4 Terrestrial reference systems and frames

4.1 Concepts and terminology

4.1.1 Basic concepts

Terrestrial Reference Systems and their realizations. A Terrestrial Reference System (TRS) is a spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points attached to the solid surface of the Earth have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations). In the physical model adopted in astrogeodesy, a TRS is modeled as a reference trihedron close to the Earth and co-rotating with it. In the Newtonian framework, the physical space is considered as a Euclidean affine space of dimension 3. In this case, such a reference trihedron is a Euclidean affine frame (O, E). O is a point of the space named **origin** and E is a basis of the associated vector space. The currently adopted restrictions on E are to be right-handed, orthogonal with the same length for the basis vectors. The triplet of unit vectors collinear to the basis vectors expresses the **orientation** of the TRS and the common length of these vectors its **scale**,

$$\lambda = \|\vec{E_i}\|_i \qquad i = 1, 2, 3. \tag{4.1}$$

Here, we consider geocentric TRSs for which the origin is close to the Earth's center of mass (geocenter), the orientation is equatorial (the Z axis is the direction of the pole) and the scale is close to an SI meter. In addition to Cartesian coordinates (naturally associated with such a TRS), other coordinate systems, *e.g.* geographical coordinates, could be used. For a general reference on coordinate systems, see Boucher (2001).

Under these hypotheses, the general transformation of the Cartesian coordinates of any point close to the Earth from TRS (1) to TRS (2) is given by a three-dimensional similarity ($\vec{T}_{1,2}$ is a translation vector, $\lambda_{1,2}$ a scale factor and $R_{1,2}$ a rotation matrix)

$$\vec{X}^{(2)} = \vec{T}_{1,2} + \lambda_{1,2} \cdot R_{1,2} \cdot \vec{X}^{(1)}. \tag{4.2}$$

This concept can be generalized in the frame of a relativistic background model such as Einstein's General Theory of Relativity, using the spatial part of a local Cartesian coordinate system (Boucher, 1986). For more details concerning general relativistic models, see Chapters 10 and 11.

In the application of Equation (4.2), the IERS uses the linearized formulas and notation. The standard transformation between two reference systems is a Euclidean similarity of seven parameters: three translation components, one scale factor, and three rotation angles, designated respectively, $T1$, $T2$, $T3$, D, $R1$, $R2$, $R3$, and their first time derivatives: $\dot{T}1$, $\dot{T}2$, $\dot{T}3$, $\dot{D}$, $\dot{R}1$, $\dot{R}2$, $\dot{R}3$. The transformation of a coordinate vector $\vec{X}_1$, expressed in reference system (1), into a coordinate vector $\vec{X}_2$, expressed in reference system (2), is given by

$$\vec{X}_2 = \vec{X}_1 + \vec{\mathcal{T}} + D\vec{X}_1 + \mathcal{R}\vec{X}_1, \tag{4.3}$$

where $\vec{\mathcal{T}} = \vec{T}_{1,2}$, $D = \lambda_{1,2} - 1$, $\mathcal{R} = (R_{1,2} - I)$, and I is the identity matrix so that

$$\mathcal{T} = \begin{pmatrix} T1 \\ T2 \\ T3 \end{pmatrix}, \quad \mathcal{R} = \begin{pmatrix} 0 & -R3 & R2 \\ R3 & 0 & -R1 \\ -R2 & R1 & 0 \end{pmatrix}.$$

It is assumed that Equation (4.3) is linear for sets of station coordinates provided by space geodesy techniques. Origin differences are about a few hundred meters, and differences in scale and orientation are at the level of 10^{-5}. Generally, $\vec{X}_1, \vec{X}_2, \mathcal{T}, D$ and $\mathcal{R}$ are functions of time. Differentiating Equation (4.3) with respect to time gives

$$\dot{\vec{X}}_2 = \dot{\vec{X}}_1 + \dot{\vec{\mathcal{T}}} + \dot{D}\vec{X}_1 + D\dot{\vec{X}}_1 + \dot{\mathcal{R}}\vec{X}_1 + \mathcal{R}\dot{\vec{X}}_1. \tag{4.4}$$

