Analysis Coordinator Report

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1. Introduction

The first 15 months of working as the IVS Analysis Coordinator have shown significant progress towards making IVS a successful service. Many small tasks have been completed, eventually leading to a number of steps forward worth reporting.

Some of the ground work of the IVS Analysis Coordinator had already been laid by the IVS Acting Analysis Coordinators prior to October 1, 1999 (Eubanks, Ma, Vandenberg, 1999). In the meantime 19 centers have been accepted either as IVS Analysis Centers or as IVS Associate Analysis Centers. The distinction between these two groups has been streamlined in the current IVS Terms of Reference (ToR) reducing the number of classes included in the initial version of the ToR.

Although the ToR calls for regular submissions of a full list of IVS products, so far only EOP results from 24 hour VLBI sessions and of Intensive UT1 observing sessions are available. By now four IVS Analysis Centers

- Bundesamt für Kartographie und Geodäsie (BKG) Leipzig, Germany
- Institute for Applied Astronomy (IAA), St. Petersburg, Russia
- Astronomical Institute of St. Petersburg University (SPU), St. Petersburg, Russia
- NASA Goddard Space Flight Center (GSFC), Greenbelt MD, USA

regularly submit their EOP results from 24 hour sessions to the IVS Data Centers for use by many scientists around the world. Up to now the four IVS Analysis Centers and the

- US Naval Observatory (USNO), Washington D.C., USA

have regularly submitted UT1 results from quasi-daily Intensive observations. Unfortunately, USNO teminated its VLBI analysis activities in October 2000.

Currently all submissions are formatted according to the IERS submission format using one data line per epoch with correlation coefficients only between EOP parameters of the same epoch. No information on the terrestrial reference frames (TRF) underlying the EOP solutions are submitted as yet. Under a different directory of the IVS data structure the results of a single TRF solution are available which are the basis of the current GSFC EOP solution.

The Analysis Centers have taken great efforts to organize their resources for regular analysis activities and submissions of the results. The regular delivery is of particular importance for the long term maintenance of consistent series. Currently, all Analysis Centers use a TRF of their choice either by fixing the corresponding values in the least squares adjustment or by transferring the TRF covariance information using pre-reduced normal equations.

Starting on October 1, 2000 the individual session EOP results are processed further in a combination procedure at the Analysis Coordinator's office in order to generate a combined IVS EOP product (see section 2). Before the comparison and combination activities of the EOP results could be started a number of obstacles had to be removed in a concerted effort. The data format and auxiliary information, although specified as standards, had to be corrected in some of the submissions. File names and directory structures were reorganized, and Analysis Centers had to be summoned to speed up their submissions. As of today the delay between observations and result dissemination is on the order of 14 days.

The combination of the results of different solutions to one combined product serves several purposes. In the combination process the individual solutions complement and control each other leading to a higher accuracy and a higher reliability. Considering the facts that the constellation of analysis centers may change for various reasons or that errors in data and product submissions occur, the redundancy of analyses is of general importance: the more Analysis Centers contribute the smaller the effect of taking out or adding a contributor. This improves not only the individual results but stabilizes long-standing series in general. Any differences can be analysed for the detection of outliers and their causes can be investigated. Another aspect of combination is that more objective error bounds can be established which is of particular importance where formal errors are not representative.

Although one of the fundamental rules of statistics is to never use an observation more than once, it is still appropriate to produce combined results from submissions of different Analysis Centers. They are using different software packages and/or different analysis strategies by e.g. rejecting different data points, using different weighting schemes, or using different reference frames for station coordinates or radio source positions. All this leads to independent analyses as well as to independent and slightly different results.

An important aspect of carrying out the combinations is, of course, the correct relative weighting of the Analysis Centers. For this the use of the scatter in the nutation offset results of each center relative to a combined average is currently deemed to be the most appropriate approach which is unique for combinations of space geodetic results.

2. IVS Combination Procedure

On December 22, 2000, the availability of the combined IVS EOP products was officially announced by the IVS Analysis Coordinator. This section provides a description of the combination strategy being used. In addition, some topics are listed which will need further investigation to refine this strategy or to mitigate known problems of the combination.

The combination strategy can be divided into two steps. In the first step, a comparison of the results is carried out to derive relative weights for the Analysis Centers and to determine biases to maintain consistency with a reference series. In the second step the results of the individual Analysis Centers are combined into one solution by applying the weighting factors and the biases.

In the following formulae the total number of Analysis Centers contributing to the combination is denoted by n, the index i designates the respective Analysis Center (AC). The total number of epochs is m, the epochs are labelled by j.

