How can combination help to achieve consistency at the 0.1 ppb level?

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Abstract.

Although the accuracy or consistency of space geodesy products at the level of 0.1 ppb, or 0.6 mm over the Earth surface, is not yet achieved today, it should however be a challenging target within the Global Geodetic Observing System (GGOS) perspective in order to meet Earth science requirement. Neither an individual space geodesy technique nor their combination could be regarded as achieving that level of accuracy or consistency. For simplicity, we mean here by accuracy, the quantitative metric level at which space geodesy techniques are able to determine positions of points or objects over the Earth surface or in its nearby space. This of course implies the availability of a global reference frame, the indispensable standard against which our geodetic products are evaluated. Combination, and implicitly comparison of multiple solutions of geodetic products of a single or several techniques, is considered to be an efficient tool to both bring to the fore discrepancies between solutions/techniques and to yield a more reliable combined product, being gathering the strengths of the combined solutions/techniques. Combination of raw observations of all or multiple space geodesy techniques, using a coherent and unique modeling, could be regarded, ideally, as the rigorous way to allow consistency between the different products. Based on our experience of both types of combination, we try in this paper to (1) evaluate the current attainable accuracy or consistency and to (2) underline the limitation factors of space geodesy techniques and their combination. We restrict our discussion in this paper to two main space geodesy products: the Terrestrial Reference Frame (TRF) and Earth Orientation Parameters (EOPs).

Introduction

In the following we structure this paper over the two main approaches of geodetic combination, namely the combination of products and the combination of the raw observations of multiple space geodesy techniques. While the first approach is the one that is adopted since the eighties for the determination of the official products of the International Earth Rotation and Reference Systems Service (IERS), the second method is still in the research domain and necessitate more development and improvement. We note however that some groups start to produce some solutions as results from the combination at the observation level.

Regarding the first combination method, the subsequent discussion will be illustrated by the experience of the activities related to the determination of the International Terrestrial Reference Frame (ITRF), being the result of combination of individual solutions provided by the technique services of the International Association of Geodesy (IAG): the International VLBI Service (IVS); the International Laser Ranging Service (ILRS); the International GNSS

Service (IGS); the International DORIS Service (IDS). The reader may also refer to (Altamimi et al., 2005) for more discussion regarding the TRF requirements within GGOS perspective. Particular emphasis will be given here to the results obtained from the analysis of individual solutions submitted to the ITRF2005 which are under the form of time series of station positions and Earth Orientation Parameters (EOPs). One of the advantages of time series analysis is that it allows the assessment of the temporal behavior of geodetic parameters of interest to geodynamical investigation. These results will be used to guide our evaluation of the current level of consistency between the 4 techniques in terms of positioning over the Earth surface and in terms of the frame parameters and in particular those having their importance for geodynamical applications: the origin and the scale. Moreover, the ITRF2005 combination includes for the first time Earth Orientation Parameters (EOPs) whose results will also be used to enrich the discussion of this paper.

The second method consists in combining directly the raw geodetic observables that are measured by various space geodetic techniques. Although such a combination is carried out by some research groups and some results are already available, the experience of such computations is very recent, compared to that of the combination at the product level. Regarding this second combination method, the discussion will be mainly illustrated by the experiment carried out by the French Groupe de Recherche en Géodésie Spatiale (GRGS) in 2004-2005. Although much emphasis has been put on the design of the method of combination during this research, preliminary results can help to evaluate the current level of consistency between the four techniques inside the combination. But, due to our recent expertise (no more than three years) in this field, the discussion linked to combinations carried out at the measurement level will mainly consist in underlining the limitation factors of such computations and in giving some prospects to improve these latter.

I - Current status of combinations

I.A – Combination of individual solutions

The approach that is currently adopted for the combination of various TRF solutions provided by a single or several space geodesy techniques is built on the construction of a unique (combined) TRF, making use of the mathematical Helmert transformation formula. It considers defining the combined TRF at a given (arbitrary) reference epoch and adopting a TRF time evolution law that is supposed to be linear (secular). Consequently, 14 degrees of freedom are always necessary to completely ensure the TRF datum definition: 6 for the TRF origin and its rate (time derivative), 2 for the scale and its rate and 6 for the orientation and its rate. The inclusion of EOPs into the combination requires additional equations where the link between the TRF and EOPs is ensured via the 6 orientation parameters. The combination model considered here (as the one used by the ITRF Product Center) allows the estimation of station positions and velocities, transformation parameters of each individual TRF solution with respect to the combined TRF and, if included, consistent series of EOPs. The input solutions usually used in this kind of combination are either (1) time series of station positions and EOPs or (2) long-term solutions composed by station positions and velocities and EOPs. In the first case where the combination amounts to rigorously stacking the time series, the un-modeled non-linear part of geodetic parameters are implicitly embedded in the combination output: possible seasonal (e.g. annual or semi-annual) station or/and geocenter motions are respectively left in the output time series of station residuals and the transformation parameters.