D and $\mathcal{R}$ are at the 10^{-5} level and $\dot{\vec{X}}$ is about 10 cm per year, so the terms $D\dot{\vec{X}}_1$ and $\mathcal{R}\dot{\vec{X}}_1$ which represent about 0.1 mm over 100 years are negligible. Therefore, Equation (4.4) could be written as

$$\dot{\vec{X}}_2 = \dot{\vec{X}}_1 + \dot{\vec{\mathcal{T}}} + \dot{D}\vec{X}_1 + \dot{\mathcal{R}}\vec{X}_1. \tag{4.5}$$

It is fundamental to distinguish between a TRS, having a theoretical definition, and its realization, a Terrestrial Reference Frame (TRF), to which users have access.

Terrestrial Reference Frame (TRF). A Terrestrial Reference Frame is defined as the realization of a TRS, through the realization of its origin, orientation axes and scale, and their time evolution. We consider here that the realization is achieved by a set of physical points with precisely determined coordinates in a specific coordinate system as a realization of a Terrestrial Reference System. It is also designated as a crust-based TRF and described in more detail in Section 4.1.3.

4.1.2   TRF in space geodesy

Seven parameters are needed to fix a TRF at a given epoch, to which are added their time derivatives to define the TRF time evolution. The selection of the 14 parameters, called "datum definition," establishes the TRF origin, scale, orientation and their time evolution.

Space geodesy techniques are not sensitive to all the parameters of the TRF datum definition. The origin is theoretically accessible through dynamical techniques (LLR, SLR, GNSS, DORIS), being the center of mass (point around which the satellite orbits). The scale depends on some physical parameters (*e.g.* geogravitational constant GM and speed of light c) and relativistic modeling. The orientation, unobservable by any technique, is arbitrary or conventionally defined. Meanwhile it is recommended to define the orientation's time evolution using a no-net-rotation condition with respect to horizontal motions over the Earth's surface.

Since space geodesy observations do not contain all the necessary information to completely establish a TRF, some additional information is needed to complete the datum definition. In terms of normal equations, usually constructed upon space geodesy observations, this situation is reflected by the fact that the normal matrix, N, is singular, since it has a rank deficiency corresponding to the number of datum parameters which are not reduced by the observations.

In order to cope with this rank deficiency, the analysis centers currently add one of the following constraints upon all or a sub-set of stations:

1. Removable constraints: solutions for which the estimated station positions and/or velocities are constrained to external values within an uncertainty $\sigma \approx 10^{-5}$ m for positions and m/y for velocities. This type of constraint is easily removable, see for instance Altamimi *et al.* (2002a; 2002b).

2. Loose constraints: solutions where the uncertainty applied to the constraints is $\sigma \geq 1$ m for positions and ≥ 10 cm/y for velocities.

3. Minimum constraints used solely to define the TRF using a minimum amount of required information. For more details on the concepts and practical use of minimum constraints, see for instance Sillard and Boucher (2001) or Altamimi *et al.* (2002a).

Note that the old method, where very tight constraints ($\sigma \leq 10^{-10}$ m) are applied (which are numerically not easy to remove), is no longer suitable and may alter the real quality of the estimated parameters.

In case of removable or loose constraints, this amounts to adding the following observation equation

$$\vec{X} - \vec{X}_0 = 0, \tag{4.6}$$

where $\vec{X}$ is the vector of estimated parameters (positions and/or velocities) and $\vec{X}_0$ is that of the *a priori* parameters.

Meanwhile, in the case of minimum constraints, the added equation is of the form

$$B(\vec{X} - \vec{X}_0) = 0, \tag{4.7}$$

where $B = (A^T A)^{-1} A^T$ and A is the design matrix of partial derivatives, constructed upon *a priori* values $(\vec{X}_0)$ given by either

$$A = \begin{pmatrix} . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i \\ 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i \\ 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 \\ . & . & . & . & . & . & . \end{pmatrix} \tag{4.8}$$

when solving for only station positions, or

$$A = \begin{pmatrix} . & . & . & . & . & . & . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i & & & & & & \\ 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i & & & 0 & & & \\ 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 & & & & & & \\ & & & & & & & 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i \\ & & \approx 0 & & & & & 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i \\ & & & & & & & 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 \\ . & . & . & . & . & . & . & . & . & . & . & . & . \end{pmatrix} \tag{4.9}$$

when solving for station positions and velocities.

