Combination of Station Positions and Velocities

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Summary: The main focus of this position paper is to review the current status of the combination of station positions and velocities with an emphasis on the modelling, strategies and datum definition. A particular attention will be given to the current achievement, underlying accuracy level, weaknesses and limitation factors inherent to individual techniques as well as the distribution and quality of collocation sites. Goals and recommendations for future improvements are proposed.

1 Background

Although this paper deals with combination of station positions and velocities in a broad sense, it should be inscribed in the context of the IERS activities. Therefore, in order to illustrate the discussion of this paper, some examples will be taken from ITRF results and particularly the most recent version, namely ITRF2000 (Altamimi et al., 2002).

On the other hand, it is important to delimit the scope of this paper by assuming the following:

- Combination of time series of stations positions is outside the scope of this paper. However, some suggestions are proposed at the end of this paper for future IERS products and improvement of the consistency between IERS products.
- Although it would be a promising approach, multi-technique processing at the observation level is not discussed here.
- Station velocities are assumed here constant and linear.
- Station non-linear motion should be treated at the level of individual techniques or time series analysis and not at the combination level. However, since non-linear motions of some observing stations of space geodesy could be important, some recommendations are suggested hereafter.

In this paper we try to summarize the current status of this activity and draw some recommendations for improvements. These recommendations are presented in a broad sense of the IERS combination activities and they apply to the ITRF in particular. They (and other possible specific ITRF recommendations) should be discussed/adopted by the Working Group on ITRF Datum (WGID), the ITRS Center as well as the IERS Directing Board.

2 Combination model

The basic model currently used for combination of different sets of station coordinates is the one based on the formula of 7 transformation parameters. Given the context of this paper, we assume that the 7 parameters are valid at a given epoch and have linear time variations.

The input data are:

- individual solutions (station positions at given epochs and velocities) provided by analysis centers of the different techniques, expressed in various reference frames
- local ties (expressed as values at given epochs and linear variations), connecting stations of different techniques in collocation sites

The unknowns are:

- 14 transformation parameters between each individual frame and the combined one
- positions and velocities of all stations available in individual solutions, expressed in the combined frame

There are currently two combination approaches:

Type A:

One step combination: simultaneous estimation of transformation parameters of each individual solution w.r.t. the combined frame as well as combined station positions and velocities. In this case the datum definition of the combined frame could be achieved either by:

- fixing the 14 degrees of freedom
- using minimum constraint equations relating the combined frame to an external frame

Type B:

Two step procedure: in the first step, individual solutions are transformed in a selected given frame and in the second step, all the transformed individual solutions are combined together by stacking their normal matrices, assuming that they are all expressed in the same frame. In this case the datum definition is implicitly realized through the selected frame.

Note that in Type A approach, all common stations between at least two individual solutions interact in the estimation of the transformation parameters, whereas in Type B, stations which are common to two individual solutions and are not available in the selected frame may bias the combined frame.

We intentionally concentrate on the basic combination model only, excluding all other analysis strategies, such as stochastic modelling, weighting, minimum constraint equations, etc.

Current status

- IGN ITRF CC is using the Type A approach
- DGFI ITRF CC is using the Type A approach
- NRC ITRF CC is using the Type B approach and software upgrade is in progress
- Other combination groups: unknown

Recommendation 1:

The combination centers (groups) are asked to evaluate the consistency/impact of the above two approaches on the combined TRF.

3 Datum definition

The concept of reference systems is in fact a purely mathematical convention (or model) introduced to describe the physical Earth and the temporal variation of its shape. Therefore, all the parameters (origin, scale, orientation) needed to define a Terrestrial Reference System (TRS) or its physical materialization by a Terrestrial Reference Frame (TRF) could be selected arbitrarily or by convention. Meanwhile, space geodesy observations allow access to some of the TRF parameters. Satellite techniques sense the Earth Center of Mass, which could be used as a natural TRF origin, the scale depends on the modelling of some physical parameters and the orientation (unobservable by any technique) is still arbitrarily (or conventionally) defined.

In the context of IERS, the ITRS definition fulfills the following conditions:

- it is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere.
- the unit of length is the meter (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions. This is obtained by appropriate relativistic modelling.
- its orientation was initially given by the Bureau International de l'Heure (BIH) orientation at 1984.0.
- the time evolution of the orientation is ensured by using a no-net-rotation condition with regards to horizontal tectonic motions over the whole Earth.