I.A.1.Current achievement

It is of course hard to estimate one single value that is characterizing the level of accuracy or consistency of and between products and techniques. The consistency evaluation is more realistically assessable over specific types of estimable quantities, as for instance point position determination and the TRF parameters, although both of them are intimately related.
In order to illustrate our discussion below, we select to use the results of the analysis of the time series submitted to the ITRF2005. Note that one single set of weekly (daily) solutions per technique is submitted to the ITRF2005, by the IAG services, except for the IDS where two solutions are provided. At the time of writing, the ITRF2005 is not yet finalized so that we refer to the results of the preliminary ITRF2005 solution called ITRF2005P.

1.A.1.1 Positioning Performance

When stacking station positions time series (weekly for satellite techniques and daily for VLBI), global WRMS per week (day) is computed, that is to characterize the internal precision and repeatability over time of each individual position time series. Figure 1 illustrates the WRMS per week (day) for each one of the 4 technique time series over the horizontal and vertical components and Table 1 summarizes the WRMS range. It is to be noted that the WRMS values do not qualify the techniques, but rather the solutions of the techniques, and they are highly dependent on the quality of each station/instrument. Other factors are also important such as the number of the satellites available, e.g. in case of DORIS it was shown (Altamimi et al. 2006) that the quality (WRMS) improves when the number of satellites increases. However, from Figure 1 and Table 1, we can postulate that the current positioning performance for the best cases is around 2 mm for the horizontal component and around 5 mm for the vertical component.

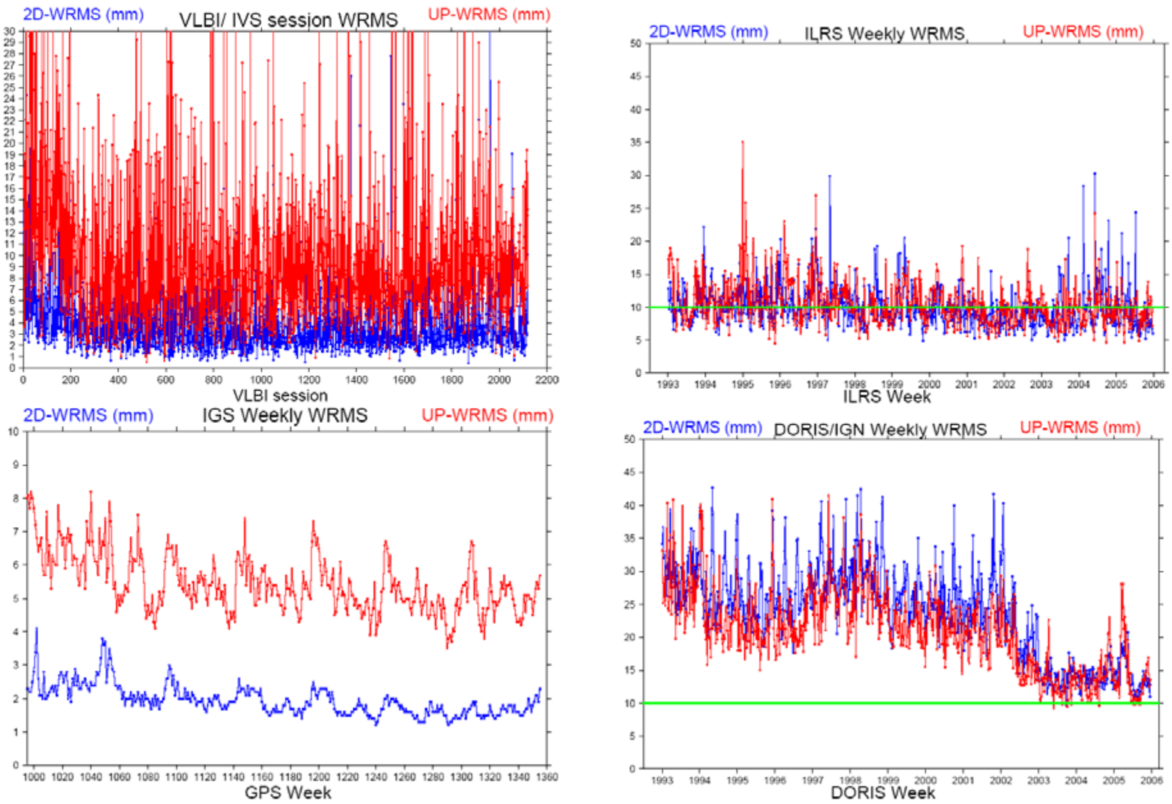

Figure 1. Weekly (daily) WRMS as results from the time series stacking.

