External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2

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Abstract

Ideally, the origin of the Terrestrial Reference Frame (TRF) is defined as the center of mass of the whole Earth system, the time evolution of its orientation is such that no global net rotation of the whole Earth's surface is possible and the TRF scale is specified through the adoption of some physical constants and time-scale. These parameters need to be accurately determined since their choice has an influence on many Earth's science applications. The aim of the task force "External evaluation of the Terrestrial Reference Frame" is to review all the applications for which the TRF accuracy is of fundamental importance. As the TRF choice has an influence on the interpretation of the results in these specific applications, we investigate if some evaluation procedures could be established. We classified the methods that allow evaluation of the TRF using ground, geodetic data or models that have not been used in the TRF construction, based on their expected contributions. Some of these methods have been applied to the latest International Terrestrial Reference System realizations and the results are presented here. Although further analysis will be necessary to deliver a more precise error budget, our findings demonstrate that the most recent realizations of the ITRS are more accurate than the previous in terms of origin and scale rate definition. The current level of ITRF2008 accuracy is likely to be at the level of 0.5 mm/year along each origin component and better than 0.3 mm/year in the scale rate according to the most recent studies.

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1 TRF and Geosciences

A Terrestrial Reference Frame (TRF) is required for measuring Earth orientation in space, for positioning objects at the Earth's surface as well as satellites in orbit around the Earth, and for the quantification of geophysical processes and their changes in time. In order to be useful, the TRF needs to be specified by a consensus so that most of the users adopt the same definition. TRFs are currently materialized by sets of tridimensional coordinates of well defined ground markers, or instrument related points, that implicitly realize the three axes of the frame. As the Earth is deformable, these coordinates are currently piece-wise linear functions of time (Petit and Luzum 2010). As they are the result of statistical adjustments, they are affected by random errors but also by systematic errors related to modeling deficiencies either in the geodetic data adjustments or in the modeling of the non-linear deformations. Mitigating these errors is one of the main reasons why TRFs need to be frequently updated.

The displacement of the Earth's center of mass and the Earth's rotational motion in space need to be monitored since they are not fully predictable. They are of particular interest today, in the era of climate change. As the main relevant example, the study of sea level change requires accurate TRF coordinates for altimeter calibration (Bonnefond et al. 2011), for correcting tide gauge records for crustal motion (Wöppelmann et al. 2007) and for the precise determination of altimeter satellite orbits (Beckley et al. 2007; Cerri et al. 2010). Sea level changes related to Glacial Isostatic Adjustment (GIA) need also to be understood since they are not related to present day ice mass changes. As a consequence GIA models need to be validated by highly accurate geocentric velocities, which in parallel add a constraint on the Earth's mantle viscosity. For all these reasons, the science community needs coordinates with accuracy better than 1 mm and 0.1 mm/year (Plag and Pearlman 2009), which is not achievable at the present time.

Evaluation of the TRF accuracy is a real challenge since the true coordinates remain unknown. However, it is desirable to verify if they follow the specifications that have been proposed by scientists. The justification of the current International Terrestrial Reference System (ITRS) specifications (Petit and Luzum 2010) can be found in both practical realization issues and theoretical requirements (Boucher 1989). It can be especially demonstrated that the Earth's rotational motion equations can be simplified if the following requirements are adopted (Gross 2007; Moritz and Mueller 1988):

- ITRS Origin: center of mass of the Earth System (including oceans and atmosphere) (CM).
- ITRS Orientation: conventional at a reference epoch and defined by using a no-net-rotation (NNR) condition with respect to horizontal motions (this would nullify the relative angular momentum of the Earth's lithosphere assuming uniform density).
- ITRS Scale: meter (SI) as unit of length and Geocentric coordinate time (TCG) as time scale.

Note that the current ITRS realization, ITRF2008, is compatible with Terrestrial Time (TT). Its origin is the mean CM as observed by SLR over the time span of the Satellite Laser Ranging (SLR) observations used.