The meaning of datum definition to be retained here is to specify the frame origin, scale and orientation parameters and their time evolution.

Delimiting the scope of this paper to combination of station positions and linear velocities, it is therefore assumed that the corresponding TRF time evolution is linear.

Any geodesy based TRF, used by a variety of users and in particular geophysicists, should preserve the physical properties embedded in space geodesy observations. Consequently, datum definition parameters accessed by the observations (such as the scale and the origin) should be selected as part of the TRF datum definition.

Unlike the TRF origin and scale, there is no physical property (or geodetic technique) known to allow the TRF orientation determination or its time evolution. To conventionally define the later (called also "rotational datum"), the current approach is to use the No-Net-Rotation (NNRC). Note that this choice is the one specified in the ITRS definition. On the other hand, one of the justifications for NNRC is that the Tisserand frame (the basis of NNRC) is used in the theory of Earth rotation, having the property to minimize the Earth's crust motion and deformation that would affect the Earth Orientation Parameters. Moreover, the TRF long-term stability is certainly more easy to maintain using NNRC than using other conditions, such as the hot-spot hypothesis.

Given the nature of this activity (assuming linear station velocities), a reasonable approach for the TRF orientation time evolution, is the selection of TRF core sites for which linear motion is assumed. The long-term stability of the TRF rotational datum should then be ensured over the selected core sites. However, non-linear motions of the TRF core sites should be clearly investigated (see recommendation 5 below).

Note: It should be emphasized that the strict ITRF datum definition issue constitutes the main mission of the WGID. Therefore, TRF datum definition recommendations formulated below should be discussed and possibly adopted by the WGID.

Current status

TRF origin: In the ITRF experience, SLR is currently providing the best determination of the Earth Center of Mass. However, the translation rate differences between satellite TRFs are heavily dependent on the network configuration, the orbit and the used observations. Moreover, the geocenter motion, affecting the TRF origin stability, is not clearly handled by the ACs.

The ITRF2000 origin is defined by fixing to zero the translation and translation rate parameters between ITRF2000 and the weighted mean of most consistent SLR solutions. As result from ITRF2000 solution, the origin accuracy of ITRF2000 (over 10 years) is estimated to be about 1.5 mm in X and Y and about 4 mm in Z translation components.

Recommendation 2 on TRF origin:
The ILRS is urged to investigate refinement of the SLR origin to reduce small, but still existing, discrepancies between the ILRS ACs and in particular in the Z component and its correlation with the SLR TRF scale. The IGS is urged to investigate methods to properly handle all GPS-antenna and transmitter related effects to improve GPS TRF origin. The capability of satellite techniques to accurately determine geocenter motion has to be clarified within a joint effort by the Technique Centers, together with the WGID. IGS should study the inclusion of LEO satellites into their global solutions in order to help improve the geocenter estimates.

TRF scale: the current analysis also showed that the best scale inter-technique agreement is between VLBI and SLR solutions. However, TRF scale and scale rate are affected by station vertical motions and other modelling such as the troposphere, as well as technique-specific effects, such as VLBI, GPS and DORIS antenna-related effects, and SLR station-dependent ranging biases.

The ITRF2000 scale is defined by fixing to zero the scale and scale rate parameters between ITRF2000 and the weighted mean of 5 SLR and 3 VLBI solutions. The ITRF2000 global scale accuracy (over 10 years) is estimated to be at 0.5 ppb (3mm) level. While the largest scale discrepancy between the 3 VLBI solutions (using the same software) does not exceed 0.3 ppb, it may reach 1 ppb in case of SLR and exceed 5 ppb in case of DORIS solutions.

Recommendation 3 on TRF scale:
IVS, IGS and IDS are urged to refine / investigate their various modelling, such as the troposphere and antenna-related effects in order to improve the TRF scale consistency. ILRS is asked to clarify the range bias impact on the SLR TRF scale. The effect of IGS equipment changes on station height determinations needs to be minimized. A joint effort by all Technique Centers is needed to monitor station height variations in order to minimize effect on the TRF scale.