Table 1. WRMS range per technique

Solution	2-D WRMS mm	Up WRMS Mm
VLBI	2-3	5-7
SLR	5-10	5-10
GPS	2-3	5-6
DORIS	12-25	10-25

1.A.1.2 Accuracy of the TRF Parameters (Datum Definition)

Among the 14 parameters that are necessary to define a TRF, one should retain 8 of them that are important, namely the 3 translations components (defining the TRF origin), the scale as well as their time variations. The origin, the scale and their time variations are critical for specific studies related to Earth science applications such as the evaluation of the mean sea level variability (Blewitt et al. 2006) . Up to now, the ITRF origin and scale are based on SLR and VLBI results.

The Origin: Although it is hard to assess the origin accuracy of the single ILRS solution that is submitted to ITRF2005, we attempt however to evaluate its consistency with respect to ITRF2000. Figure 2 shows the 3 translation time variations with respect to ITRF2000, using a reference set of 12 stations. Given their observation history and good performance, these are the only stations that are usable to link the combined SLR TRF resulting from the stacking of the time series to the ITRF2000 frame. Because the estimated transformation parameters are heavily sensitive to the network geometry, the distribution of the reference set of 12 stations is far from being optimal; only two of them are in the southern hemisphere (Yaragadee, Australia, and Arequipa, Peru). Apart from the seasonal variations that could be estimated over the translation parameters, the linear trends are of great importance to the ITRF origin stability over time. From Figure 2 we can easily see that the most significant trend is that of the Z-translation component, being of the order of 1.6 mm/yr. This bias will therefore exist between ITRF2000 and ITRF2005, and could be regarded as the current level of the origin accuracy as achieved by SLR. From that figure we can also distinguish a "piece-wise" behavior of the Z-translation: between respectively 1993-1996; 1996-2000 and 2000-2006. In our opinion, this is completely related to and correlated with the change of the ILRS network geometry over time. In order to illustrate that effect, we plotted on Figure 3 the number of SLR stations available in each weekly solution. From this plot, one can easily see the decreasing tendency of the number of stations, starting around 2000, which should be correlated with the Tz component that starts to significantly drifting at this same epoch (see Figure 2). In addition, among the approximately 97 SLR stations available in the ITRF2005, approximately 20 of them have sufficient time-span of observations to be considered as core stations for useful and comprehensive analysis.

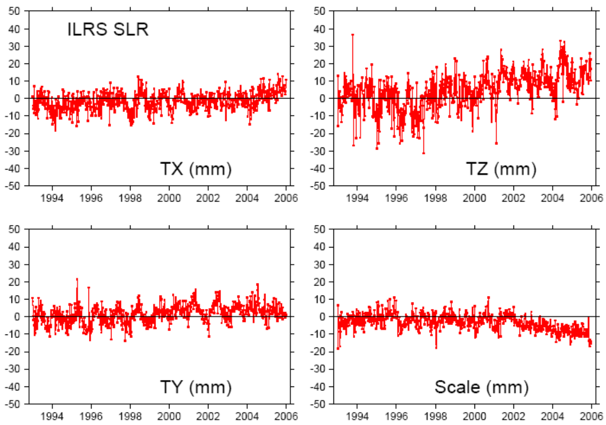

Figure 2. Translations and scale variations with respect to ITRF2000 of the ILRS SLR time series submitted to ITRF2005P.

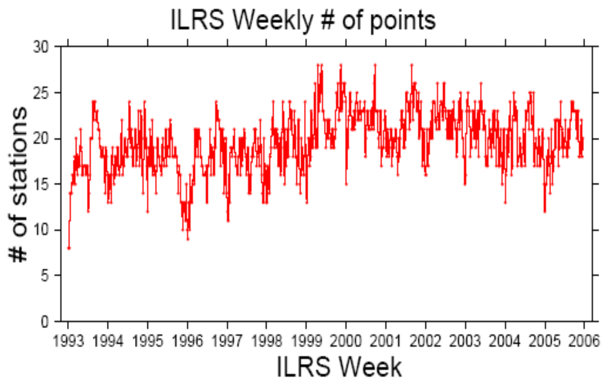

Figure 3. Number of stations included in the weekly ILRS SLR time series submitted to the ITRF2005.