In the current combination **the full variance/covariance matrix is used**, whereas in the following formulae the correlations between the parameters are omitted for more clarity.

2.1. Data Preparation

2.1.1. Weighting Factors

For the comparisons the question arises of how to establish relative weights for the individual analysis centers since weighted averages have to be computed as a first reference. It is quite clear that these cannot only depend on the formal errors assigned by the Analysis Centers alone. For this purpose the scatter of the nutation angels $d\psi$ and $d\epsilon$ appears to be a suitable indicator. The celestial reference frame as such is very stable at the sub-milliarcsecond level and deficiencies of individual sources average out in the large number of sources used in geodetic VLBI series. Therefore, most of the scatter to be found in the individual nutation offset series can be attributed to the way the analysis is carried out, e.g. which software and parameterization is used (analyst's noise).

Initial mean values are computed for each epoch where the input data is only weighted according to the formal errors assigned by the Analysis Centers.

$$\overline{d\psi}_j \sin\epsilon_0 = \frac{\sum_{i=1}^{n} p_{d\psi_{ij}} d\psi_{ij} \sin\epsilon_0}{\sum_{i=1}^{n} p_{d\psi_{ij}}} \tag{1}$$

and

$$\overline{d\epsilon}_j = \frac{\sum_{i=1}^{n} p_{d\epsilon_{ij}} d\epsilon_{ij}}{\sum_{i=1}^{n} p_{d\epsilon_{ij}}} \tag{2}$$

with $p_{d\psi_{ij}}$ and $p_{d\epsilon_{ij}}$ being the respective weights

$$p_{d\psi_{ij}} = \frac{1}{\sigma^2_{d\psi_{ij}}} \tag{3}$$

and

$$p_{d\epsilon_{ij}} = \frac{1}{\sigma^2_{d\epsilon_{ij}}} \tag{4}$$

In the next step biases for each nutation offset and analysis center are computed from the residuals:

$$v_{d\psi_{ij}\sin\epsilon_0} = d\psi_{ij}\sin\epsilon_0 - \overline{d\psi}_j \sin\epsilon_0 \tag{5}$$

and

$$v_{d\epsilon_{ij}} = d\epsilon_{ij} - \overline{d\epsilon}_j \tag{6}$$

$$bias_{i,d\psi\sin\epsilon_0} = \frac{\sum_{j=1}^{m} p'_{d\psi_{ij}} v_{d\psi_{ij}\sin\epsilon_0}}{\sum_{j=1}^{m} p'_{d\psi_{ij}}} \tag{7}$$

and

$$bias_{i,d\epsilon} = \frac{\sum_{j=1}^{m} p'_{d\epsilon_{ij}} v_{d\epsilon_{ij}}}{\sum_{j=1}^{m} p'_{d\epsilon_{ij}}} \tag{8}$$

where $p'_{d\psi_{ij}}$ and $p'_{d\epsilon_{ij}}$ are the weights of the respective residuals, computed from

$$p'_{d\psi_{ij}} = \frac{1}{\sigma'^2_{d\psi_{ij}}} \tag{9}$$

and

$$p'_{d\epsilon_{ij}} = \frac{1}{\sigma'^2_{d\epsilon_{ij}}} \tag{10}$$

with

$$\sigma'^2_{d\psi_{ij}} = \chi^2_{d\psi_j}(\sigma^2_{d\psi_{ij}} - \frac{1}{\sum\limits_{i=1}^{n} p_{d\psi_{ij}}}) \tag{11}$$

and

$$\sigma'^2_{d\epsilon_{ij}} = \chi^2_{d\epsilon_j}(\sigma^2_{d\epsilon_{ij}} - \frac{1}{\sum\limits_{i=1}^{n} p_{d\epsilon_{ij}}}) \tag{12}$$

with the respective χ^2 per degree of freedom

$$\chi^2_{d\psi_j} = \frac{\sum\limits_{i=1}^{n} p_{d\psi_{ij}} v^2_{d\psi_{ij}\sin\epsilon_0}}{n-1} \tag{13}$$

and

$$\chi^2_{d\epsilon_j} = \frac{\sum\limits_{i=1}^{n} p_{d\epsilon_{ij}} v^2_{d\epsilon_{ij}}}{n-1} \tag{14}$$

