4 Conventional Terrestrial Reference System and Frame

4.1 Concepts and Terminology

4.1.1 Basic Concepts

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). A Terrestrial Reference Frame (TRF) is a set of physical points with precisely determined coordinates in a specific coordinate system (Cartesian, geographic, mapping...) attached to a Terrestrial Reference System. Such a TRF is said to be a realization of the TRS. These concepts have been defined extensively by the astronomical and geodetic communities (Kovalevsky *et al.*, 1989, Boucher, 2001).

Ideal Terrestrial Reference Systems. An ideal Terrestrial Reference System (TRS) is defined as a reference trihedron close to the Earth and co-rotating with it. In the Newtonian framework, the physical space is considered as an Euclidian affine space of dimension 3. In this case, such a reference trihedron is an Euclidian affine frame (O,E). O is a point of the space named **origin**. 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 will express the **orientation** of the TRS and the common length of these vectors its **scale**,

$$\lambda = \|\vec{E}_i\|_{i=1,2,3}. \tag{1}$$

We consider here systems 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) will be 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)

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

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

In the application of (2), the IERS uses the linearized formulas and notation. The standard transformation between two reference systems is a Euclidian 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

$$\vec{X}_2 = \vec{X}_1 + \vec{T} + D\vec{X}_1 + \mathcal{R}\vec{X}_1, \tag{3}$$

$\lambda_{1,2} = 1 + D$, $R_{1,2} = (I + \mathcal{R})$, and I is the identity matrix with

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

It is assumed that equation (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, $\vec{X}_1, \vec{X}_2, \mathcal{T}, D, \mathcal{R}$ are functions of time. Differentiating equation (3) with respect to time gives

$$\dot{\vec{X}}_2 = \dot{\vec{X}}_1 + \dot{\mathcal{T}} + \dot{D}\vec{X}_1 + D\dot{\vec{X}}_1 + \dot{\mathcal{R}}\vec{X}_1 + \mathcal{R}\dot{\vec{X}}_1. \tag{4}$$

D and $\mathcal{R}$ are at the 10^{-5} level and $\dot{X}$ is about 10 cm per year, 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) could be written as

$$\dot{\vec{X}}_2 = \dot{\vec{X}}_1 + \dot{\mathcal{T}} + \dot{D}\vec{X}_1 + \dot{\mathcal{R}}\vec{X}_1. \tag{5}$$

Conventional Terrestrial Reference System (CTRS). A CTRS is defined by the set of all conventions, algorithms and constants which provide the origin, scale and orientation of that system and their time evolution.

Conventional Terrestrial Reference Frame (CTRF). A Conventional Terrestrial Reference Frame is defined as a set of physical points with precisely determined coordinates in a specific coordinate system as a realization of an ideal Terrestrial Reference System. Two types of frames are currently distinguished, namely dynamical and kinematical, depending on whether or not a dynamical model is applied in the process of determining these coordinates.

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, GPS, DORIS), being the center of mass (point around which the satellite orbits). The scale depends on some physical parameters (*e.g.* geo-gravitational constant GM and speed of light c) and relativistic modelling. The orientation, unobservable by any technique, is arbitrary or conventionally defined. Meanwhile it is recommended to define the orientation 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 then 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) and 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

$$\vec{X} - \vec{X}_0 = 0, \tag{6}$$

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

$$B(\vec{X} - \vec{X}_0) = 0, \tag{7}$$

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

$$A = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & 0 & 0 & x_0^i & 0 & z_0^i & -y_0^i \\ 0 & 1 & 0 & y_0^i & -z_0^i & 0 & x_0^i \\ 0 & 0 & 1 & z_0^i & y_0^i & -x_0^i & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix} \tag{8}$$

when solving for only station positions, or

$$A = \begin{pmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 & & & & & & & \\ 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 & & & & \approx 0 & & & \\ 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 & & & & & & & \\ & & & & & & & 1 & 0 & 0 & x_i^0 & 0 & z_i^0 & -y_i^0 \\ & & & \approx 0 & & & & 0 & 1 & 0 & y_i^0 & -z_i^0 & 0 & x_i^0 \\ & & & & & & & 0 & 0 & 1 & z_i^0 & y_i^0 & -x_i^0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{pmatrix} \tag{9}$$

when solving for station positions and velocities.

