

The Terrestrial Reference Frame and the Dynamic Earth

As early as the 15th century, Swedes noticed that rocks in their harbors were slowly rising out of the sea [Ekman, 1991]. These local observations were not sufficient to distinguish whether the rocks were rising or the sea level falling. Later, it was realized that Fennoscandia was still rebounding from the last Ice Age. This historical observation is still relevant today. How can you know whether a point on the Earth's surface is slowly moving up, down, or horizontally? One must relate local measurements to a stable and accurate reference frame, one whose scale is much larger than the problem at hand. We remain concerned with sea-level variations, but present-day studies recognize that change must be measured from a global point of view and with respect to a globally well-defined reference frame. Thus, the regional and national geodetic datums developed over the past 200 years are inappropriate for studying global-level problems.

One of the main tasks of modern geodesy—the science of measuring and mapping the Earth's surface—is to define and maintain this global terrestrial reference frame. How well the reference frame can be realized has important implications for our ability to study both regional and global properties of the Earth, including post-glacial rebound, sea-level change, plate tectonics, regional subsidence and loading, plate boundary deformation, and Earth orientation excitation.

What is a Terrestrial Reference Frame?

Two coordinate frames are commonly used: a rotating system fixed to the Earth's surface (terrestrial; used for most practical applications) and an essentially inertial system fixed to the stars (celestial; where dynamical equations of motion can be solved). The celestial reference frame was historically specified by the equator, ecliptic, and pole of rotation of the Earth and was realized by the two-dimensional coordinates of a large number of stars. The present-day International Celestial Reference Frame (ICRF) is defined by the coordinates of a much smaller set of essentially stationary quasars whose positions are far better known.

The terrestrial reference frame, on the other hand, was realized mostly through national conventions. In 1895, the International Latitude Service (ILS) formed, marking the development of the first international group of globally

distributed stations to define and monitor the evolution of the frame. In 1962, this group evolved into the much broader International Polar Motion Service (IPMS). The establishment of the International Earth Rotation Service (IERS) in 1988 shifted the responsibility for establishing and maintaining both frames to a single international authority. This was the genesis of the International Terrestrial Reference Frame (ITRF).

In a break with the past, IERS based its definition of the ITRF and ICRF on modern observational techniques: Doppler and laser tracking of satellites, very long baseline interferometry (VLBI) astrometry, and later, global positioning system (GPS) tracking. Although far more accurate than classical techniques, none of these techniques is sensitive to all degrees of freedom—translational, rotational, and scale—of a reference frame. We thus need to use the relevant information from each to define the frame in its entirety. Since one of the primary reasons behind establishing a unique global reference frame is to provide a common reference in comparing observations and results from different locations and epochs, "continuity" between the older realizations and the new ones is of utmost importance. Thus, it is not by chance that while the new frames do not rely on astronomical observations, the Greenwich meridian is still used as the "primary meridian" containing the x and

z axes of the ITRF. Similarly, the z-axis is defined to coincide with the Conventional International Origin (CIO), which was defined by ILS as the mean pole of rotation over the period 1900–1905.

To relate the celestial and terrestrial reference frames, knowledge of the Earth's variable rotation vector in space is required. This includes motions with respect to both inertial space and the crust. Earth orientation variations, particularly those with respect to the crust, cannot be accurately predicted. Developments in space geodetic techniques over the past 2 decades now allow these processes to be monitored at a level comparable to the accuracy of the terrestrial and celestial frame realizations. IERS coordinates the programs to monitor the Earth orientation parameters that relate the ICRF and ITRF.

How Is the ITRF Formed?

The ITRF is realized through the global Cartesian coordinates and linear velocities of a global set of sites equipped with various space geodetic observing systems, and it is maintained by participating agencies (Figure 1). It is assembled by combining sets of results from independent techniques as analyzed by a number of separate groups organized under the IERS and cooperating services. The space geodetic techniques used at present are lunar and satellite laser ranging (LLR, SLR), VLBI, GPS, and Doppler orbit determination and radio positioning integrated on satellites (DORIS). Each technique is organized as a service by the International Association of Geodesy. In addition to these observations, the frame also depends on the surveyed tie vectors that relate