The quantity χ^2 is also called variance of unit weight (Koch 1988). From the bias-free series a weighted root mean squared error (wrms) is computed for each analysis center combining both nutation components in a root sum squared (rss) sense:

$$wrms_{i,nut} = \sqrt{wrms^2_{i,d\psi\sin\epsilon_0} + wrms^2_{i,d\epsilon}} \tag{15}$$

with

$$wrms_{i,d\psi\sin\epsilon_0} = \sqrt{\frac{\sum\limits_{j=1}^{m} p'_{d\psi_{ij}\sin\epsilon_0}(v_{d\psi_{ij}} - bias_{i,d\psi\sin\epsilon_0})^2}{\sum\limits_{j=1}^{m} p'_{d\psi_{ij}}}} \tag{16}$$

and

$$wrms_{i,d\epsilon} = \sqrt{\frac{\sum\limits_{j=1}^{m} p'_{d\epsilon_{ij}}(v_{d\epsilon_{ij}} - bias_{i,d\epsilon})^2}{\sum\limits_{j=1}^{m} p'_{d\epsilon_{ij}}}} \tag{17}$$

The combined wrms of the nutation offsets are then used to derive new weighting factors for each of the analysis centers:

$$f_i = \frac{wrms_{i,nut}}{\overline{wrms}_{nut}} \tag{18}$$

where

$$\overline{wrms}_{nut} = \frac{1}{n}\sum_{i=1}^{n} wrms_{i,nut} \tag{19}$$

Finally new weights $p_{d\psi_{ij}}^{(new)}$ and $p_{d\epsilon_{ij}}^{(new)}$ for the input data are calculated:

$$p_{d\psi_{ij}}^{(new)} = f_i p_{d\psi_{ij}}^{(old)} \tag{20}$$

and

$$p_{d\epsilon_{ij}}^{(new)} = f_i p_{d\epsilon_{ij}}^{(old)} \tag{21}$$

For fine tuning, the process is then repeated by applying the new weights to the input data (Fig. 1). Table 1 gives an impression of the current level of agreement of the weighting factors.

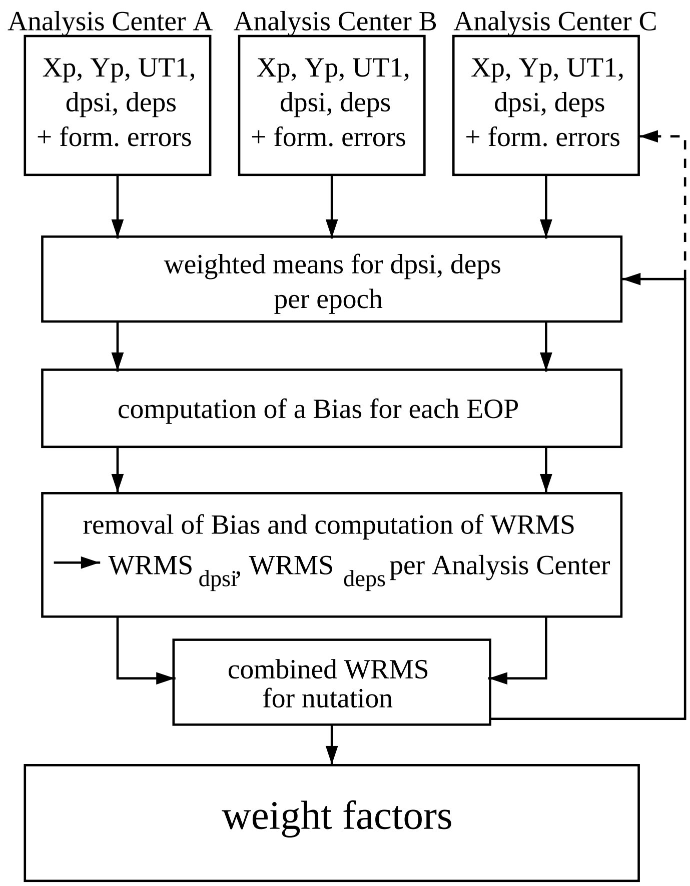

Figure 1. Comparison procedure

2.1.2. Offsets relative to IERS C04

Since the users of the combined series will also rely on the long term stability of EOP series this requirement has to be taken into account in the combination process. While the nutation offset series are fairly uncritical due to their young history and their direct connection to VLBI observations, polar motion and UT1-UTC series have a long history. Consistency with the reference series C04 of the International Earth Rotation Service (IERS) (e.g. IERS, 1996) is considered to be of importance and should, therefore, be maintained. The next step before combination is,

Table 1. Weighting factors

AC	weighting factor
BKG	1.06
GSFC	1.00
IAA	0.90
SPU	1.06

thus, the determination of offsets between the individual series and the IERS C04 series. Biases are computed from data sets of each individual Analysis Center which cover the period from the beginning of 1999 to September 30, 2000, the date immediately prior to the first epoch of combination. The computation is shown by example for the x component of polar motion.