The fundamental distinction between the two approaches is that in equation (6), we force $\vec{X}$ to be equal to $\vec{X}_0$ (to a given σ), while in equation (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 (7) could be written as

$$(B^T \Sigma_\theta^{-1} B)\vec{X} = (B^T \Sigma_\theta^{-1} B)\vec{X}_0, \tag{10}$$

where Σ_θ is a diagonal matrix containing small variances for each of the transformation parameters. Adding equation (10) to the singular normal matrix N allows it to be inverted and simultaneously to express the estimated solution 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

In general, various types of TRF can be considered. In practice two major categories are used:

- positions of satellites orbiting around the Earth, expressed in a TRS. This is the case for navigation satellite systems or satellite radar altimetry, see section 4.3;
- positions of points fixed on solid Earth crust, mainly tracking instruments or geodetic markers (see sub-section 4.2.1).

Such crust-based TRF are those currently determined in IERS activities, either by analysis centers or by combination centers, and ultimately as IERS products (see sub-section 4.1.5).

The general model connecting the instantaneous actual 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

$$\vec{X}(t) = \vec{X}_R(t) + \sum_i \Delta\vec{X}_i(t). \quad (11)$$

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 regular time variation. In this case, $\vec{X}_R$ can be estimated by using models and numerical values. The current model is linear (position at a reference epoch t_0 and velocity):

$$\vec{X}_R(t) = \vec{X}_0 + \dot{\vec{X}} \cdot (t - t_0). \quad (12)$$

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

Conventional models are presented in Chapter 7 for solid Earth tides, ocean loading, pole tide, atmospheric loading, and geocenter motion.

4.1.4 The International Terrestrial Reference System

The IERS is in charge of defining, realizing and promoting the International Terrestrial Reference System (ITRS) as defined by the IUGG Resolution No. 2 adopted in Vienna, 1991 (*Geodesist's Handbook*, 1992). The resolution recommends the following definitions of the TRS: "1) CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system, 2) the geocentric non-rotating system to be identical to the Geocentric Reference System (GRS) as defined in the IAU resolutions, 3) the coordinate-time of the

CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG), 4) the origin of the system to be the geocenter of the Earth's masses including oceans and atmosphere, and 5) the system to have no global residual rotation with respect to horizontal motions at the Earth's surface."

The ITRS definition fulfills the following conditions.

1. It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere;
2. 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;
3. Its orientation was initially given by the Bureau International de l'Heure (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

Realizations of the ITRS are produced by the IERS ITRS Product Center (ITRS-PC) under the name International Terrestrial Reference Frame (ITRF). The current procedure is to combine individual TRF solutions computed by IERS analysis centers using observations of space geodesy techniques: VLBI, LLR, SLR, GPS and DORIS. These individual TRF solutions currently contain station positions and velocities together with full variance matrices provided in the SINEX format. The combination model used to generate ITRF solutions is essentially based on the transformation formulas of equations (3) and (5). The combination method makes use of local ties in collocation sites where two or more geodetic systems 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 Positioning System (GPS). As they represent a key element of the ITRF combination, they should be better or at least as accurate as the individual space geodesy solutions incorporated in the ITRF combination.

Currently, ITRF solutions are published nearly annually by the ITRS-PC in the *Technical Notes* (*cf.* Boucher *et al.*, 1999). The numbers (yy) following the designation "ITRF" specify the last year whose data were used in the formation of the frame. Hence ITRF97 designates the frame of station positions and velocities constructed in 1999 using all of the IERS data available until 1998.

The reader may also refer to the 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.

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 collocation sites or for site stability checks.

Each point is currently identified by the attribution of a DOMES number. The explanations of the DOMES numbering system is given below. Close points are clustered into a site. The current rule is that all points which could be linked by a collocation survey (up to 30 km) should be included as a unique site of the IERS network having a unique DOMES site number.

Collocations

In the frame of the IERS, the concept of collocation 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.

As typical illustrations of the potential use of such data, we can mention:

1. calibration of mobile systems, for instance SLR or GPS antennas, using simultaneous measurements of instruments of the same technique;
2. repeated measurements on a marker with mobile systems (for instance mobile SLR or VLBI), using non-simultaneous measurements of instruments of the same technique;
3. changes in antenna location for GPS or DORIS;
4. collocations between instruments of different techniques, which implies eccentricities, except in the case of successive occupancies of a given marker by various mobile systems.

Usually, collocated points should belong to a unique IERS site.