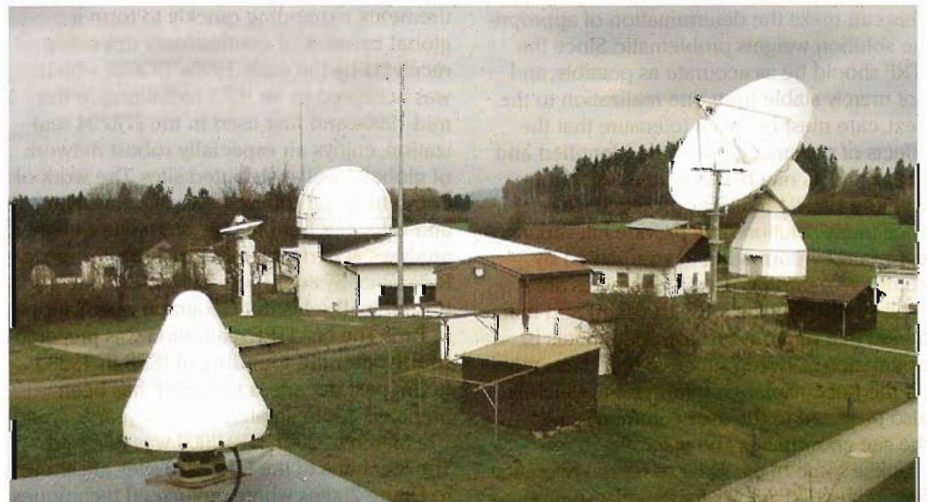


Fig. 1. ITRF sites in Wettzell, Germany, with GPS in the foreground, and SLR and VLBI in the background.

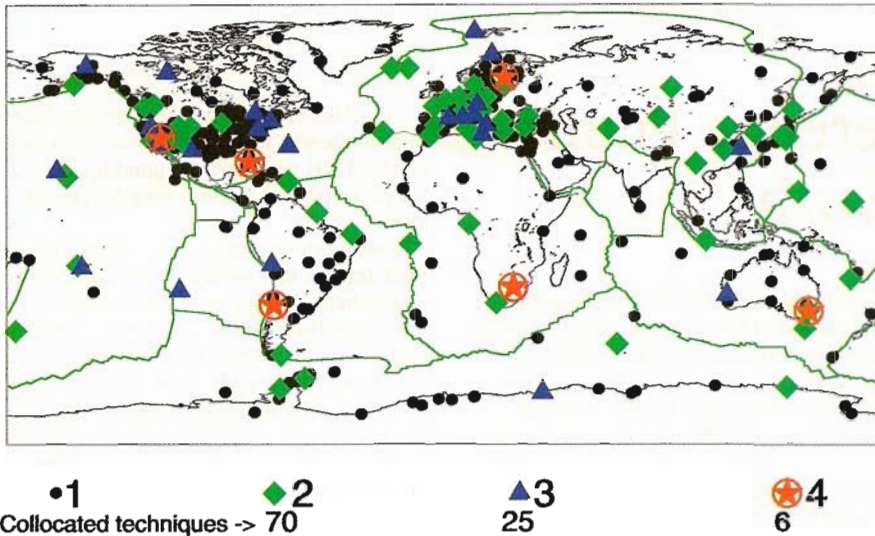


Fig. 2. Location of geodetic sites defined in ITRF2000.

co-located systems at a subset of the ITRF sites. Without these ties, each geodetic technique would realize individual terrestrial frames rather than a single unified one. The complementarity of the independent techniques used by the IERS requires an integrated approach to achieve the highest possible accuracy and consistency for the ITRF. All techniques can contribute to the ITRF, given appropriate weights and allowing for possible systematic differences. The advantage of using as many different techniques and solutions as possible is that the errors of the combined ITRF can be significantly smaller than for any of the individual contributors, if the error sources are largely independent. This also improves stability from one ITRF realization to the next and improves reliability.

However, it is expected that in many cases the dominant errors in individual solutions will be mainly systematic rather than random. This can make the determination of appropriate solution weights problematic. Since the ITRF should be as accurate as possible, and not merely stable from one realization to the next, care must be taken to ensure that the effects of systematic errors are identified and controlled as much as possible. Beginning with the ITRF94 realization, only those reference frame solutions that provide full variance-covariance information accompanied by complete *a priori* constraint matrices are used. In this way, the ITRF is formed and maintained in a rigorous fashion. Alignments in orientation between successive updates rely on the full covariance information, which is also provided to the user community with the site coordinates and velocities.

Unlike some of the older terrestrial reference frames, the ITRF allows for the relative motions of sites on the Earth's surface, due to plate tectonics as well as other local effects. These observations of contemporary motions can be compared to plate motion models, which are based on geological data spanning the past 3 million years. Outside of plate boundary defor-

mation zones, the rates generally agree very well. Difficulties do arise in certain cases, particularly when a station's motion is not at a constant velocity. Position offsets can be introduced to account for episodic events such as earthquakes, but the assumption of constant velocities is not always adequate for describing post-seismic motions. Such situations must be treated as special cases.