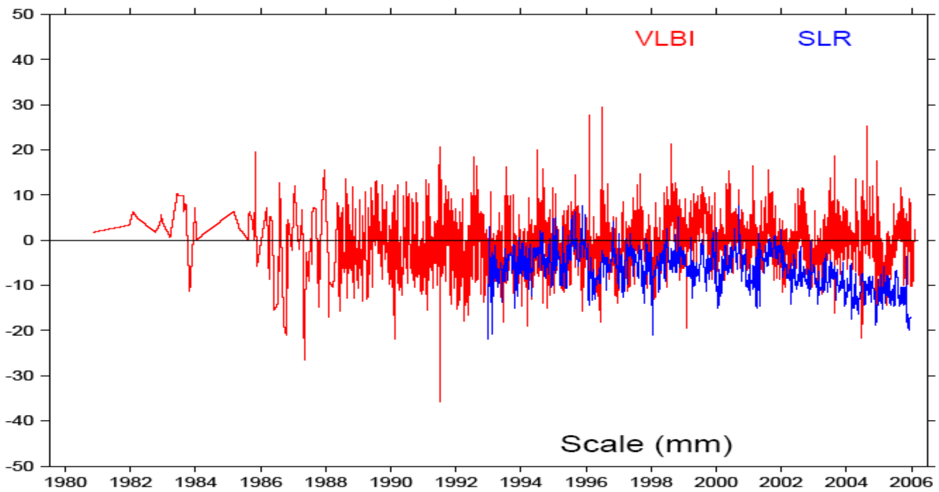

Figure 4. VLBI and SLR Scale factor variations with respect to ITRF2005P.

<u>The Scale</u>: The ITRF2005 combination (making use of local ties in co-location sites) revealed a scale bias of about 1 ppb between VLBI and SLR solutions at epoch 2000.0 and a scale drift slightly less than 0.1 ppb/yr. Given the availability of VLBI time series covering its full history of observations (26 years of observations for VLBI, versus 13 years for SLR), more weight was given to VLBI scale in the ITRF2005P combination. Figure 4 above displays ILRS SLR and IVS VLBI scale variations with respect to ITRF2005P. The accuracy assessment of the ITRF scale is not easy to evaluate, being dependent on several factors, as for instance, the quality and distribution of the local ties, the SLR range bias effect, the tropospheric modeling in case of VLBI and other possible systematic errors of the two techniques. However, given the level of consistency mentioned above between VLBI and SLR scales and despite the optimistic accuracy estimate of the ITRF2000 datum definition as stated in (Altamimi et al., 2002a), and to be more conservative, we can postulate that the current level of accuracy of ITRF scale is around 1 ppb and 0.1 ppb/yr.

1.A.1.3 Earth Orientation Parameters

In order to ensure the IERS EOPs and ITRF consistency, and as mentioned already, the EOP's are for the first time included in the ITRF2005 combination. As results from this combination, Figure 5 shows a zoom of ± 1 *mas* of polar motion residuals, indicating the level of consistency between the time series of the 4 techniques. The WRMS computed over these residuals are at the level of 50 µas for GPS, 135-170 µas for VLBI and SLR and 650-750 µas for DORIS.

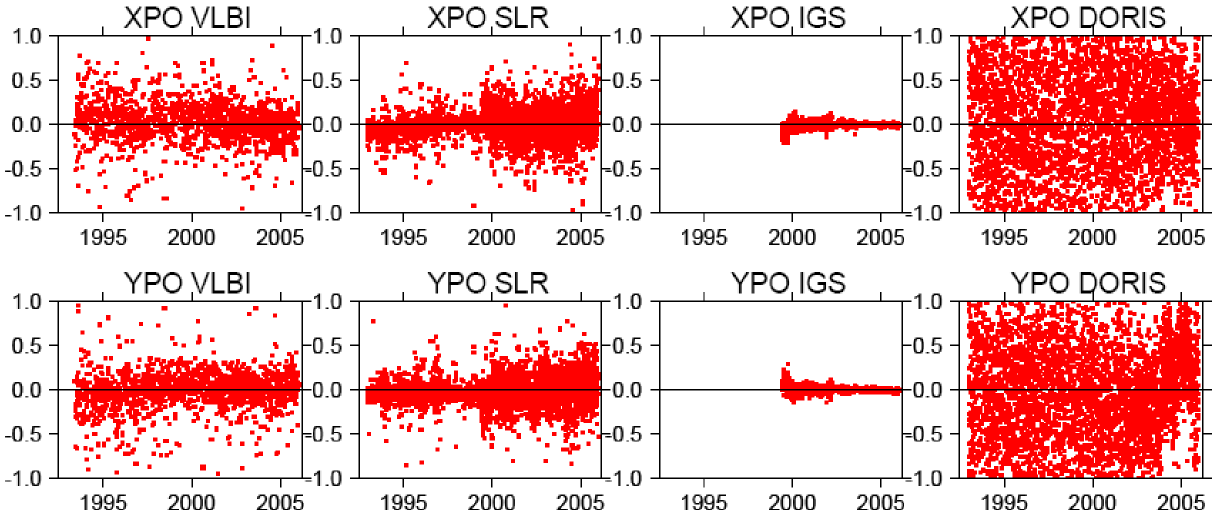

Figure 5. ± 1 *mas* zoom of polar motion residuals as results from the ITRF2005P combination.

