IERS SINEX Combination Campaign

Detlef Angermann[1], Daniela Thaller[2], Markus Rothacher[2]

[1] *Deutsches Geodätisches Forschungsinstitut, Munich, Germany*
[2] *Forschungseinrichtung Satellitengeodäsie, Munich, Germany*

Abstract: This position paper briefly summarizes the present status and still existing deficiencies regarding the combination of space geodetic techniques concentrating thereby on a rigorous and consistent combination of ITRF, EOP (and ICRF). Further subjects include the intention, goal and setup of the IERS SINEX combination campaign, as well as a list of participants, a summary of the data pool and of the individual solution characteristics. Finally, we propose some future steps in view of the goals of the SINEX combination campaign.

1 Introduction and motivation

The space geodetic observation techniques (e.g. VLBI, SLR/LLR, GPS, DORIS) contribute in a different and unique way to the determination of geodetic parameters (e.g. site positions and velocities, EOPs, atmospheric parameters, gravity field coefficients) and each technique has its strengths and weaknesses concerning the determination of various parameters (e.g. Rothacher, 2000, Angermann, 2002). The goal of the combination is to make optimal use of the complimentary properties of the different techniques. Besides this it has to be considered that the accuracy achieved today is mainly limited by technique-related and/or solution-related systematic effects (biases), which are often poorly characterized or quantified. This can lead to highly optimistic precision estimates that provide too optimistic accuracy expectations. Both, the different characteristics of the various space techniques for determining several parameters and the existing differences between space techniques observations (solutions) strongly require the development of rigorous integration and combination methods. This is of vital importance to exploit the full potential of the space techniques and to provide highly accurate and consistent results.

Currently the IERS products (e.g. ICRF, ITRF, EOPs) are computed (combined) separately by the responsible product centers. Consequently, they are not fully consistent, and not tolerable systematic biases between the different IERS products may exist. To overcome this problem it is necessary to develop suitable combination methods to generate consistent IERS products. To achieve this ambitious goal, the SINEX combination campaign was initiated by the IERS Analysis Coordinator. Objective of this campaign is to combine daily, weekly or monthly solutions from SINEX files of different techniques (VLBI, SLR, GPS and DORIS) with station coordinates and earth orientation parameters (EOPs) and to assess systematic biases between the individual space techniques. Finally, new combination strategies should be developed by the IERS Combination Research Centers (CRCs) and other participating groups. The final goal is that these new combination methods should be implemented by the IERS product centers for the computation of the IERS products.

2 Present status of combination issues and deficiencies

Within IAG a large number of organizations and institutes significantly contribute to the integration and combination of space geodetic observations, such as the IERS, CSTG, and the technique centers (IGS, ILRS, IVS and

IDS). It would exceed the scope of this position paper to review the present status regarding all these different institutes/services and to cover the entire field of combination and integration issues. Therefore we concentrate on aspects that are relevant for the objectives of the SINEX combination campaign and we try to minimize duplications with other sessions of this IERS workshop. We summarize the present status and still existing deficiencies regarding the intra- and inter-technique combination:

2.1 Intra-technique combination

The combination of data (solutions) of the same observation technique is one of the major tasks of the corresponding technique centers.