Extensions of the IERS network

Recently, 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):

- satellite laser ranging (SLR) (L),
- lunar laser ranging (LLR) (M),
- VLBI (R),
- GPS (P),
- DORIS (D) also Doppler NNSS in the past,
- optical astrometry (A) –formerly used by the BIH–,
- PRARE (X),
- tide gauge (T),
- meteorological sensor (W).

For instance, the cataloging of tide gauges collocated with IERS instruments, in particular GPS 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 GPS, VLBI, or DORIS space techniques. Other systems could also be considered if it was considered as useful (for instance systems for time transfer, super-conducting or absolute gravimeters...) These developments were undertaken to support the conclusions of the CSTG Working Group on Fundamental Reference and Calibration Network.

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 GPS network) or at least to get DOMES numbers (for instance the Continuously Operating Reference Stations (CORS) network in USA). Such extensions are supported by the IAG Commission X on Global and Regional Geodetic Networks (GRGN) in order to promulgate the use of the ITRS.

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 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 Inter-comparison of Techniques) (Wilkins, 2000). Three other successive BTS realizations were then achieved, ending with BTS87, when in 1988, the IERS was created by the IUGG and the International Astronomical Union (IAU).

Until the time of writing, 10 versions of the ITRF were published, starting with ITRF88 and ending with ITRF2000, each of which superseded its predecessor.

From ITRF88 till ITRF93, the ITRF Datum Definition is 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 and ITRF89 and 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, and ITRF92 to NNR-NUVEL-1A (Argus and Gordon, 1991), while ITRF93 was aligned to the IERS EOP series.

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

- Origin: defined by a weighted mean of some 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 in the TCG (Geocentric Coordinate Time) time-frame instead of TT (Terrestrial Time) used by the analysis centers;
- Orientation: aligned to the ITRF92;
- Orientation time evolution: aligned the velocity field to the model NNR-NUVEL-1A, over 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 ITRF network has improved with time in terms of the number of sites and collocations as well as their distribution over the globe. Figure 4.1 shows the ITRF88 network having about 100 sites and 22 collocations (VLBI/SLR/LLR), and the ITRF2000 network containing about 500 sites and 101 collocations. The ITRF position and velocity precisions have also improved with time, thanks to analysis strategy improvements both by the IERS Analysis Centers and the ITRF combination as well as their mutual interaction. Figure 4.2 displays the formal errors in positions and velocities, comparing ITRF94, 96, 97, and ITRF2000.

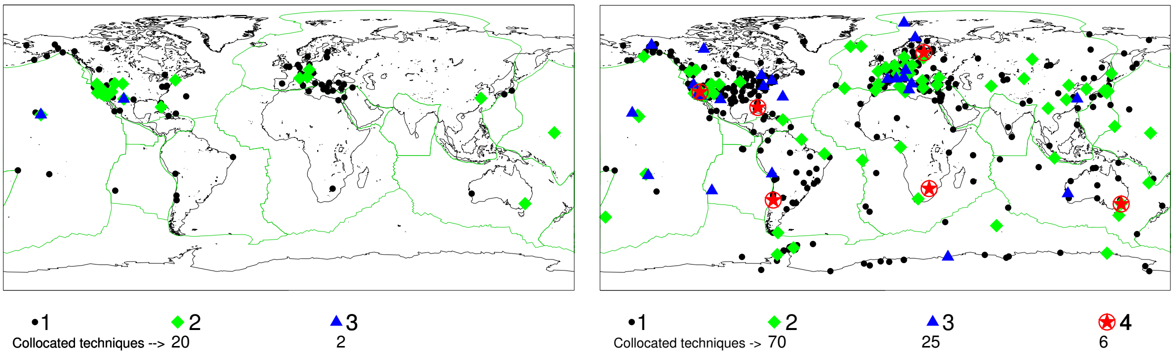

Fig. 4.1 ITRF88 (left) and ITRF2000 (right) sites and collocated techniques.