I.B – Combination at the measurement level

The first combination at the measurement level over a long period (one year) carried out by the GRGS was computed during the years 2004 and 2005 (Coulot et al. 2006). This kind of combination has already been investigated in the recent past and has been applied for combining VLBI sessions (Andersen 2000) and for combining several techniques albeit on a shorter period of time of three months with a unique estimation of station positions (Yaya 2002).

The main goal of the GRGS combination was to prove the efficiency of such space-geodetic combinations at the observational level for the computation of EOPs. Nevertheless we have taken the opportunity of these computations to study the underlying TRFs. Theoretically this approach is the most satisfactory as it is closer to measurements. Furthermore, by using the same software to carry out the computations, we guarantee that any inaccuracy is identically shared by all the involved techniques.

We have used observations of the four techniques: VLBI SLR, GPS and DORIS. Our parameters of interest were EOPs (pole coordinates x_p and y_p and Universal Time UT1-UTC) with six-hour or one-day sampling together with weekly station positions. The computations have been made for one year test (the year 2002) and with an homogeneous computational framework; indeed, the same software was used to process the data of each technique involved. Regarding these individual computations, the data processing were based on the experience and the expertise of the GRGS research groups such as the Centre National d'Etudes Spatiales (CNES)/Observatoire Midi-Pyrénées (OMP), the GEMINI department of the Observatoire de la Côte d'Azur (OCA), the Institut Géographique National (IGN) research laboratory LAREG and the companies Noveltis and Collecte Localisation Satellite (CLS).

I.B.1. Current achievement

It is obvious that such a real rigorous combination at the measurement level is a very ambitious computation and, so, is still an utopia as the problems involved are numerous and still arduous. But such a combination is clearly the goal to reach in the future.

As a first computation, we have carried out a more reasonable and simple combination. Indeed we do not have considered the atmospheric delays as common parameters between techniques: the GINS/DYNAMO software did not yet allow us to consider atmospheric delays as links between geodetic techniques. We have limited us to terrestrial links and, more particularly, to EOPs (x_p, y_p and UT1). We did not use local ties between instruments in co-located sites. The reason is the problem of the heterogeneity between the terrestrial reference frames of each technique inside the combination. This problem is exhaustively discussed in a following subsection. Finally, considering our recent experience for GPS and VLBI computations with the GINS software, we have decided to keep only EOPs and station positions as parameters of interest.

So this first combination carried out at the measurement level aimed to

- prove that mixing the sensitivities of the four techniques involved with respect to UT1 can allow to derive an absolute Universal Time with the density of the GPS solutions;
- give a methodology of combination which can be used as a starting point by other groups in the world;
- give a concise but precise review of what can be expected of such a combination at the measurement level;
- underline some important problems and give some clear and precise prospects to take these critical aspects into account in the near future.

I.B.1.1. Earth Orientation Parameters

As previously mentioned, the actual status of our software does not reproduce the “state-of-the-art” analysis of each technique. However, the comparison of our individual solutions with the combined one allows to identify the capabilities of the combination at the measurement level. In Table 2, we give biases and WRMS of the differences between each EOP solution and the EOPC04 time series.

First of all, we can notice that the combination at the measurement level allows to compute UT1 by mixing sensitivities of all techniques, which is not possible when the combination is done at the level of individual solutions. The absolute information brought in by VLBI cancels existing correlations between longitudes of ascending nodes and UT1 in orbital signals sensed by artificial satellites. Moreover, the UT1 WRMS of the combined solution is close to the value obtained with the VLBI technique only. The combined UT1 series presents also the advantage of a regular sampling in opposition with the VLBI series. These results show the great importance of the VLBI technique inside the combination.

Concerning the pole coordinates, the WRMS of the combined solution are better than the best values obtained for any of our individual solutions. The combined solution presents a significant bias for y_p equal to the value found for the GPS-only solution. We can also notice that biaises for x_p are very close (-37 and -31 µas) . Furthermore, the WRMS of the differences between the combined solution and the GPS-only solution is 44 µas for x_p and 41 µas for y_p (nearly 1mm). This clearly shows that GPS dominates the three others techniques in the combination regarding pole coordinates, as VLBI does regarding UT1.

Table 2. Statistics (Bias/WRMS) of the differences between individual and combined solutions (with six-hour and one-day samplings) and the EOPC04 time series. Values are given in µas for x_p and y_p and in 0.1 µs for UT1.