- The IGS (see http://igscb.jpl.nasa.gov) was established in 1994 with the primary objective to provide products for a wide variety of GPS applications. To fulfil this role IGS computes a large number of different combined products, such as satellite orbits, station and satellite clocks, station positions and velocities, troposphere, etc. on a weekly basis (Weber and Springer, 2002). In addition NRCan combines sets of station coordinates, velocities, EOPs and apparent geocenter positions provided by the analysis centers, to produce the IGS official combined station position and EOP solutions (Ferland, 2002).
- The ILRS (see http://ilrs.gsfc.nasa.gov) was established in 1998 in order to support programs in geodetic, geophysical, and lunar research activities and to provide the IERS with products important for the realization and maintenance of the ITRF. Within the ILRS the Analysis Working Group (AWG) coordinates and stimulates analysis activities. The AWG has initiated a number of pilot projects on "positioning and earth orientation" aimed at the development of an unique and official ILRS product on EOPs and station coordinates/velocities. Besides this, a pilot project aims at the benchmarking of software and analysis procedures in use by the various analysis groups. Recently a call for participation "Positioning & Earth Orientation" for two types of contributions was released: (i) providing individual SLR solutions and/or (ii) the quality control and combination of such individual solutions to an official ILRS product (Noomen et al., 2002).
- The IVS (see http://ivscc.gsfc.nasa.gov) was established in 1999 to support VLBI programs for geodetic, geophysical and astrometric work on reference systems, Earth science research, and operational activities. The responsibilities of the IVS Analysis Coordinator include regular dissemination of high quality EOPs as an official IVS product. In this respect a first pilot project was initiated to compare individual EOP series produced by several IVS Analysis Centers and to achieve a rigorous combination into a single series (Nothnagel and Steinforth, 2002). A second pilot project concentrates on the comparison and combination of EOP on the basis of fixed ITRF2000 station coordinates and ICRF source positions for a period of 2 years (1999–2000). The results of an IVS analysis pilot project on troposphere parameter comparison are very satisfactory (Böhm et al., 2002) and a proposal was announced to make combined VLBI troposphere parameters a regular IVS product.
- The creation of an IDS (see http://ids.cls.fr) was initiated by a DORIS pilot project experiment (e.g. Tavernier, 2000). This scientific service will structure the DORIS community in order to provide scientific products for a broad range of potential users. This will be done in a similar way to what is done in the IGS, ILRS and IVS.

At present, IGS is the only technique center providing a single-technique combined solution with station positions and EOPs. Considering the ongoing

activities within the other services, we assume that those will be able to provide these combined solutions in near future.

2.2 Inter-technique combination

Since several years the combination of data (solutions) of different space techniques is done by the responsible IERS product center on a routine basis. A review of the status of combination issues, deficiencies, future recommendations, etc. related to the IERS product centers (responsible for ICRF, ITRF, and EOPs) are subject of separate sessions of this IERS workshop and are described elsewhere in this volume. In this position paper we address some specific aspects that are important for the IERS SINEX combination campaign.

- Currently, the IERS products (ITRF, ICRF and EOPs) are computed (combined) separately by different product centers. Consequently, the results are not fully consistent, e.g., different ITRF realizations produce offsets and drifts in the EOP series (Rothacher, 2000). There is an urgent need to develop optimal methods (and software) for the combination of the relevant parameter types to obtain fully consistent IERS products. This is the main task of the IERS Combination Research Centers and is the final goal of the SINEX combination campaign.
- Systematic effects (biases) between solutions/techniques are one of the major problems and can be considered as a limiting factor for the accuracy of the space geodetic observations. Hence it is an important issue to investigate these differences with regard to several aspects (e.g., modeling, parameterization, software-related aspects, analysis strategies, datum definition) and to identify the source of the existing inconsistencies.
- Concerning the combination methodology more investigations are necessary regarding the level, on which the combination should be performed (e.g., observation level, normal equation level, solution level).
- The current situation regarding co-location sites and the accuracy and availability of the local ties is still not satisfactory. This can be considered one major limiting factor with regard to the consistency and long-term stability of the reference frames and the IERS products. It is important to achieve further improvements regarding co-location sites and local ties, and to study their impact on the combination results.