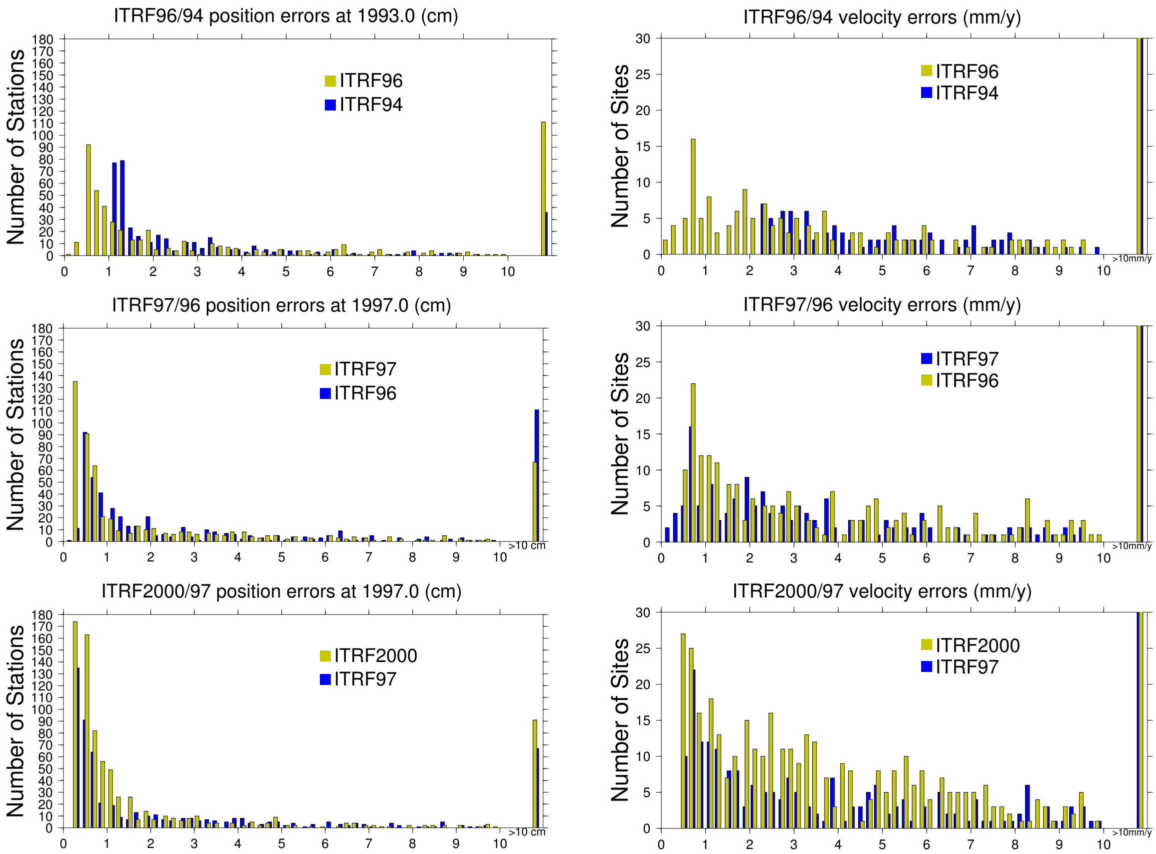

Fig. 4.2 Formal errors evolution between different ITRF versions in position (left) and velocity (right).

4.2.3 ITRF2000, the Current Reference Realization of the ITRS

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

The individual solutions used in the ITRF2000 combination are 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:

- the scale is realized by setting to zero the scale and scale rate parameters between ITRF2000 and a weighted average of VLBI and most consistent SLR solutions. Unlike the ITRF97 scale expressed in the TCG-frame, that of the ITRF2000 is expressed in the TT-frame;
- the origin is realized by setting to zero the translation components and their rates between ITRF2000 and a weighted average of most consistent SLR solutions;
- the orientation is aligned to that of the ITRF97 at 1997.0 and its rate is aligned, conventionally, to that of the geological model NNR-NUVEL-1A (Argus and Gordon, 1991; DeMets *et al.*, 1990; 1994). This is an implicit application of the no-net-rotation condition, in agreement with the ITRS definition. The ITRF2000 orientation and its rate were established using a selection of ITRF sites with high geodetic quality, satisfying the following criteria:
  1. continuous observation for at least 3 years;
  2. locations far from plate boundaries and deforming zones;
  3. velocity accuracy (as a result of the ITRF2000 combination) better than 3 mm/y;
  4. velocity residuals less than 3 mm/y for at least 3 different solutions.