The fundamental distinction between the two approaches is that in Equation (4.6), we force $\vec{X}$ to be equal to $\vec{X}_0$ (to a given σ), while in Equation (4.7) we express $\vec{X}$ in the same TRF as $\vec{X}_0$ using the projector B containing all the necessary information defining the underlying TRF. Note that the two approaches are sensitive to the configuration and quality of the subset of stations $(\vec{X}_0)$ used in these constraints.

In terms of normal equations, Equation (4.7) could be written as

$$B^T \Sigma_\theta^{-1} B(\vec{X} - \vec{X}_0) = 0, \tag{4.10}$$

where Σ_θ is a diagonal matrix containing small variances for each of the transformation parameters.

The general form of the singular normal equation constructed upon space geodesy observations could be written as

$$N(\Delta\vec{X}) = K, \tag{4.11}$$

where $\Delta\vec{X} = \vec{X} - \vec{X}_0$ designates the linearized unknowns and K is the right-hand side of the normal equation. Adding Equation (4.10) to the normal equation (4.11) allows it to be inverted and simultaneously to express the estimated solution $\vec{X}$ in the same TRF as the *a priori* solution $\vec{X}_0$. Note that the 7 columns of the design matrix A correspond to the 7 datum parameters (3 translations, 1 scale factor and 3 rotations). Therefore, this matrix should be reduced to those parameters which need to be defined (*e.g.* 3 rotations in almost all techniques and 3 translations in case of VLBI). For more practical details, see, for instance, Altamimi *et al.* (2002a).

4.1.3   Crust-based TRF

Crust-based TRFs are those currently determined in IERS activities, either by analysis centers or by combination centers, and ultimately as IERS products (see Section 4.1.5).

The general model connecting the instantaneous position of a point anchored on the Earth's crust at epoch t, $\vec{X}(t)$, and a regularized position $\vec{X}_R(t)$ is

$$\vec{X}(t) = \vec{X}_R(t) + \sum_i \Delta \vec{X}_i(t). \tag{4.12}$$

The purpose of the introduction of a regularized position is to remove high-frequency time variations (mainly geophysical ones) using conventional corrections $\Delta \vec{X}_i(t)$, in order to obtain a position with more regular time variation.

It is essential that the same conventional models be adopted and used by all analysis centers dealing with space geodesy data. The currently adopted models are described in Chapter 7.

4.1.4   The International Terrestrial Reference System

The IERS is in charge of defining, realizing and promoting the International Terrestrial Reference System (ITRS). The ITRS has been recently formally adopted by the IUGG at its General Assembly in Perugia (2007), through its Resolution 2 (see Appendix C).

To summarize and synthesize these legal texts (IAG and IUGG resolutions of 1991 and 2007, consistent with latest IAU Resolutions)

- GTRS (geocentric terrestrial reference system) is the new designation of CTRS (conventional terrestrial reference system), while the term CTRS is now used as a generic term to designate the identification of a specific TRS through a list of conventional rules fixing the origin, scale and orientation.

- The GTRS origin is the geocenter, considered for the whole Earth system body, including oceans and atmosphere.

- The GTRS time coordinate is TCG (Geocentric Coordinate Time). Therefore, the scale of the spatial coordinates is consistent with this fact.

- The time evolution of the orientation of GTRS follows a no-net-rotation (NNR) condition with regards to the horizontal Earth surface.

In fact, the IAG Resolution of 1991, as well as various scientific and practical considerations, led explicitly to defining the ITRS as three-dimensional. For example, we note that accurate geophysical models are presently developed within the Newtonian framework and that all practical applications (mapping, navigation) consider ITRS as a three-dimensional system.