3 The IERS SINEX Combination Campaign

3.1 Intention and goals of the campaign

The deficiencies in the actual combination processes for ITRF and EOP series mentioned above led to the initiation of a special campaign with the aim of developing new combination strategies with consistent ITRF and EOP (and ICRF) as result. The analysis centers of the different space geodetic techniques or other interested groups are asked to produce solutions with at least station coordinates and EOPs. When solutions of all space geodetic techniques (VLBI, GPS, SLR, DORIS) are available the existing systematic biases between these different techniques can be studied and tried to be solved. As preparation for the combination the individual solutions must be tested with regard to rank deficiencies of the normal equation, the ability of removing the constraints applied to the solution and reconstructing the solution. The experiences of these tests should result in a feedback to the analysis centers. Furthermore, recommendations about common standards of modeling and parameterization in the technique solutions, derived from the combination experiences during this campaign should be compiled and provided to the analysis centers. At the end of the campaign, combined solutions of high quality that can be used as the basis for consistent TRF and EOP series will

Table 1 Participating groups in the IERS SINEX combination

Participants		Step 1	Step 2
AIUB	Urs Hugentobler	*Weekly global GPS (2 series)*	
ASI	Giuseppe Bianco	*Monthly + weekly SLR*	*Combination*
BKG	Volkmar Thorandt, Gerald Engelhardt	*Session VLBI*	
DGFI	Detlef Angermann	*Session VLBI* *Monthly SLR* *Weekly regional GPS*	*Combination*
FESG	Markus Rothacher		*Combination*
FFI	Per-Helge Andersen	*VLBI + SLR solution, combined at the observation level*	
GFZ	Shengyuan Zhu		*Combination*
IGN	Zuheir Altamimi		*Combination*
JCET	Erricos Pavlis	*Monthly + weekly SLR*	*Combination*
NCL	Konstantin Nurutdinov		*Combination*
NRCan	Rémi Ferland	*Weekly global GPS*	*Combination*

be available. In the long term, the IERS SINEX combination campaign is a contribution to the replacement of the separate combinations of TRF and EOPs by a common and consistent combination process.

3.2 Setup of the campaign

The IERS SINEX combination campaign is divided into two parts:

As a first step, solutions for each space geodetic technique have been and are generated by different analysis centers or other interested groups. These solutions must contain station coordinates and EOPs (at least x-pole, y-pole, UT1–UTC; if possible LOD, rates for x-pole and y-pole, and nutation parameters). The solutions themselves can be daily (as usual for VLBI), weekly (as usual for GPS; preferred time span for all solutions) or monthly (as usual for SLR), and should be delivered at least for the entire year of 1999. The SINEX (= Solution INdependent EXchange) format was chosen for delivering the individual solutions because it has many advantages:

- it is already in use for GPS, SLR, VLBI (and DORIS);
- a consistent format description for all techniques is now available, i.e. SINEX 2.00 (see <[1]>);
- statistical information, a priori information and constraints are included;
- the full variance-covariance information is available;
- the possibility of delivering free (reduced) normal equations is given, which avoids the problematical procedure of removing constraints.

All series of individual solutions contributing to the campaign have been collected in a data pool.

The second step is dedicated to the combination of the SINEX solutions stemming from the first step. The IERS Combination Research Centers (CRCs) and other interested groups should combine the terrestrial reference frame together with EOPs by using the strengths of one technique to compen-

[1] ftp://alpha.fesg.tu-muenchen.de/iers/sinex/format/

sate the deficiencies of another technique. The combination of more techniques must make use of the local tie information that is available in SINEX format as well.

The time table for the campaign looks as follows:

- May 27, 2002: Call for participation (see IERS Message No. 27)
- June 15, 2002: Deadline for submitting proposals
- August 15, 2002: Envisaged deadline for submission of SINEX series of step 1
- August 23, 2002: First status report (see IERS Message No. 31)
- November 18–21, 2002: IERS Workshop in Munich: Presentation of first results; discussion of the experiences, encountered problems, etc.
- April 6–11, 2003: EGS General Assembly in Nice: Presentation of (final) results, recommendations on strategies and standards for modeling, parameterization, etc.

3.3 Participants

Table 1 summarizes the participating groups, the primary scientists and their contributions to the campaign. The proposals of all participants are collected on the web site of the IERS SINEX combination campaign (see <[1]>). Altogether eleven groups have sent a proposal: six groups are delivering SINEX series for the first step of the campaign, eight groups are participating in the combination step, and one group delivers a solution that is combined already at the observation level.