The ITRF2000 results show significant disagreement with the geological model NUVEL-1A in terms of relative plate motions (Altamimi *et al.*, 2002b). Although the ITRF2000 orientation rate alignment to NNR-NUVEL-1A is ensured at the 1 mm/y level, regional site velicity differences between the two may exceed 3 mm/y. Meanwhile it should be emphasized that these differences do not at all disrupt the internal consistency of the ITRF2000, simply because the alignment defines the ITRF2000 orientation rate and nothing more. Moreover, angular velocities of tectonic plates which would be estimated using ITRF2000 velocities may significantly differ from those predicted by the NNR-NUVEL-1A model.

4.2.4 Expression in ITRS using ITRF

The procedure used in the IERS to determine ITRF products includes several 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 adoption for the ITRF of a set of conventional corrections and ensures the consistency of the combination by removing possible differences between corrections adopted by each contributing analysis centers;

3. definitions of corrections for users to get best estimates of positions in ITRS.

In this procedure, the current status is as follows:

A) *Solid Earth Tides*

Since the beginning, all analysis centers use a conventional tide-free correction, first published in MERIT Standards, $\Delta\vec{X}_{tidM}$. Consequently, the ITRF has adopted the same option and is therefore a "conventional tide free" frame, according to the nomenclature in the Introduction. To adopt a different model, $\Delta\vec{X}_{tid}$, a user then needs to apply the following formula to get the regularized position $\vec{X}_R$ consistent with this model:

$$\vec{X}_R = \vec{X}_{ITRF} + (\Delta\vec{X}_{tidM} - \Delta\vec{X}_{tid}). \tag{13}$$

For more details concerning tidal corrections, see Chapter 7.

B) *Relativistic scale*

All individual centers use the TT scale. In the same manner the ITRF has also adopted this option (except ITRF94, 96 and 97, see sub-section 4.2.2). It should be noted that the ITRS is specified to be consistent with the TCG scale. Consequently, the regularized positions strictly expressed in the ITRS have to be computed using

$$\vec{X}_R = (1 + L_G)\vec{X}_{ITRF} \tag{14}$$

where $L_G = 0.6969290134 \times 10^{-9}$ (IAU Resolution B1.9, 24th IAU General Assembly, Manchester 2000).

C) *Geocentric positions*

The ITRF origin is fixed in the datum definition. In any case, it should be considered as a figure origin related to the crust. In order to obtain a truly geocentric position, following the ITRS definition, one must apply the geocenter motion correction $\Delta\vec{X}_G$

$$\vec{X}_{ITRS} = \vec{X}_{ITRF} + \Delta\vec{X}_G. \tag{15}$$

Noting $O_G(t)$ the geocenter motion in ITRF, (see, Ray *et al.*, 1999), then

$$\Delta\vec{X}_G(t) = -\vec{O}_G(t). \tag{16}$$

4.2.5 Transformation Parameters between ITRF Solutions

Table 4.1 lists transformation parameters and their rates from ITRF2000 to previous ITRF versions, which should be used with equations (3) and (5) given above. The values listed in this table have been compiled from those already published in previous IERS Technical Notes as well as from the recent ITRF2000/ITRF97 comparison. 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 m, eccentricity^2 =0.00669438002290). See the IERS Conventions' web page for the subroutine at <[3]>.

[3]http://maia.usno.navy.mil/conv2000.html

Table 4.1 Transformation parameters from ITRF2000 to past ITRFs. "ppb" refers to parts per billion (or 10^{-9}). The units for rate are understood to be "per year."

ITRF Solution	$T1$ (cm)	$T2$ (cm)	$T3$ (cm)	D (ppb)	$R1$ (mas)	$R2$ (mas)	$R3$ (mas)	Epoch
ITRF97	0.67	0.61	-1.85	1.55	0.00	0.00	0.00	1997.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF96	0.67	0.61	-1.85	1.55	0.00	0.00	0.00	1997.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF94	0.67	0.61	-1.85	1.55	0.00	0.00	0.00	1997.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF93	1.27	0.65	-2.09	1.95	-0.39	0.80	-1.14	1988.0
rates	-0.29	-0.02	-0.06	0.01	-0.11	-0.19	0.07	
ITRF92	1.47	1.35	-1.39	0.75	0.0	0.0	-0.18	1988.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF91	2.67	2.75	-1.99	2.15	0.0	0.0	-0.18	1988.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF90	2.47	2.35	-3.59	2.45	0.0	0.0	-0.18	1988.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF89	2.97	4.75	-7.39	5.85	0.0	0.0	-0.18	1988.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	
ITRF88	2.47	1.15	-9.79	8.95	0.1	0.0	-0.18	1988.0
rates	0.00	-0.06	-0.14	0.01	0.00	0.00	0.02	

4.3 Access to the ITRS

Several ways could be used to express point positions in the ITRS. We mention here very briefly some procedures:

- direct use of ITRF station positions;
- 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 in the generation of the IGS products. Note also that IGS/GPS orbits themselves belong to the first TRF category described in sub-section 4.1.3;
- Fixing or constraining some ITRF station coordinates in the analysis of GPS measurements of a 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).