The Perugia text should be read in such a way that the ITRS is assimilated to the spatial part of GTRS (and not to the 4d coordinate system). Following the previous summary, the ITRS is therefore fully fixed, considering the statement that its orientation fulfills the international agreements (Bureau International de l'Heure (BIH) orientation). The practical procedure adopted by the IERS at the beginning of its work led to the consideration that the ITRS orientation coincides with the previous BIH system at the epoch 1984.0.

The ITRS definition fulfills the following conditions:

1. It is geocentric, its origin being the center of mass for the whole Earth, including oceans and atmosphere;

2. The unit of length is the meter (SI). The 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 modeling;

3. Its orientation was initially given by the BIH orientation at 1984.0;

4. 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.

4.1.5 Realizations of the ITRS

Primary realizations of the ITRS are produced by the IERS ITRS Center (ITRS-PC) under the name International Terrestrial Reference Frame (ITRF). Twelve ITRF versions were produced, starting with ITRF88 and ending with the ITRF2008. Up to the ITRF2000 solution, long-term global solutions (comprising station positions and velocities) from four techniques (VLBI, SLR, GPS and DORIS) were used as input for the ITRF generation. As described in more detail later, starting with the ITRF2005, time series of station positions and Earth Orientation Parameters (EOPs) are used as input data for the ITRF construction. The current procedure is to combine the technique TRF solutions using a combination model which is essentially based on the transformation formulas (4.3) and (4.5). The combination method makes use of local ties in co-location sites where two or more geodetic techniques are operated. The local ties are used as additional observations with proper variances. They are usually derived from local surveys using either classical geodesy or the global navigation satellite systems (GNSS). As they represent a key element of the ITRF combination, they should be more, or at least as accurate as the individual space geodesy solutions incorporated in the ITRF combination.

Up to ITRF2000 ITRF solutions were published by the ITRS-PC in *Technical Notes* (*cf.* Boucher *et al.*, 1996, 1998, 1999, 2004). The number following the designation "ITRF" specifies the last year whose data were used for the formation of the frame. Hence, ITRF2008 designates the frame of station positions and velocities constructed in 2010 using data available until the end of 2008 (2009.5 for GPS).

The current ITRF model is linear (position at a reference epoch t_0 and velocity). Therefore, the station position at an epoch t is expressed as:

$$\vec{X}(t) = \vec{X}_0 + \dot{\vec{X}} \cdot (t - t_0). \tag{4.13}$$

The numerical values are $(\vec{X}_0, \dot{\vec{X}})$. In the past (ITRF88 and ITRF89), constant positions were used as models $(\vec{X}_0)$, the linear motion being incorporated as conventional corrections derived from a tectonic plate motion model (see Section 4.2.2).

The reader may also refer to an earlier report of the ITRF Working Group on the ITRF Datum (Ray *et al.*, 1999), which contains useful information related to the history of the ITRF datum definition. It also details technique-specific effects on some parameters of the datum definition, in particular the origin and the scale. More details on the formation of ITRF2000 and ITRF2005 are available in Altamimi *et al.* (2002b, 2007).

4.2 ITRF products

4.2.1 The IERS network

The initial definition of the IERS network

The IERS network was initially defined through all tracking instruments used by the various individual analysis centers contributing to the IERS. All SLR, LLR and VLBI systems were included. Eventually, GPS stations from the IGS were added as well as the DORIS tracking network. The network also included, from its beginning, a selection of ground markers, specifically those used for mobile equipment and those currently included in local surveys performed to monitor local eccentricities between instruments for co-location sites or for site stability checks.

Each point is currently identified by the assignment of a DOMES (Directory of MERIT Sites) number. The explanation of the DOMES numbering system is given below. Close points are clustered into one site. The current rule is that all points which could be linked by a co-location survey (up to 30 km) should be included into the IERS network as a unique site having a unique DOMES site number. In reality, for a local tie to be precise at the 1 mm level, the extension of a co-location site should not exceed 1 km.

Co-locations

In the frame of the IERS, the concept of co-location can be defined as the fact that two instruments are occupying simultaneously or subsequently very close locations that are very precisely surveyed in three dimensions. These include situations such as simultaneous or non-simultaneous measurements and instruments of the same or different techniques. Usually, co-located points should belong to a unique IERS site.