3.4 Data pool

The data pool contains all files and information that is necessary for the combination step of the campaign and is accessible via the web site of the IERS SINEX combination campaign (see <[2]>).

In detail, the data pool contains the following files:

- All SINEX solution series stemming from the first step of the campaign, i.e., 3 weekly global GPS solutions, 1 weekly regional GPS solution, 3 monthly SLR solutions, 2 weekly SLR solutions, 2 session (= daily) VLBI solutions (Attention: BKG files were resubmitted Nov. 6, 2002 !), and 1 combined (at observation level) VLBI / SLR solution.
- Some additional solution series are available and can be used in the combination step, but there is no official proposal from these groups:
  - session VLBI solutions from GSFC (2 series: from a recomputation and from an older computation),
  - weekly global GPS solutions of all seven IGS analysis centers for the entire year 1999, i.e., GPS weeks 991 – 1042 (the series from AIUB and NRCan that are officially contributing to the campaign stem from a recomputation, therefore they are not identical with the routine solutions),
  - monthly SLR solutions from the ILRS pilot project ‘positioning and earth orientation’ (altogether 11 analysis centers, but three of them are official participants of the IERS SINEX Combination Campaign, i.e., ASI, DGFI, JCET),
  - weekly DORIS solutions from IGN,
  - session VLBI solutions from IAA, but only with station coordinates.
- The ITRF2000 SINEX files are available as one file per technique.
- The local tie information that was used in the ITRF2000 combination is available in two forms: one SINEX file per site and a table with all local ties in text format.

[1] http://alpha.fesg.tu-muenchen.de/iers/sinex/sinex_campaign.html
[2] http://alpha.fesg.tu-muenchen.de./iers/sinex/datapool.html

3.5 Characteristics of individual solutions contained in the data pool

Comparing the individual solutions with respect to the parameters that are included in the solution, see Table 2, it is clearly visible that there are some differences, especially regarding the EOPs. At the moment the ICRF is not yet included, because in both VLBI series that are directly contributing to the campaign (BKG and DGFI) the ICRF-Ext.1 was kept fix.

Regarding the variance-covariance information respectively the (reduced) normal equation contained in the SINEX files, all analysis groups deliver the variance-covariance information using the SOLUTION blocks MATRIX_ ESTIMATE, MATRIX_APRIORI, APRIORI and ESTIMATE, but in some solutions the apriori information has been omitted. Only the VLBI solutions from BKG, DGFI and the recomputed GSFC solutions include normal equations in addition to the variance-covariance information.

Differences between the individual solutions are also present concerning the constraints that are used for generating a solution: For the terrestrial reference frame both, inner constraints for rotation, translation, scale with respect to an a priori reference frame as well as loose constraints directly on the station coordinates are used. The EOPs are loosely constrained but in some solutions not all EOPs are constrained. In addition to the sort of constraints, the size of the constraints differs from analysis center to analysis center as well.

4 Ongoing activities and proposal for future steps

The major goal of the IERS SINEX combination campaign is to develop methods (and tools) for a rigorous and consistent combination of ITRF, EOP (and ICRF), which should eventually replace the separate combinations by different IERS product centers. To achieve this ambitious goal a wide range of combination aspects has to be considered and the success will fundamentally depend on the cooperation of the participating groups and on well-coordinated activities. In the following we summarize ongoing activities and we address relevant scientific topics, which need to be studied in future.