Solution	Bias	WRMS	Solution	Bias	WRMS.
DORIS x_p	-416	939	SLR x_p	39	245
DORIS y_p	-229	837	SLR y_p	210	208
GPS x_p	-37	102	VLBI x_p	-135	225
GPS y_p	159	101	VLBI y_p	187	243
			VLBI UT1	38	111
COMBI xp 6 hours	-28	197	COMBI x_p 1 day	-31	90
COMBI yp 6 hours	166	193	COMBI y_p 1 day	159	92
COMBI UT1 6 hours	-20	152	COMBI UT1 1 day	-11	121

Finally, regarding values obtained for individual solutions, we can notice a relative agreement between the y_p biases between GPS, SLR and VLBI (the DORIS technique is clearly inconsistent with other techniques). The same can not be said regarding x_p biases. It seems that references underlying the SLR and VLBI coordinates x_p are not consistent with GPS ones. The reason is certainly the weakness of the observation networks of these two techniques.

I.B.1.2. Datum definition and TRF parameters

The previous subsection shows inconsistencies between techniques regarding EOPs. Tables 3 and 4 underlines inconsistencies regarding involved TRFs. More particularly, the table 3 gives the mean reference system effects (Sillard & Boucher 2001) of individual techniques inside the combination. The only common parameters being the EOPs, the effects on the three rotations are clearly coherent. It is not the case for the other four parameters, the three translations and the scale factors.

The same situation appears in the table 4. Indeed, this table gives the mean values of the seven parameters per technique inside the combination with respect to the ITRF2000. Minimum constraints have been applied per technique in agreement with the reference system effects of the table 3 (Coulot et al. 2006).

Table 3. Mean reference system effects computed per technique inside the combination through variance matrices of station positions of weekly combined solutions for EOPs and station positions estimated with weak constraints at 1m. Effects are translated into standard deviations of the seven parameters. Values are given in cm.

Technique	TX	TY	TZ	D	RX	RY	RZ
DORIS	0.09	0.09	***0.38***	0.09	***8.03***	***7.41***	***17.40***
GPS	0.07	0.07	***0.39***	0.02	***8.01***	***7.40***	***15.59***
SLR	0.04	0.04	0.11	0.03	***8.01***	***7.39***	***23.04***
VLBI	***41.31***	***41.29***	***40.98***	0.19	***7.72***	***8.21***	***15.41***

Table 4. Mean values of the seven estimated parameters of transformation per technique between combined weekly TRF solutions computed with minimum constraints and ITRF2000. Values are given in mm.

Technique	TX	TY	TZ	D	RX	RY	RZ
DORIS	-6.9	-20.0	-2.6	36.9	-1.3	0.4	-1.5
GPS	-2.2	0.3	-1.6	11.7	0.1	0.5	-0.1
SLR	-1.4	2.7	9.2	1.4	0.0	2.3	.-1.4
VLBI	0.0	-1.0	1.3	-4.0	0.0	0.0	0.1

The values listed in table 4 show small values for the three rotations, due to the minimum constraints used. But they also show great inconsistencies between techniques regarding the other parameters. Furthermore, we can notice, in table 3, the TZ effect for the DORIS and GPS technique. As the SLR does, these techniques should be able to detect the geocenter motion. It is not the case as shown by inconsistent mean values between translation values obtained for the satellite technique translation parameters (without minimum constraints, mean values obtained for TZ are 19.7 mm for DORIS and -96.8 mm for GPS). Finally, scale factor values are also inconsistent between all techniques. The difference between VLBI and SLR scales is nearly 6 mm so nearly 1 ppb; it is the same value than the one noticed for the ITRF2005 results (see section 1.A.1.2).

II – How can combinations help to achieve a 0.1 ppb consistency?

Combination and implicitly comparison of geodetic products or observations is the only way allowing the evaluation of the level of consistency between the techniques. By revealing disagreements between techniques for specific geodetic parameters, it then stimulates research and development to improve modeling and measurements. However, individual techniques as well as their combination will be limited in accuracy by several factors which need to be addressed and improved in order to go toward 0.1 ppb consistency. In this section we try to make the inventory of major domains where improvement should and could be done to improve the accuracy of both types of combination.

The areas where improvement and new developments are needed could be gathered in the following three categories

- the techniques and their networks;
- the data processing;

- the combination methods.

II.1. How to improve the Techniques and their networks ?