Extensions of the IERS network

Following the requirements of various user communities, the initial IERS network was expanded to include new types of systems which are of potential interest. Consequently, the current types of points allowed in the IERS and for which a DOMES number can be assigned are (IERS uses a one character code for each type):

- L for satellite laser ranging (SLR),

- M for lunar laser ranging (LLR),

- R for very long baseline interferometry (VLBI),

- P for global navigation satellite systems (GNSS),

- D for détermination d'orbite et radiopositionnement intégrés par satellite (DO-RIS; also Doppler Navy Navigation Satellite System (NNSS) in the past),

- A for optical astrometry (formerly used by the BIH),

- X for precise range and range rate equipment (PRARE),

- T for tide gauge,

- W for meteorological sensor.

For instance, the cataloging of tide gauges co-located with IERS instruments, in particular GNSS or DORIS, is of interest for the Global Sea Level Observing System (GLOSS) program under the auspices of UNESCO.

Another application is to collect accurate meteorological surface measurements, in particular atmospheric pressure, in order to derive raw tropospheric parameters from tropospheric propagation delays that can be estimated during the processing of radio measurements, *e.g.* made by the GNSS, VLBI, or DORIS. Other systems could also be considered, if it was regarded as useful (for instance systems for time transfer, super-conducting or absolute gravimeters, *etc.*).

Another important extension is the wish of some continental or national organizations to see their fiducial networks included into the IERS network, either to be computed by IERS (for instance the European Reference Frame (EUREF) permanent GNSS network) or at least to get DOMES numbers (for instance the Continuously Operating Reference Stations (CORS) network in the USA).

4.2.2   History of ITRF products

The history of the ITRF goes back to 1984, when for the first time a combined TRF (called BIH Terrestrial System 1984 BTS84) was established using station coordinates derived from VLBI, LLR, SLR and Doppler/TRANSIT (the predecessor of GPS) observations (Boucher and Altamimi, 1985). BTS84 was realized in the framework of the activities of BIH, being a coordinating center for the international MERIT project (Monitoring of Earth Rotation and Intercomparison of Techniques; Wilkins, 2000). Three other successive BTS realizations were then achieved, ending with BTS87, before in 1988, the IERS was created by the IUGG and the IAU.

Until the time of writing, twelve versions of the ITRF were published, starting with ITRF88 and ending with ITRF2008, each of which superseded its predecessor.

From ITRF88 till ITRF93, the ITRF datum definition can be summarized as follows:

- Origin and scale: defined by an average of selected SLR solutions;

- Orientation: defined by successive alignment since BTS87 whose orientation was aligned to the BIH EOP series. Note that the ITRF93 orientation and its rate were again realigned to the IERS EOP series;

- Orientation time evolution: No global velocity field was estimated for ITRF88, ITRF89 and ITRF90, so the AM0-2 model of Minster and Jordan (1978) was recommended. Starting with ITRF91 and till ITRF93, combined velocity fields were estimated. The ITRF91 orientation rate was aligned to that of the NNR-NUVEL-1 model (Argus and Gordon, 1991), and ITRF92 to NNR-NUVEL-1A, adapted from NNR-NUVEL-1 according to DeMets *et al.* (1994), while ITRF93 was aligned to the IERS EOP series.

Since the ITRF94, full variance matrices of the individual solutions incorporated in the ITRF combination have been used. At that time, the ITRF94 datum was achieved as follows (Boucher *et al.*, 1996):

- Origin: defined by a weighted mean of selected SLR and GPS solutions;

- Scale: defined by a weighted mean of VLBI, SLR and GPS solutions, corrected by 0.7 ppb to meet the IUGG and IAU requirement to be compatible with TCG, while analysis centers provide solutions that are compatible with TT (Terrestrial Time);

- Orientation: aligned to the ITRF92;

- Orientation time evolution: velocity field aligned to the model NNR-NUVEL-1A, using the 7 rates of the transformation parameters.

The ITRF96 was then aligned to the ITRF94, and the ITRF97 to the ITRF96 using the 14 transformation parameters (Boucher *et al.*, 1998; 1999).