TRF orientation: the definition of the TRF orientation at a given epoch is not an issue, while the current approach used to define its time evolution is the one satisfying the NNRC. The current accuracy of the NNRC realization is not yet clear and needs more investigation. Only a few models satisfying this condition are available at the present time, and their agreement is around 2 mm/y as described below. The realization of a NNR model using entirely (and uniquely) space geodesy observations is not possible currently for mainly the following two reasons:

- Space geodesy observing sites (and in particular those of high quality) are far from optimally distributed to allow an accurate discretization of the whole Earth surface.
- The rigorous realization of the NNRC is a complete integral of the Earth surface, including zones of deformation, while geodesy observations are not yet at this level of refinement.

On the other hand, we should distinguish between a NNR model realization and the TRF rotational datum definition. In the former, geophysical deformation information should be accounted for, while for the TRF long-term stability, the later should rely on core sites, whose motions could be accurately monitored.

The ITRF2000 orientation is defined by adding to the combination model a TRF minimum constraint equation (restricted to the orientation and its rate), allowing the alignment of ITRF2000 orientation to ITRF97 at epoch 1997.0 and its orientation time evolution to the geophysical model NNR-NUVEL-1A. This alignment is operated over 50 sites of high geodetic quality having the following properties: (1) continuously observed during at least 3 years; (2) located on rigid parts of tectonic plates and far away from deforming zones; (3) velocity formal error (as result of the ITRF2000 combination) less than 3 mm/y; and (4) velocity residuals less than 3 mm/y for at least 3 different solutions. The 50 sites used in the alignment are located on rigid parts of tectonic plates according to (Argus and Gordon, 1996).

In a recent GRL publication (Altamimi et al., 2003), it is demonstrated that the ITRF2000 alignment to NNR-NUVEL-1A model (satisfying the NNRC) is achieved at (or better than) the 1 mm/y level. This publication also presents comparative analysis between ITRF2000 and two other NNR models: the one published by Kreemer and Holt (2001) and APKIM2000.0 derived following procedure published in (Drewes, 1998). The agreement between these two models, ITRF2000 and NNR-NUVEL-1A, in terms of NNRC realization, range between 1–2.3 mm/y at the equator of the Earth surface.

Recommandation 4 on TRF orientation:
The WGID and ITRS Center are asked to set up criteria selection and to establish a list of TRF core sites. These sites should be of high geodetic quality so that they can be used in the definition of TRF datum orientation and its time evolution. They are also asked to adopt an optimal method to ensure the best accuracy and stability of the TRF NNRC realization. Some suggestions would be:

- Given the conventional nature of the orientation/rate definition, ITRF2000 could be adopted as a standard/conventional frame for TRF orientation rate definition.
- NNR-NUVEL-1A is being inadequate, another conventional NNR model could be adopted. More models need to be tested and evaluated.

4 Non-linear Site Motions

There are mainly two types of combinations for the TRF:

Case A:
An ITRF style of station positions (at a given epoch) and constant or linear velocities which correspond to the main focus of this paper. In this case, the combiner has no choice other than combining positions and velocities as they are submitted by the ACs. This means that if a particular modelling should be applied to stations having non-linear motions, this should be done at the AC's level and not at the combination level. For instance, modelling discontinuities of station positions (break-wise modelling) requires that all AC's (within each TC) need to adopt the same time breaks, and in a coordinated way between all the TCs for collocation sites.

Case B:
Time series combination of station positions. In this case, the combiner may have different choices in how the non-linear motions are handled, such as stochastic estimation of station positions.

The notion of "non-linear motion" to be retained here is that related to geophysical phenomena, e.g. Earthquakes. All other kinds of discontinuities in station positions originating from, e.g., equipment and processing changes should be addressed within each Technique Center.

Meanwhile in terms of TRF datum definition, considering the Case A approach, assuming linear TRF time evolution, it is recommended to investigate non-linear motions of TRF core sites.

Current status

Break-wise modelling is considered by some ACs (in particular within IVS and IGS) with no coordination between ACs or for time breaks consistency in the collocation sites.

Recommendation 5:
Technique Centers (IVS, ILRS, IGS, IDS) through their respective Analysis Centers, CRCs, ITRF CCs and other groups dealing with time series combination or research groups in geophysics are encouraged to investigate non-linear motions of space geodesy observing sites starting with TRF core sites. Sites with obvious non-linear motion should not be listed in the TRF core sites.

Recommendation 6:
Technique Centers (IVS, ILRS, IGS, IDS) are urged to ask their respective Analysis Centers to adopt a unique list of time breaks, as a consequence of geophysical phenomena. The ITRS Center and Technique Centers are also asked to ensure consistency of time breaks in the collocation sites.