The following issues are identified to be important limitation factors for consistency and accuracy of geodetic products and their combination:

- In terms of network distribution, we can say that GPS and DORIS do not suffer as VLBI and SLR do. VLBI and SLR network distributions and their co-locations are far from optimal and need an urgent effort for improvement under the GGOS umbrella. The imbalance between the two hemispheres is particularly alarming. The ITRF scale definition is based on these two techniques and would suffer in the long-term as the networks and instruments naturally degrade. The SLR network is in addition very critical for the ITRF origin maintenance over time and is actually in danger as illustrated earlier with ITRF2005 results.
- It was proved in case of DORIS (Altamimi et al. 2006) that the number of satellites is a critical factor of the positioning performance and frame parameters. It would then be very beneficial not only for DORIS, but also for SLR to increase the number of satellites. Indeed, only the two LAGEOS satellites are really interesting for the TRF determination, but then we only have two different orbital planes to determine the Earth's rotation. The same can be said for the DORIS technique, even if the number of dedicated satellites has been increased in the recent past (SPOT5, Jason-1 and ENVISAT). Doing so will help to improve the EOP determinations by these two techniques.
- As by nature the geodetic instrumentations degrade over time, their replacement or and upgrade is fundamental to improve the precision and the accuracy of the measurements of each technique.
- IAG/GGOS, via IGS activities should be prepared to integrate and support the GALILEO system which, together with GPS, will certainly help improving the geodetic products.
- An evaluation study might be needed regarding the feasibility and benefit of "near real-time" and continuous measurements for both SLR and VLBI techniques. Indeed, these techniques are "human and budget" dependent leading to important gaps in their observations. Some SLR stations can provide a very poor number of measurements on a given week (the reason is not only human; the weather is also responsible). The sparseness of and the poor connection between VLBI sessions makes it difficult to ensure robust analysis at the observation level with the other techniques. Dedicated and repeated global TRF and EOP VLBI sessions are needed in order to avoid the current gaps, especially for Universal Time.
- An exhaustive knowledge and better characterization of all technique systematic errors is fundamental to improve consistency and accuracy: SLR range biases, clocks for GPS and VLBI, all antenna related effects for GPS and DORIS, etc.

II.2. Data processing Improvements

Among the various issues related to data processing, improvements are needed, e.g.:

- Comparison campaigns between international software should be carried out to ensure that all international analysis centers involved (currently or in the near future) in combinations really use the same a priori models in order to make the data processing consistent under the millimeter level. On the one hand, it would help to reduce inconsistencies between solutions of the same technique for ITRF-kind combinations. On the other hand, it is a necessary pre-requisite for a combination at the measurement level at an international level.

- It seems necessary to have a better knowledge of the effect of the atmosphere on the measurements used. Indeed all the techniques involved are not affected at the same level by the atmospheric crossing so this effect can give rise to inconsistencies between techniques.
- For satellite techniques, to improve the orbit quality and, as a consequence, the quality of the models used for orbit computations (Earth's gravity field, atmospheric density, etc.) can help to improve results (i.e. station position and EOP time series for individual solution combinations) and even a priori residuals used for measurement combinations.

II.3. Improvement of the Combination methods

Continuous refinement of the combination methods and their inputs is a key element to at least preserve the current consistency between the techniques and their products. The reader may also refer to (Altamimi et al., 2002b) for more detailed discussion on issues that need to be improved for more reliable combination of geodetic products. Among other areas for improvements, we can cite the following two issues:

- Number and distribution of co-locations and the quality of local ties are the key-element of multi-technique combination and in particular for the first type combination. The current situation is indeed far from optimal, despite the IERS initiative to improve the co-location issue. Accurate and repeated local surveys and optimal adjustment yielding local ties with full variance-covariance information in SINEX files are the pre-conditions for robust multi-technique combinations. More discussion regarding co-locations could be found in (Altamimi et al., 2005).
- Geodetic stations at tectonic plate boundaries, deformation and seismic zones need better modeling of their behavior (pre and co-seismic effects as well) and an assessment of their impact on the TRF stability over time. Seasonal, transient and all kind of non-linear motions are also important events which need to be considered by refined time series analysis. Ideally, co-location sites in such areas would help discriminating between real motions and technique related artifact effects. Increasing the number of those stations in such areas would help better characterizing these effects.

II.4. Specific look at the measurement combinations

The main difficulty in this kind of combination carried out at the observational level is that the inconsistencies between the technique measurements must be taken into account to derive a robust combination. On the other hand, we can take advantage of working at the measurement level to find and use several robust links at different levels between the different techniques involved. The main requirement is to find optimal links between techniques from the starting point (the measurements – multi-technique satellites and common atmospheric delays) to the products (mainly TRF and EOP – common global parameters, local ties and common residual signals at colocated sites) to insure the consistency between all techniques.