The ITRF2000 was intended to be a standard solution for geo-referencing and all Earth science applications. Therefore, in addition to primary core stations observed by VLBI, LLR, SLR, GPS and DORIS, the ITRF2000 was densified by regional GPS networks in Alaska, Antarctica, Asia, Europe, North and South America and the Pacific.

The individual solutions used for the ITRF2000 combination were generated by the IERS analysis centers using removable, loose or minimum constraints.

In terms of datum definition, the ITRF2000 is characterized by the following properties:

- Origin: realized by setting to zero the translation components and their rates between ITRF2000 and a weighted average of the most consistent SLR solutions;

- Scale: realized by setting to zero the scale and scale rate parameters between ITRF2000 and a weighted average of VLBI and the most consistent SLR solutions. Unlike the ITRF97 scale which is compatible with TCG, that of the ITRF2000 is compatible with TT;

- Orientation: aligned to that of the ITRF97 at 1997.0;

- Orientation time evolution: aligned, conventionally, to that of the geological model NNR-NUVEL-1A (Argus and Gordon, 1991; DeMets *et al.*, 1990; 1994).

The ITRF network has improved with time in terms of the number of sites and co-locations as well as their distribution over the globe. Figure 4.1 shows the ITRF88 network including about 100 sites and 22 co-locations (VLBI/SLR/LLR), and the ITRF2008 network containing 580 sites and 105 co-locations (VLBI/SLR/GPS/-DORIS).

4.2.3   ITRF2005

For the first time in ITRF history, the ITRF2005 used as input data time series of station positions (weekly from satellite techniques and 24-hour session-wise from VLBI) and daily EOPs. One set of time series per space geodesy technique was considered as input to the ITRF2005 combination. These solutions are the official
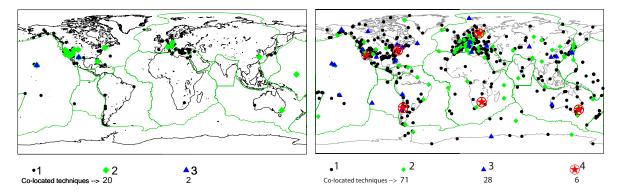
Figure 4.1: ITRF88 (left) and ITRF2008 (right) sites and co-located techniques.

time series provided by the international services of the 4 techniques, known as Technique Centers (TC) within the IERS. Note that these official TC solutions result from a combination at the weekly (daily) basis of the corresponding individual solutions provided by the analysis centers participating in the activities of each TC. Official time series were submitted to the ITRF2005 by the International VLBI Service for Geodesy and Astrometry (IVS), the International Laser Ranging Service (ILRS) and the International GNSS Service (IGS). At the time of the ITRF2005 release, official weekly combined solutions from the International DORIS Service (IDS) were not available, so that individual solutions were submitted by two DORIS analysis centers. For more details the reader may refer to Altamimi *et al.* (2007).

The ITRF2005 generation consisted of two steps: (1) stacking the individual time series to estimate a long-term solution per technique comprising station positions at a reference epoch and velocities as well as daily EOPs; and (2) combining the resulting long-term solutions of the four techniques together with the local ties in co-location sites. Therefore, in addition to the usual ITRF products (station positions and velocities), other important ITRF2005 results are also available to the users, namely:

1. full ITRF2005 and per technique SINEX files containing station positions, velocities and EOPs with complete variance-covariance matrices;

2. time series of station position residuals resulting from the stacking of the individual time series of the 4 techniques;

3. geocenter time series from SLR and DORIS. There is no useful geocenter motion information from GPS/IGS because it has been removed <[1]>, the submitted weekly solutions being aligned to ITRF2000;

4. full time series of EOPs consistent with the ITRF2005.

The ITRF2005 origin is defined in such a way that it has zero translations and translation rates with respect to the Earth center of mass, averaged by the SLR time series spanning 13 years of observations. Its scale is defined by nullifying the scale and its rate with respect to the VLBI time series spanning 26 years of observations. It should be noted that after the release of the ITRF2005 it was discovered that the IVS VLBI solutions used for the ITRF2005 construction did not include pole tide corrections referenced to the mean pole path recommended by the IERS Conventions 2003. Post-ITRF2005 analyses of IVS solutions where the mean pole tide correction was applied revealed a constant scale offset of -0.5 ppb with respect to the IVS solutions used for ITRF2005 (Altamimi and Collilieux, 2008). The ITRF2005 orientation (at epoch 2000.0) and its rate are aligned to ITRF2000 using 70 stations of high geodetic quality.

