. (available electronically at http://ivscc.gsfc.nasa.gov/publications/gm2008/).

Behrend, D., J. Böhm, P. Charlot, T. Clark, B. Corey, J. Gipson, R. Haas, Y. Koyama, D. MacMillan, Z. Malkin, A. Niell, T. Nilsson, B. Petrachenko, A. Rogers, G. Tuccari and J. Wresnik (2008) Recent Progress in the VLBI2010 Development. In: Sideris, M. G. (Eds.), *Observing our Changing Earth*, Volume 133 of the series International Association of Geodesy Symposia. Springer Berlin Heidelberg, 833–840. ISBN 978-3-540-85425-8, ISSN 0939-9585.

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Abbreviations

AC	Analysis Center
AUS	Geoscience Australia
BKG	Federal Agency for Cartography and Geodesy (Bundesamt für Karthographie und Geodäsie)
CONT02	Continuous VLBI Campaign 2002
CRF	Celestial Reference Frame
DGFI	German Geodetic Research Institute (Deutsches Geodätisches Forschungsinstitut)
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EOP	Earth Orientation Parameter
FES	Finite Element Solution
GGOS-D	Global Geodetic-Geophysical Observing System - Deutschland
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
IAA	Institute of Applied Astronomy
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IDS	International DORIS Service
IERS	International Earth Rotation and Reference Systems Service
IGG	Institute of Geodesy and Geoinformation
IGS	International GNSS Service
ILRS	International Laser Ranging Service
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IVS	International VLBI Service for Geodesy and Astrometry
LLR	Lunar Laser Ranging
LOD	Length Of Day
LOD-R	reduced LOD (LOD corrected for the effect of tidal deformation on the physical variations in the rotation of the Earth)
OPA	Paris Observatory (Observatoire de Paris)
RMS	Root Mean Squared
SHAO	Shanghai Observatory
SINEX	Solution INdepenend EXchange
SLR	Satellite Laser Ranging
TRF	Terrestrial Reference Frame
USNO	US Naval Observatory
VCE	Variance Component Estimation
VLBI	Very Long Baseline Interferometry
VMF1	Vienna Mapping Function 1
WRMS	Weighted Root Mean Squared
ZWD	Zenith Wet Delay

A. Appended Papers

A.1 Paper A

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A.2 Paper B

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A.3 Paper C

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A.4 Paper D

Böckmann, S., A. Nothnagel, T. Artz, V. Tesmer (2010a) *International VLBI Service for Geodesy and Astrometry: Earth orientation parameter combination methodology and quality of the combined products.* J Geophys Res, 115, B04404, DOI 10.1029/2009JB006465.

A.5 Paper E

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A.6 Paper F

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A.7 Paper G

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