It implies an exhaustive knowledge of the error budget of each technique involved, and as previously seen, i) to increase the number of multi-technique satellites and to study and understand their optimal use in the framework of such combinations, ii) to improve instrumentations involved and iii) to support combinations carried out at the measurement level and to support research carried out in this field, that is to say: atmospheric delays as common parameters between techniques, use of multi-technique satellites as spatial links, study of the impact of the use of local ties in geodetic co-located sites, to derive common global parameters (geocenter motion, scale) and to find and use optimal weighting of techniques on a weekly basis.

It also requires a well-suited model which allows the simultaneous computation of TRF, EOP and global parameters in a consistent way. This model is currently under design and tests (Pollet 2006).

II.5 . Prospects

Ideally, we think that combination or estimation (using raw observations of all techniques) of all geodetic products is the challenging target to follow. Meanwhile, some intermediate steps have to be validated: the ITRF2005 and subsequent ITRF solutions integrate now the EOPs in the combination, the addition of the radio-sources should follows. Regarding the combination at the observation level, it should ultimately include the Earth's gravity field in the same process as the other geodetic reference products to take the advantage of the dynamical character of such computations.

Furthermore, if we want to obtain such robust and consistent combinations at the 0.1ppb level, we have first to study and understand geophysical effects under the millimetre level which are also challenging issues not only for Geodesy but for all Earth sciences.

Conclusion

How can combinations help to achieve a 0.1 ppb consistency ? An interesting question to which we tried to bring some answers in this paper, far from being complete. Based on concrete examples of analysis done using the two combination approaches, we showed that 0.1 ppb accuracy or consistency of geodetic products is not reached today. We underlined important limitation factors inherent to individual techniques and their combination that should be undertaken in future research and development to help achieving that level of consistency. These limitation factors imply improvement of the measuring techniques, their networks, co-location sites, the data processing and modeling of physical phenomena affecting the geodetic observations and of course the combination methods themselves. We believe that the combination at the observation level, integrating all kind of geodetic raw observations, unique, consistent and coherent modeling, is ideally the target to be pursued. In the mean time, before definitely and ultimately embarking on this ambitious project, we believe also that there are important intermediate steps to overcome and areas of research and development to be undertaken while continuing to learn with the combination of the products. Last but not least, our geodetic networks with their instrumentations over which we build observations and valuable products need to be continuously improved and upgraded. This effort need a collective investment of all IAG services, the national and international space geodesy agencies and we hope that GGOS we will be able to find all the measures to achieve this challenge.

References

Altamimi, Z., P. Sillard, and C. Boucher, 2002a, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, Journal of Geophys. Res., 107(B10), 2214, doi:10.1029/2001JB000561.

Altamimi, Z., C. Boucher, H. Drewes, R. Ferland, K. Larson, J. Ray and M. Rothacher, 2002b, Combination of station positions and velocities, IERS Workshop on combination research and global geophysical fluids.

Altamimi, Z., C. Boucher and P. Willis, 2005, Terrestrial Reference Frame Requirements within GGOS Perspective, Journal of Geodynamics, 40, 363-374, doi:10.1016/j.jog.2005.06.002.

Altamimi, Z., X. Collilieux, C. Boucher, 2006, DORIS contribution to ITRF2005, Journal of Geodesy, doi: 10.1007/s00190-006-0065-5.

Andersen, P.H., 2000, Multi-level arc combination with stochastic parameters, Journal of Geodesy, 74, 531-551.

Blewitt, G., Z. Altamimi, J. Davis, R. Gross, C. Kuo, F. Lemoine, R.Neilan, H.P. Plag, M. Rothacher, C.K. Shum, M.G. Sideris, T. Schöne, P. Tregoning, S. Zerbini, 2006, Geodetic Observations and Global Reference Frame Contributions to Understanding Sea Level Rise and Variability, Workshop on Understanding Sea Level Rise and Variability, UNESCO, Paris, 2006.

Coulot, D., Ph. Berio, R. Biancale, S. Loyer, L. Soudarin, A.-M. Gontier, 2006, Towards a direct combination of space-geodetic techniques at the measurement level: methodology and main issues, Journal of Geophys. Res. , submitted and revised.

Gambis, D., 2004, Monitoring Earth orientation using space-geodetic techniques: state-of-the-art and prospective, Journal of Geodesy, 78, 295-305.

Pollet, A., 2006, Cumul de mesures de télémétrie laser sur satellites. Contributions aux systèmes de référence terrestres et aux paramètres d'orientation de la Terre, research curse report, Observatoire de Paris.

Sillard, P., C. Boucher, 2001, Review of algebraic constraints in terrestrial reference frame datum definition, Journal of Geodesy, 75, 63-73.

Yaya, Ph., 2002, Apport des combinaisons de techniques astrométriques et géodésiques à l’estimation des paramètres d’orientation de la Terre, PhD thesis, Observatoire de Paris.