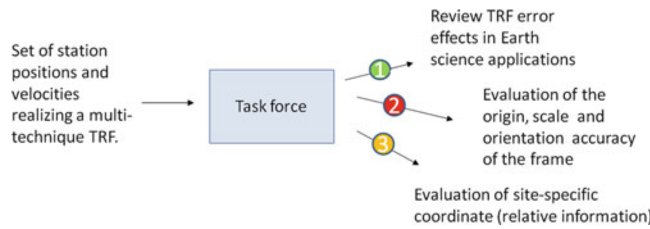

Fig. 1 Mission of the task force "External Evaluation of the TRF"

2 Aim of the Task Force

A task force has been created within sub-commission 1.2 "Global Reference Frames" of the International Association of Geodesy (IAG) (previously http://iag.ign.fr/index.php?id=39, now http://iag.uni.lu/index.php?id=39) to review all methods that allow evaluating the accuracy of a TRF. Figure 1 summarizes with more details the expected deliverables of the working group.

The TRF users need to be identified and the effect of TRF error on their derived products should be investigated (action 1 on Fig. 1). For example, it was shown that if the TRF origin is not at the Earth's CM, geocentric sea level estimated from space altimetry may be biased by a latitude dependent error (Morel and Willis 2005). As a consequence, the exact requirement of the scientific community in terms of TRF accuracy should be quantified. Conversely, evaluation methods of the TRF errors might be derived based on the observed magnitude of the errors.

We expect to review existing methods that evaluate TRF origin, orientation and scale accuracy based on external datasets (action 2 on Fig. 1). The orientation of the TRF axis w.r.t. crust, hereafter referred as TRF orientation w.r.t. crust in order to distinguish it from the TRF orientation in space, mainly impacts users that interpret the drift of the Earth Orientation Parameters (EOPs). As conversion between various NNR models can be done easily using published rotations and because the community needs are less critical, we concentrate this paper on the TRF origin and scale evaluation for which any error maps into geosciences products (Collilieux and Wöppelmann 2011; Morel and Willis 2005). We suggest considering the following sign convention for the TRF datum

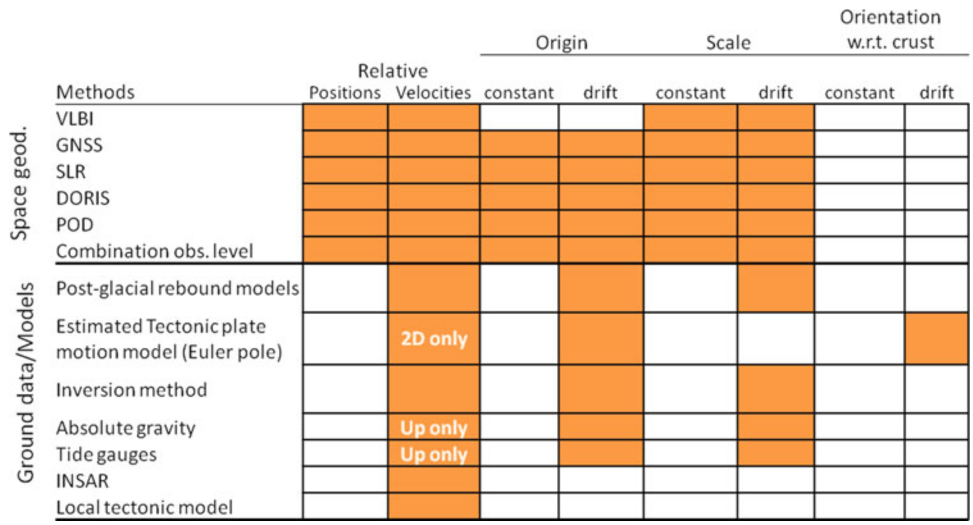

Fig. 2 Classification of the TRF evaluation methods and their contributions

errors that are origin and scale error parameters and their rates:

$$X_{trf} + T + d \cdot X_{trf} = X_{CM} + \delta_{noise} \quad (1)$$

$$X'_{trf} + T' + d' \cdot X_{trf} = X'_{CM} + \delta'_{noise}$$

where X_{trf} is the tri-dimensional position vector of one point and X_{CM} its expected position. T is the position of the TRF origin with respect to the true CM and is called the origin error vector and d is the scale factor that need to be applied to the TRF coordinates to get unbiased coordinates and will be called scale error in the following. The notation x' is used for time derivative of parameter x. We distinguish here between the random and systematic errors affecting individual station coordinates reflected by the noise term δ_{noise} and the common systematic errors T and d that are related to TRF datum. In the real world, any estimates of T and d are dependent on the network of stations used and could be estimated only if a priori information on X_{CM} or products derived from X_{CM} are available.

We consider any source of information as being external if it is not a space geodesy product used in the TRF estimation. The following products will be considered as external:

- Any type of geodetic product that has not been considered in the TRF construction. Space geodesy products can be considered if a more reliable modeling has been used for the data reduction or if additional data (older or more recent) have been included.
- Any processing of space geodetic data that uses the TRF coordinates as a priori as for example orbit fit residuals or EOPs.
- Any geophysical model of the crust displacement.

Site specific coordinates are also worth evaluating since the frame parameters are always transferred using a subset of site coordinates and because only one site coordinate error may impact derived products (Morel and Willis 2002) (action 3 on Fig. 1). An indirect evaluation is also possible by assessing the EOP time series estimated simultaneously with the TRF.

3 TRF Evaluation

Collilieux and Altamimi (2013) reviewed existing evaluation methods that rely on models or geodetic data. We have extended that review here and established a classification of the methods (see Fig. 2). It is useful to identify which frame parameter each data or evaluation method is intended to provide. We are especially interested in evaluating the TRF origin, scale and orientation, and relative coordinates. Due to the limited size of the paper, we had to select only a few results that will be reported below.

Space geodesy data are of course relevant for almost all frame parameters (see upper part of Fig. 2) except the TRF orientation w.r.t. the Earth's crust since station positions and EOPs are estimated simultaneously. However, VLBI observation equations are insensitive to coordinate shift and so VLBI is insensitive to the origin of the TRF. We included GPS for assessing TRF scale in this classification. Indeed, Haines et al. (2004) have inferred scale information from GPS-only solutions by relying on GPS antenna maps of receivers on board of Low Earth Orbiting (LEO) satellites. Haines et al. (2010) recently found using GRACE satellites a TRF scale offset of 17 mm w.r.t. ITRF2008 with a scale drift of −0.3 mm/year. The scale drift was independently confirmed by Collilieux and Schmid (2013) and is close to VLBI and SLR scale rate determination, respectively +0.15 and −0.15 mm/year w.r.t. ITRF2008 (Altamimi et al. 2011). The relatively large scale offset from Haines et al. (2010) could be explained by unmodeled multipath.

Table 1 Adapted from Table 7 of Cerri et al. (2010) Ratios between Jason-1 satellite z-positions and a priori TRF origin error along z, obtained for a simulated error of 5 mm, are shown in the 3rd column

Data used	Simulated error	
SLR	(z-Position shifted)	100 %
DORIS	(z-Position shifted)	74 %
GPS	(z-Orbit of GPS sat. shifted)	24–32 %
DORIS + SLR + GPS	(z-Position shifted + z-orbit of GPS sat. shifted)	80 %