At first, differences between the respective data point of each analysis center and the corresponding C04 point are calculated:

$$v_{x_{ij}} = x_{C04,j} - x_{ij} \tag{22}$$

The differences $v_{x_{ij}}$ are then used to compute the biases:

$$bias_{i,x} = \frac{\sum_{j=1}^{m} p_{x_{ij}} v_{x_{ij}}}{\sum_{j=1}^{m} p_{x_{ij}}} \tag{23}$$

As long as no changes in the strategy of the solution are introduced the biases are frozen (cf. Table 2). New biases are computed from time to time for controlling purposes and may be applied if necessary.

2.2. Final Combination

For each data point the respective bias and weighting factor are applied before a weighted average is computed yielding the combined EOP value (Fig. 2). As an example the formula for the combined x component of the polar motion for epoch j is given by the following equation (24):

$$x_{j,combi} = \frac{\sum_{i=1}^{n} f_i p_{x_{ij}} (x_{ij} - bias_{i,x})}{\sum_{i=1}^{n} f_i p_{x_{ij}}} \tag{24}$$

and for y and UT1-UTC analogously. For the combination of the nutation offsets cf. equation (27). The accuracy of one combination data point can be obtained by applying the law of error propagation (Koch 1988):

$$\sigma^2_{x_{j,combi}} = \frac{\hat{\sigma}^2_{0,x_j}}{\sum_{i=1}^{n} f_i p_{x_{ij}}} \tag{25}$$

with the χ^2 per degree of freedom

$$\hat{\sigma}^2_{0,x_j} = \chi^2_{x_{j,combi}} = \frac{\sum\limits_{i=1}^{n} f_i p_{x_{ij}} [x_{j,combi} - (x_{ij} - bias_{i,x})]^2}{n-1} \tag{26}$$

In equation (24) the biases and the weighting factors are regarded to have no errors. In a refined strategy, which has to be set up soon, these errors have to be taken into account, too.

No bias is applied to the combination of the nutation offsets, only the weighting factors are used

$$d\epsilon_{j,combi} = \frac{\sum\limits_{i=1}^{n} f_i p_{d\epsilon_{ij}} d\epsilon_{ij}}{\sum\limits_{i=1}^{n} f_i p_{d\epsilon_{ij}}} \tag{27}$$

and for $d\psi$ analogously. The results of the combinations are regularly updated. They are available

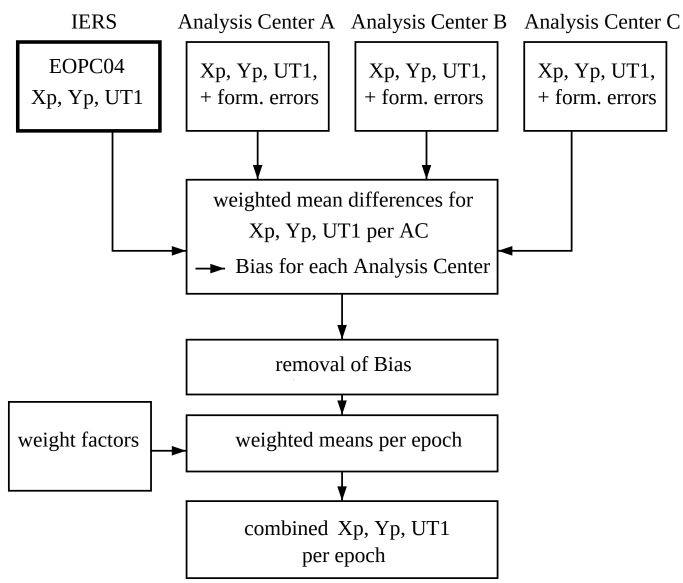

Figure 2. Combination strategy

both graphically and numerically on the IVS Analysis Coordinator's web page via the IVS Home page or directly from *http://miro.geod.uni-bonn.de/vlbi/IVS-AC/index.html*. As an example the combined series for polar motion is printed in Figure 3 and Table 2 summarizes the average statistics of the current combination solution.