References

Altamimi, Z., Boucher, C., and Sillard, P., 2002a, "New Trends for the Realization of the International Terrestrial Reference System," *Adv. Space Res.*, **30, No. 2**, pp. 175–184.

Altamimi, Z., Sillard, P., and Boucher, C., 2002b, "ITRF2000: A New Release of the International Terrestrial Reference Frame for Earth Science Applications," *J. Geophys. Res.*, **107, B10**, 10.1029/2001JB000561.

Argus, D. F. and Gordon, R. G., 1991, "No-Net-Rotation Model of Current Plate Velocities Incorporating Plate Motion Model Nuvel-1," *Geophys. Res. Lett.*, **18**, pp. 2038–2042.

Boucher, C., 1986, "Relativistic effects in Geodynamics," in *Reference Frames in Celestial Mechanics and Astrometry*, Kovalevsky, J. and Brumberg, V. A. (eds.), Reidel, pp. 241–253.

Boucher, C., 2001, "Terrestrial coordinate systems and frames," in *Encyclopedia of Astronomy and Astrophysics*, Version 1.0, Nature Publishing Group, and Bristol: Institute of Physics Publishing, pp. 3289–3292,

Boucher, C. and Altamimi, Z., 1985, "Towards an improved realization of the BIH terrestrial frame," *The MERIT/COTES Report on Earth Rotation and Reference Frames,* Vol. 2, Mueller, I. I. (ed.), OSU/DGS, Columbus, Ohio, USA.

Boucher, C. and Altamimi, Z., 1996, "International Terrestrial Reference Frame," *GPS World*, **7**, pp. 71–74.

Boucher, C., Altamimi, Z., Feissel, M., and Sillard, P., 1996, "Results and Analysis of the ITRF94," *IERS Technical Note*, **20**, Observatoire de Paris, Paris.

Boucher, C., Altamimi, Z., and Sillard, P., 1998, "Results and and Analysis of the ITRF96," *IERS Technical Note*, **24**, Observatoire de Paris, Paris.

Boucher, C., Altamimi, Z., and Sillard, P., 1999, "The 1997 International Terrestrial Reference Frame (ITRF97)," *IERS Technical Note*, **27**, Observatoire de Paris, Paris.

DeMets , C., Gordon, R. G., Argus, D. F., and Stein S., 1990, "Current plate motions," *J. Geophys. Res.*, **101**, pp. 425–478.

DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1994, "Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions," *Geophys. Res. Lett.*, **21**, pp. 2191–2194.

Geodesist's Handbook, 1992, *Bulletin Géodésique*, **66**, 128 pp.

Kovalevsky, J., Mueller, I. I., and Kolaczek, B., (Eds.), 1989, *Reference Frames in Astronomy and Geophysics,* Kluwer Academic Publisher, Dordrecht, 474 pp.

Minster, J. B., and Jordan, T. H., 1978, "Present-day plate motions," *J. Geophys. Res.*, **83**, pp. 5331–5354.

Ray, J., Blewitt, G., Boucher, C., Eanes, R., Feissel, M., Heflin, M., Herring, T., Kouba, J., Ma, C., Montag, H., Willis, P., Altamimi, Z., Eubanks, T. M., Gambis, D., Petit, G., Ries, J., Scherneck, H.-G., Sillard, P., 1999, "Report of the Working Group on ITRF Datum."

Sillard, P. and C. Boucher, 2001, "Review of Algebraic Constraints in Terrestrial Reference Frame Datum Definition," *J. Geod.*, **75**, pp. 63–73.

Wilkins, G. A. (Ed.), 2000, "Report on the Third MERIT Workshop and the MERIT-COTES Joint Meeting," Part 1, Columbus, Ohio, USA, 29-30 July and 3 August 1985, *Scientific Technical Report STR99/25,* GeoForschungsZentrum Potsdam.