Table 2 Parameters contained in the SINEX solutions available in the data pool

SINEX solution		**Station coord.**	**x-/y-pole**	**UT**	**Pole rates**	**LOD**	**Nutation**	**Additional parameters**
GPS	AIUB	***X***	***X***	*UT1-UTC*	***X***	***X***		
GPS	NRCan	***X***	***X***		***X***	***X***		*Geocenter*
GPS	DGFI	***X***						
SLR monthly	ASI	***X***	***X***	*UT1-UTC*				*Range bias*
SLR monthly	DGFI	***X***	***X***	*UT1-UTC*				*Range bias, Time bias*
SLR monthly	JCET	***X***	***X***	*UT1-UTC*	***X***	***X***		*Range bias*
SLR weekly	ASI							
SLR weekly	JCET							
VLBI	BKG	***X***	***X***	*UT1*	***X***	***X***	***X***	
VLBI	DGFI	***X***	***X***	*UT1-UTC*			*Corrections to the model*	
VLBI	GSFC new	***X***	***X***	*UT1*	***X***	***X***	***X***	
VLBI	GSFC old	***X***	***X***	*UT1*		***X***	***X***	
VLBI	IAA	***X***						
DORIS	IGN	***X***	***X***	*UT1-UTC*	***X***	*LODR*		

CRC Mail Exploder:

An e-mail exploder "CRC Mail Forum" has been installed at the webpage of the IERS Analysis Coordination at Technical University of Munich (see <[1]>) together with the IERS Central Bureau at BKG for the exchange of mails between CRCs and other interested groups. We propose that all participants of the IERS SINEX combination campaign should be members of this mail exploder to ensure an effective communication between different groups. Individuals that would like to be included in this exploder should send an e-mail to <lothhammer@iers.org>. This mail exploder <crc_forum@iers.org> should be used for all communications concerning the SINEX combination campaign.

Validation of individual SINEX Files:

The number of individual solutions from the different space techniques and their characteristics is very heterogeneous. In view of the goals of the SINEX combination campaign the available solutions had to be checked concerning various aspects, such as format and suitability for a rigorous combination:

- Focus on a set of solutions as homogeneous as possible concerning time interval, parameterization and modeling
- Check SINEX format
- Ensure that all constraints can be removed successfully
- Perform rank deficiency analysis
- Make sure that a correct solution can be produced

As a result of this step a report for each individual solution should be generated and then distributed to the analysis centers (ACs). If necessary, corrected SINEX files should then be resubmitted by the ACs asap.

Form concerning modeling and parameterization:

A form has been distributed in December 2002 to all ACs that are contributing to the SINEX campaign. This form should be filled in and returned to the IERS Analysis Coordinator to archive it together with the solutions in the SINEX data pool.

Consistent modeling and parameterization:

The SINEX series of the various techniques have to be as consistent as possible. Based on the forms common standards have to be defined and updated series complying with the standards should be produced by the ACs.

Scientific Studies / Combinations:

The participating combination groups presented results of the IERS SINEX combination campaign at the EGS-AGU-Meeting in Nice (6–11 April 2003), Session G15 "Interactions and Combination of Space Geodesy Techniques". The results have shown, that various shortcomings and deficiencies regarding a rigorous and consistent combination still exist. To achieve the final goal of the IERS SINEX combination campaign a wide spectrum of combination issues has to be considered and need to be studied in more detail. Below some relevant topics are outlined:

- Local ties: Assess the quality of the local tie information and study the impact of local ties on the combination.
- Study the weighting of solutions in the intra- and inter-technique case. Develop weighting methods, study variance component estimation, etc.

[1] http://alpha.fesg.tu-muenchen.de/iers

- Investigate how to handle non-linear site motions (e.g. sites located in deformation zones).
- Study datum definition issues for combined solutions.
- Study systematic biases between the techniques concerning, e.g., scale, geocenter, LOD (and nutation rates) from satellite techniques, biases in time series of station coordinates (especially for co-location sites), biases in time series of EOPs.
- Study consistency between TRF and EOPs, and impact of combination on the ICRF realization.

Some open issues which probably need further discussions among the relevant groups are:

- Who (which groups) will participate in all these activities? Besides the analysis centers and combination centers of the IERS SINEX combination campaign (see Table 1) we would like to encourage also other groups (e.g., CRCs, WG on ITRF Datum) to participate.
- Another question is how the work should be organized?
  - Definition of work packages ?
  - Different groups for different tasks ?
  - Relationship to the goals of other groups (e.g., CRCs, ITRS Combination Centers, WG on ITRF datum) ?

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