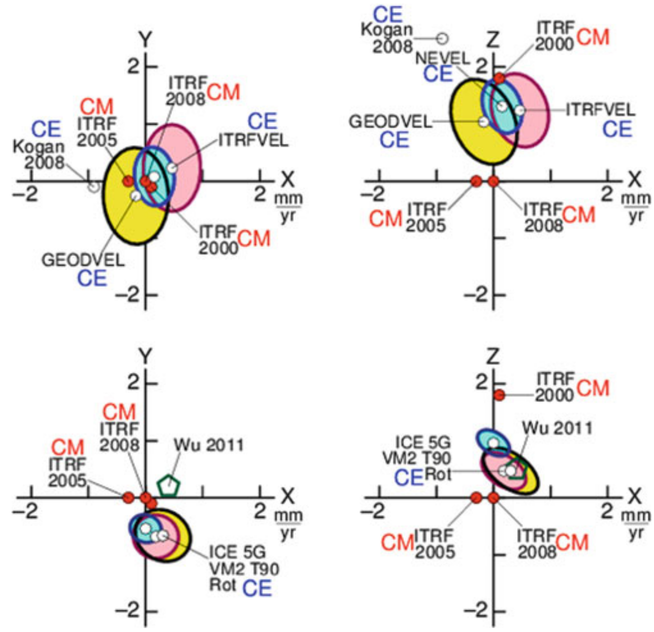

Fig. 3 *Upper plot*: positions of various frame origins determined from horizontal velocities only w.r.t. ITRF2008 origin (Argus et al. 2011; Kogan and Steblov 2008). *Lower plot*: positions of various frame origins determined from vertical velocities only and GIA models (Argus et al. 2011) w.r.t. ITRF2008 origin. Wu et al. (2011) result used both horizontal and vertical velocities. In these two plots, ITRF2000 and ITRF2005 Altamimi et al. (2007) are superimposed for comparison

LEO satellite orbits determined using Precise Orbit Determination (POD) procedures tend to be insensitive to errors in the radial positioning of the tracking network (Morel and Willis 2005). However, a frame origin offset along the z-axis can have a significant impact on the mean centering of the LEO satellite orbit (see, for example, Beckley et al. 2007). As shown in Table 1, differences between orbits computed by different techniques may highlight TRF datum errors since the impact of a TRF datum error on orbits is a function of the technique, at least along the z component. As some LEOs carry instruments from independent techniques the orbits computed using each technique can be compared (see Fig. 10 of Cerri et al. 2010). In addition, we note that altimeter crossovers computed from precise altimeter satellite orbits can provide an overall assessment of TRF performance (Cerri et al. 2010; Lemoine et al. 2010).

Models have been also suggested for TRF evaluation either based on tectonic plate motions (only the horizontal displacements can be constrained), GIA, elastic ground deformation due to mass trends or eventually local tectonic models (see lower part of Fig. 2). Such models are able to constrain the rate of the frame parameters. Whereas tectonic plate motion models cannot constrain scale rate (no vertical velocities in the models), they are the only method that can constrain the time evolution of the orientation of the TRF w.r.t. the crust since NNR models can be derived theoretically. Argus (2007) estimated an origin rate error simultaneously with Euler pole models of the tectonic plate motions from space geodesy results: his method is equivalent to nullifying term *d'* in Eq. (1) and to writing $X'_{CM} = \Omega \wedge X_{CM}$ where Ω is the Euler pole of the plate where the station is located. As the Euler poles refer to the center of mass of the solid Earth (CE) and that the CM w.r.t. CE motion should be small (Argus 2007), this origin rate error estimate provides a way to evaluate the origin of the velocity field. While the origin of such a determined Euler pole model like GEODVEL (Argus et al. 2010) is closer to ITRF2000 origin (Altamimi et al. 2002), the origin inferred by comparing GIA model vertical velocities with observed velocities is closer to ITRF2008, see Fig. 3. In this second method, the term *d'* in Eq. (1) as well as horizontal velocities are omitted and X'_{CM} is provided by the model. More recently, Wu et al. (2011) have inverted simultaneously for an origin rate error, Euler pole models, GIA and also present day mass trends, thus adding a new contribution. In their inversion, the estimated parameters are constrained not only by GPS but also by Ocean Bottom Pressure data and GRACE products (Tapley et al. 2004) (monthly solutions of time variable gravity). Their estimates presented in the lower part of Fig. 3 are rather consistent with ITRF2008 at the level of −0.5 mm/year for each component with the sign convention of Eq. (1).