5 Collocation Sites and Local Ties

Collocated geodetic sites are key element of combination research. Without collocations an inter-technique combined TRF would not exist. A global distribution of collocations is desired and the quality of local ties must be high.

Current status

The currently available local ties used in ITRF combinations were collected by the ITRS Center starting in the 1980's. They are from diverse sources and of various qualities, sometimes without variances. In ITRF2000, the local ties were used as observations, with proper variances, see (Altamimi et al., 2002) for more details.

The ITRF Report 4 on local ties (March 22, 2001) summarizes local tie problems in collocation sites as result from ITRF2000 Analysis:

- ITRF2000 contains 101 sites having 2 (72 sites), 3 (25 sites) or 4 (6 sites) collocated techniques.
- The number, distribution and quality of the ITRF2000 collocations were insufficient and old SLR-VLBI mobile collocations are now obsolete.
- 200 local tie vectors were included in the combination.
- 38 local tie vectors were missing, 25 of which are highly important.
- 20 vectors were declared as dubious: post fit residuals ≥1 cm.

Since the publication of ITRF2000, some progress has been made on the collocation site issue:

- A working group has been formed within IAG/CSTG to follow up local tie problems.
- Some local tie problems were identified, confirming ITRF2000 analysis, e.g. Fairbanks.
- A new survey of the entire Hartebeestoek 4-technique site is in preparation.
- New surveys of sites in Italy (Noto and Medicina) have been finished and a new survey for Matera is in preparation.

The situation of collocation sites of the currently active stations is now more dramatic, in particular for "time series combination approach", see the appended per pair-technique maps (based on the information currently available at the ITRS Center):

- SLR and VLBI observing stations are poorly distributed.
- VLBI 24-hour session observing networks are very sparse and not all connectable in terms of common stations. The consequence of this situation is that the number of VLBI collocations with other techniques is not always the same at weekly or monthly time interval.
- The current number of SLR-VLBI collocation sites does not exceed 6.
- Almost all active VLBI and SLR stations are collocated with GPS, but there are still 6 SLR sites not collocated with GPS.
- Only 8 VLBI-DORIS collocations exist and they are not well distributed.
- Only 7 SLR-DORIS collocations exist and they are not well distributed: 5 in the southern hemisphere and 2 in the northern hemisphere.
- There are 28 well distributed GPS-DORIS collocations.

The current available local ties are values at different (mostly unknown) epochs and they are thus considered as static, i.e. without time variation. For future improvement of the combination results, it is important to consider time variations of the local ties. This implies organizing repeated (yearly!) surveys in the collocation sites.

<u>Recommendation 7</u>:
In order to improve collocation sites distribution and observing networks:

- International effort is needed to improve VLBI-SLR collocations by installing new SLR systems (e.g. SLR2000) at all VLBI sites. These are very critical for the long term TRF scale maintenance.
- IVS is urged to schedule repeated Global-TRF observing sessions.
- IDS is asked to consider installing DORIS beacons at all SLR and VLBI sites, starting with sites collocated with GPS in order to augment the number/distribution of the 4-technique “primary” sites.

<u>Recommendation 8:</u>
The Working Group on Local Ties should be recognized by the IERS DB and integrated in the IERS structure. It should involve all the Technique Centers and representatives from potential agencies willing to contribute to this issue.

<u>Recommendation 9:</u>
The Working Group on Local Ties is asked to organize repeated local surveys in the collocation sites. Per-site local tie components (at the survey epoch) and their time variations should be provided in SINEX format with full variance-covariance matrix.

6 General remarks for future products/improvement

As soon as progress is made on the recommendations listed above, the IERS should think about future products, and the improvement and consistency between products. Concerning new products, we suggest the following:

- multi-technique time series solutions of “station positions + EOP”, at weekly or monthly interval
- 3-years interval of multi-technique solutions of “station positions & velocities + EOP”.

However, these suggested new products still need investigation and in particular the first one. While we can clearly define a frame for type-2 suggested product, similarly to ITRF-style, the problem of type-1 product is much more complicated on how to maintain exactly the SAME frame definition in time, in particular if we want (we should) assume a non-linear motion. One option for type-1 product is to select TRF core sites (to be used for the datum definition), for which we assume linear motions as suggested above. However, the other non-core stations having real non-linear motion may affect the time series combination. Moreover, while in case of IGS and IDS we "can" maintain the same number/distribution of core stations, it is not the case for SLR and worse in case of VLBI. And the problem becomes more complicated for IERS given the uneven distribution/quality of the collocation sites at each time interval. Consequently, type-1 product still need much work within each Technique Center (and of course IERS), from the theoretical/mathematical as well as the numerical/stability points of view.