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[1]The removed geocenter motions are retained in the weekly SINEX files under the parameters XGC, YGC, and ZGC.

4.2.4 ITRF2008, the current reference realization of the ITRS

Following the same strategy initiated with the ITRF2005 release, the ITRF2008 is a refined solution based on reprocessed solutions of four space geodesy techniques: VLBI, SLR, GPS and DORIS, spanning 29, 26, 12.5 and 16 years of observations, respectively.

The ITRF2008 is composed of 934 stations located at 580 sites as illustrated in Fig. 4.1, with an imbalanced distribution between the northern (463 sites) and the southern hemisphere (117 sites).

As illustrated by Fig. 4.1, there are in total 105 co-location sites; 91 of these have local ties available for the ITRF2008 combination. Note that, unfortunately, not all these co-located instruments are currently operating. For instance, among the 6 sites having 4 techniques, only two are currently fully operational: Hartebeesthoek, South Africa and Greenbelt, MD, USA.

The ITRF2008 is specified by the following frame parameters:

- Origin: The ITRF2008 origin is defined in such a way that there are zero translation parameters at epoch 2005.0 and zero translation rates with respect to the ILRS SLR time series.

- Scale: The scale of the ITRF2008 is defined in such a way that there is a zero scale factor at epoch 2005.0 and a zero scale rate with respect to the mean scale and scale rate of VLBI and SLR time series.

- Orientation: The ITRF2008 orientation is defined in such a way that there are zero rotation parameters at epoch 2005.0 and zero rotation rates between ITRF2008 and ITRF2005. These two conditions are applied over a set of 179 reference stations located at 131 sites, including 107 GPS, 27 VLBI, 15 SLR and 12 DORIS sites.

4.2.5 ITRF as a realization of the ITRS

The procedure used by the IERS to determine ITRF products includes the following steps:

1. definition of individual TRF used by contributing analysis centers. This implies knowing the particular conventional corrections adopted by each analysis center;

2. determination of the ITRF by the combination of individual TRF and datum fixing. This implies the adoption of a set of conventional corrections for the ITRF and ensures the consistency of the combination by removing possible differences between corrections adopted by each contributing analysis center.

Meanwhile, for various reasons, there are particular cases where users would need to add specific corrections to ITRF coordinates in order to meet their particular applications. The currently identified cases are the following:

A) *Solid Earth tides*

To account for the displacement due to solid Earth tides, all analysis centers use a model $\Delta\vec{X}_{tidM}$ that contains a time-independent part, so that the regularized positions obtained are termed "conventional tide-free", according to the nomenclature in the Introduction of the Conventions. Such a hypothesis has been taken since the first solid Earth tides model of the MERIT Standards. Consequently, the ITRF has adopted the same option and is therefore a "conventional tide-free" frame. To adopt a different model, $\Delta\vec{X}_{tid}$, a user would need to apply the following formula to obtain coordinates $\vec{X}$ consistent with this model:

$$\vec{X} = \vec{X}_{ITRF} + (\Delta\vec{X}_{tid} - \Delta\vec{X}_{tidM}).\tag{4.14}$$

For more details concerning tidal corrections, see Chapter 7.

B) *Relativistic scale*

All individual centers use a scale consistent with TT. In the same manner the ITRF has also adopted this option (except ITRF94, 96 and 97, see Section 4.2.2).

It should be noted that the ITRS scale is specified to be consistent with TCG. Consequently, if coordinates $\vec{X}$ consistent with TCG are needed, users need to apply the following formula:

$$\vec{X} = (1 + L_G)\vec{X}_{ITRF} \tag{4.15}$$

where L_G is according to Table 1.1 in Chapter 1. Note that consistency between numerical constants should be ensured as described in Chapter 1.