Other types of measurements have been investigated. Tide gauge (TG) record trends have been suggested by Ray et al. (2010) and Bouin and Wöppelmann (2010) to evaluate the scale rate but the standard deviations that they obtained were too large. Moreover, Collilieux and Wöppelmann (2011) showed that TG records can be used jointly with GPS to assess a TRF but some assumptions on the long-term sea level spatial variability were necessary. As an independent dataset, Absolute Gravity (AG) rates were first suggested by Plag et al. (2007) to evaluate the TRF origin. We show in Fig. 4 a comparison of GPS vertical velocities and absolute gravimeter measurement rates in Fennoscandia. The AG data show a slight preference for ITRF2005 datum since the linear relationship between gravity rates and vertical uplift measurements approximates better the theoretical GIA expectations (near zero intercept for ITRF2005). This finding

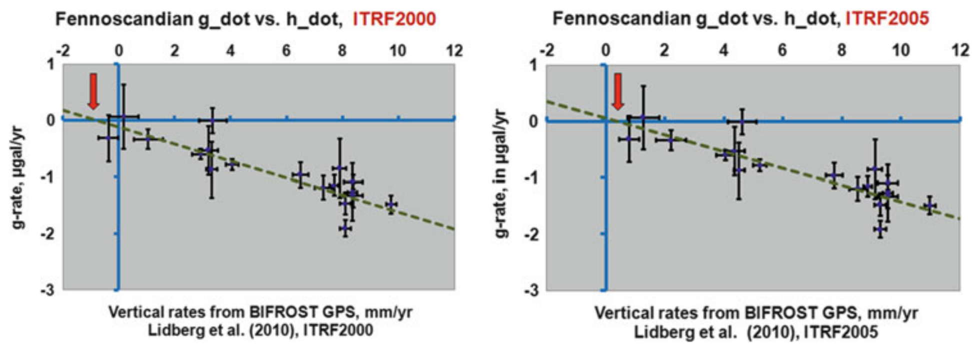

Fig. 4 Gravity rates from Nordic AG Project (coordinated by the Nordic Geodetic Commission) as a function of the vertical velocities from Lidberg et al. (2010), either in ITRF2000 or ITRF2005. As ITRF2008 and ITRF2005 translation and scale rates are negligible, see Fig. 3, ITRF2008 would show a similar near zero intercept (*right panel*)

has been recently confirmed by Mazzotti et al. (2011) over North America. Finally, we added in Fig. 2 the Interferometric Synthetic Aperture Radar (InSAR) which is a relative technique that determines the Earth surface displacement field along the radar's line-of-sight. It can be used to measure the relative displacement of two points on the same image and thus can be used for evaluation of the stability of regions around ITRF sites (Zerbini et al. 2007) or for site specific coordinate evaluation.

4 Conclusions

This paper summarizes the preliminary findings of the Task force "External evaluation of the TRF". The first part of the work has been focused on the evaluation of the origin and scale rates of the TRF. The upper limit of the current ITRF scale rate error is probably smaller than 0.3 mm/yr. The most recent result from Wu et al. (2011) showed an origin rate error of ITRF2008 smaller than −0.5 mm/year along the three directions which seems to be confirmed by joint analysis of AG rates and GPS vertical velocities. While it is a smaller error compared to previous published error budget, it still needs to be validated by other studies. It would be also valuable in the future to assess the origin, scale and self-consistency of the frame at the reference epoch, which is more subtle. Indeed, this investigation mostly relies on the space geodetic data analysis and on the handling of geodetic local ties or vectors between centers of phase of geodetic instruments onboard satellites. Station specific coordinates and velocities should be evaluated too. The activity of the task force will continue for the next 4 years (2012–2015) and will focus on these particular aspects.

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