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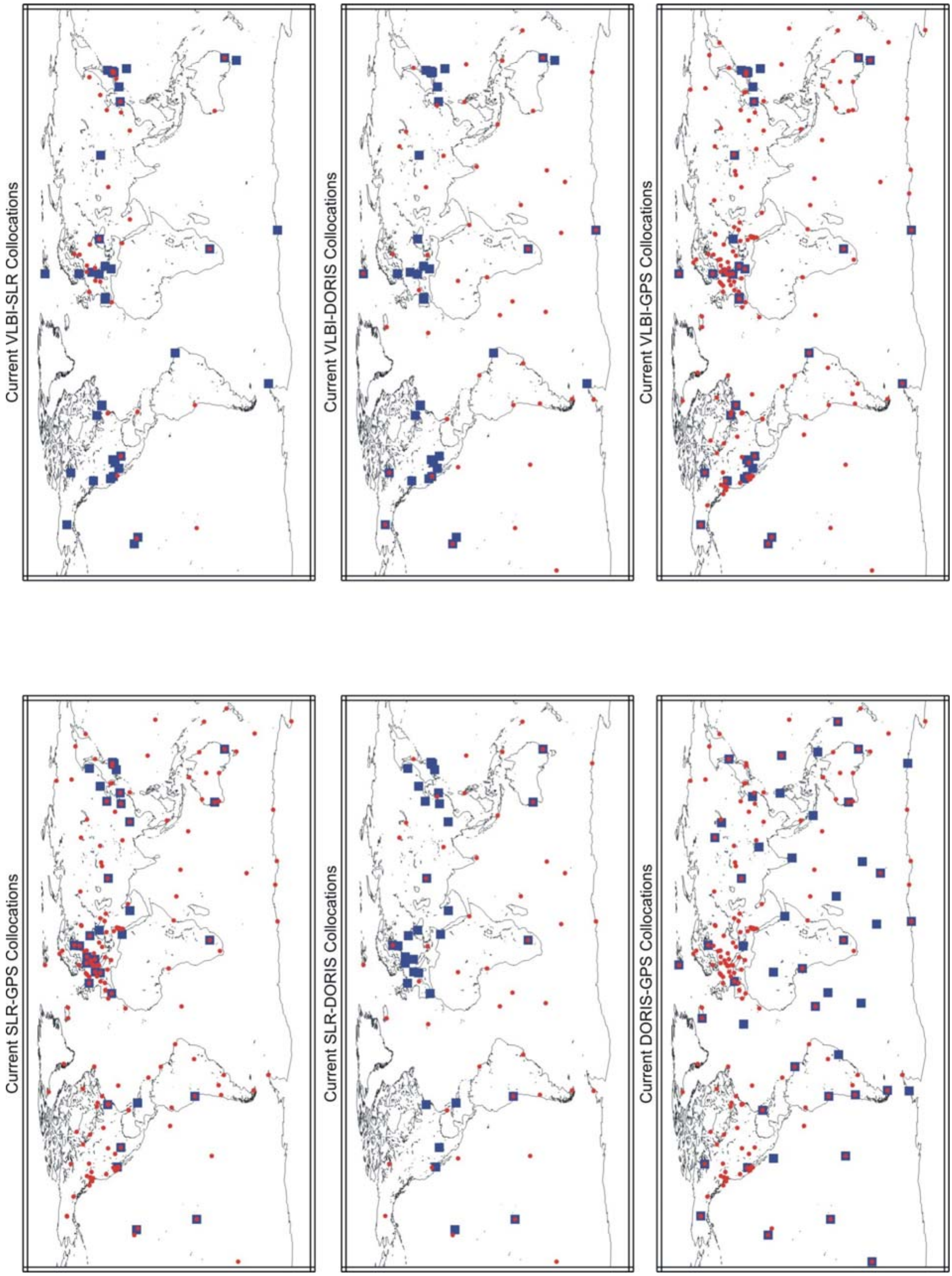

Fig. 1 Combination of co-location site for the geodetic space techniques.