C) *Geocentric positions*

The ITRF origin should be considered as the mean Earth center of mass, averaged over the time span of the SLR observations used and modeled as a secular (linear) function of time. If an instantaneous geocentric position $\vec{X}$ is required, it should be computed as

$$\vec{X} = \vec{X}_{ITRF} - \vec{O}_G, \tag{4.16}$$

where $\vec{O}_G$ represents the geocenter motion in ITRF (vector from the ITRF origin to the instantaneous center of mass) $<^2>$.

4.2.6   Transformation parameters between ITRF solutions

Table 4.1 lists transformation parameters and their rates from ITRF2008 to previous ITRF versions, which should be used with Equations (4.3) and (4.5). The values listed in this table have been compiled from those already published in previous IERS Technical Notes as well as from ITRF97/ITRF2000, ITRF2000/ITRF2005 and ITRF2005/ITRF2008 comparisons. Moreover, it should be noted that these parameters are adjusted values which are heavily dependent on the weighting as well as the number and distribution of the implied common sites between these frames. Therefore, using different subsets of common stations between two ITRF solutions to estimate transformation parameters would not necessarily yield values consistent with those of Table 4.1.

ITRF solutions are specified by Cartesian equatorial coordinates X, Y and Z. If needed, they can be transformed to geographical coordinates (λ, ϕ, h) referred to an ellipsoid. In this case the GRS80 ellipsoid is recommended (semi-major axis $a = 6378137.0\,\mathrm{m}$, inverse flattening $1/f = 298.257222101$, see Table 1.2 in Chapter 1). See the IERS Conventions' web page for the subroutine, GCONV2.F, at $<^3>$. The SOFA (Standards of Fundamental Astronomy) service $<^4>$ also provides a routine iau_GC2GDE in both Fortran 77 and ANSI C to perform the transformation.

4.3   Access to the ITRS

Several ways could be used to express point positions in the ITRS, *e.g.*

- direct use of ITRF station positions and velocities;
- use of IGS products (*e.g.* orbits and clocks) which are nominally all referred to the ITRF. However, users should be aware of the ITRF version used for the generation of the IGS products.
- fixing or constraining some ITRF station coordinates in the analysis of GNSS measurements of campaign or permanent stations;
- use of transformation formulas which would be estimated between a particular TRF and an ITRF solution.

Other useful details are also available in Boucher and Altamimi (1996). All information on ITRF solutions since ITRF94 may be found at $<^5>$.

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[2] Note that this convention is the one most often used within space geodesy but it might not be universally used *e.g.* in geophysics or other communities.

[3] http://tai.bipm.org/iers/conv2010/conv2010_c4.html

[4] http://www.iausofa.org/

[5] http://itrf.ensg.ign.fr/ITRF_solutions/index.php

Table 4.1: Transformation parameters from ITRF2008 to past ITRFs. "ppb" refers to parts per billion (or 10^{-9}). The units for rates are understood to be "per year."

ITRF Solution	$T1$ (mm)	$T2$ (mm)	$T3$ (mm)	D (ppb)	$R1$ (mas)	$R2$ (mas)	$R3$ (mas)	Epoch
ITRF2005	-2.0	-0.9	-4.7	0.94	0.00	0.00	0.00	2000.0
rates	0.3	0.0	0.0	0.00	0.00	0.00	0.00	
ITRF2000	-1.9	-1.7	-10.5	1.34	0.00	0.00	0.00	2000.0
rates	0.1	0.1	-1.8	0.08	0.00	0.00	0.00	
ITRF97	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF96	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF94	4.8	2.6	-33.2	2.92	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF93	-24.0	2.4	-38.6	3.41	-1.71	-1.48	-0.30	2000.0
rates	-2.8	-0.1	-2.4	0.09	-0.11	-0.19	0.07	
ITRF92	12.8	4.6	-41.2	2.21	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF91	24.8	18.6	-47.2	3.61	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF90	22.8	14.6	-63.2	3.91	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF89	27.8	38.6	-101.2	7.31	0.00	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	
ITRF88	22.8	2.6	-125.2	10.41	0.10	0.00	0.06	2000.0
rates	0.1	-0.5	-3.2	0.09	0.00	0.00	0.02	

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