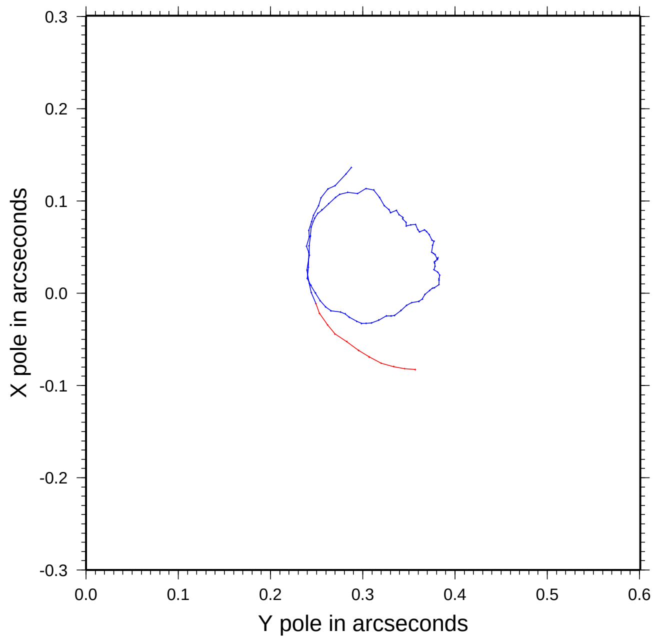

Figure 3. IVS combined polar motion

2.3. Further Investigations and known Problems

The strategy described above reflects the first steps towards a rigorous combination of Earth orientation parameters. Of course, there are well-known problems of the current combination procedures. These problems can be divided roughly into two groups:

- deficiencies of the stochastic model
- quality control and redundancy

The combination strategy presented implies actually a violation of the basic rule that the same data cannot be used twice in an adjustment process. This is presently neglected by treating the input data of the Analysis Centers as “new” data. The described deficiency can perhaps be mitigated by introducing a kind of correlation between the Analysis Centers since the data from VLBI experiments is limited. The question of the correct relative weighting has to be considered carefully, too.

Another task is the implementation of a suitable method for outlier detection and elimination to increase the reliability and robustness of the combined solution. A further extension to the stochastic model will be the estimation of variance-covariance components. Different methods of the estimation of variance-covariance components have to be checked. Furthermore, a rigorous link between EOP and TRF on the basis of SINEX input should be established in a refined combination procedure.

Table 2. Current average statistics

	x_p		y_p		$UT1-UTC$		$d\psi \sin\epsilon_0$		$d\epsilon$	
	bias [μas]	wrms [μas]	bias [μas]	wrms [μas]	bias [μs]	wrms [μs]	bias [μas]	wrms [μas]	bias [μas]	wrms [μas]
BKG	-109	56	20	62	18	3	-26	43	-1	36
GSFC	22	66	-25	80	-17	3	8	45	20	60
IAA	87	77	-133	75	-6	3	-8	51	-9	44
SPBU	42	73	-147	72	-15	3	28	47	-3	37

3. IVS Data Centers

One of the key issues of a service like IVS is a timely and reliable dissemination of the raw observing data to the IVS Analysis Centers and of the results to the users. In this scenario the IVS Data Centers play an important role since the necessity of permanent accessibility requires constant maintenance of the equipment. A careful mirroring scheme guarantees that the data at the three primary IVS Data Centers at

- Bundesamt für Kartographie und Geodäsie (BKG) Leipzig, Germany
- Observatoire de Paris (OPA), Paris, France
- NASA Goddard Space Flight Center (GSFC), Greenbelt MD, USA

are always as consistent as possible. It is noteworthy that with this scheme and with the strong commitments of the Data Centers the IVS data and the IVS products have been available worldwide without interruption.

4. First IVS Analysis Workshop

On February 24, 2000 the first IVS Analysis Workshop was organized in conjunction with the IVS 2000 General Meeting at Kötzting on Feb. 21-24, 2000. In this workshop the many different geodetic and astrometric analysis activities were discussed and some basic aspects were coordinated (Nothnagel, 2000). In view of the many tasks to be organized and to be distributed en route to the establishment of a service covering all products to be generated eventually this workshop was only a first basic step forward. A second workshop to be held in February 2001 will refine the initial ideas taking into account the achievements and experience of the first year.

During the first IVS Analysis Workshop five IVS Analysis Working Groups were established. However, the activities of the working groups were less enthusiastic than anticipated when they were established, a fact which will have to be looked at in the next workshop as well.

So far only the Analysis Coordinator's office regularly publishes combined Earth orientation parameters. However, other Analysis Centers are encouraged to take up this task in parallel in order to establish quality control and redundancy. The comparison with independent series or solutions is a helpful measure to reveal weaknesses or inconsistencies of the combination strategy in use.

Acknowledgements

The work of the IVS Analysis Coordinator would not have been possible without the many individuals who submitted data and results or provided support in any aspect of operation. Of equal importance are those who contributed in the discussions and made suggestions, of which not all could be realized. We are thankful for all these contributions.

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