Evolution of the ITRF to Present: ITRF2000

Space geodesy at the sub-decimeter level began with SLR and VLBI in the 1970s, and it benefitted particularly from the vigorous support of NASA's Crustal Dynamics Program. The first detection of contemporary intercontinental plate motion was one product of this program. In the mid-1980s, GPS began to be used for regional crustal deformation measurements, expanding quickly to form a global network of continuously operating receivers by the early 1990s. DORIS, which was accepted as an IERS technique in the mid-1990s and first used in the ITRF94 realization, enjoys an especially robust network of globally well-distributed sites. The work of combining contributed sets of coordinates and velocities from the various techniques and analyses is performed by the IERS Terrestrial Reference System Product Center, which is hosted by the Institut Géographique National in Paris. The first ITRF realization was prepared shortly after the founding of IERS in 1988. In the past decade, a new ITRF has been prepared approximately every 2 years.

In March of 2001, ITRF2000 was released. The locations of the ITRF2000 sites are shown in Figure 2; sites where collocated techniques are operating, such as shown in Figure 1, are also highlighted. ITRF2000 is the most extensive and accurate terrestrial reference frame ever developed and includes positions and velocities for about 800 stations located at about 500 sites.

As stated above, a terrestrial reference frame requires the definition of its scale, its origin, and the orientation of the coordinate axes. The sensitivities of some techniques are better suited for observing certain aspects of the frame. For example, the scale of ITRF2000 was established by a combination of VLBI and SLR results. The orientation of the frame has been aligned with the preceding realization, ITRF97, and its orientation rate is defined, by convention, so that there is no net rotation of the frame with respect to the Earth's lithosphere. To do so, the ITRF2000 orientation rate is aligned to the geological tectonic model NNR-NUVEL-1A [Argus and Gordon, 1991]. Clearly, many of the sites in Figure 2 are in plate boundary zones and thus were not used to specify the no-net-rotation condition. Sites whose velocities showed significant discrepancies with respect to NNR-NUVEL-1A or were observed only briefly were also removed from the rotational constraint.

In addition to the rotational definition, the translational origin must also be precisely defined and maintained. For the ITRF, the origin is chosen to be the center of mass of the Earth, which is determined by the mass distribution of the solid Earth (including the Earth's interior), the oceans, and the atmosphere. This is the point about which a satellite dynamically orbits, although the tracking sites are all located on the lithosphere only, and so the network origin will not generally coincide with the center of mass [Watkins and Eanes, 1997]. ITRF2000 uses SLR tracking of the Lageos spacecraft to determine the translational origin of the reference frame. Only the linear evolution of the geocenter is currently modeled, but future realizations may include periodic variations as well.

A strength of ITRF2000 is its combination of station positions and velocities that are free from any external constraint, thus reflecting the actual precision of the space geodetic techniques. Although GPS was not used in the ITRF2000 origin or scale definition, it makes a large contribution in terms of the velocity field (about 150 IGS stations, as well as many regional GPS networks). DORIS, with its homogeneous network coverage, provides an excellent tracking system for low Earth orbiting satellites. Based on the internal consistency of the independent solutions included in ITRF2000, the global frame scale and origin stability over 10 years is estimated to be accurate in scale to better than 0.5 parts per billion. This is equivalent to a shift of about 3 mm in station height and better than 4 mm in origin. Maintenance and improvement of a global frame of this accuracy requires continued collection of high-quality geodetic data.

How is a Reference Frame Used by Scientists?

Space geodesy is used to investigate a wide range of scientific questions and applications, particularly those related to crustal motions and the rotational dynamics of the Earth. In addition to the well-known tectonic deformations being monitored by space geodetic techniques, there

are other geodynamic processes that are also measurable with space geodesy, including mantle elasticity and viscosity, structure and properties of the core and core-mantle boundary, and variations in water storage. In many cases, the surface expression of these processes can be less than 1 mm/yr. Current space geodetic technology is capable of measuring these rates, but only with fairly lengthy observation campaigns, ~5–15 years. To achieve the highest accuracy possible, the reference frame must be consistently defined throughout this observation period. The recent space geodetic studies of post-glacial rebound [Argus *et al.*, 1999; Johansson *et al.*, 2001] are just a few examples in which millimeter-per-year level vertical results depend heavily on the accuracy and stability of the terrestrial reference frame.

It is straightforward to see how measuring positions on the Earth's surface—given enough time—will provide the kinematic expression needed to study the dynamics of Earth deformation. What is perhaps less appreciated is how important the terrestrial reference frame is to other scientific experiments. One example is Topex/Poseidon, which uses SLR and DORIS as its primary tracking systems. Assessments of sea-level rise derived from Topex/Poseidon studies directly benefit from accurate ITRF coordinates being used for the SLR and DORIS tracking sites. Likewise, the upcoming JASON-1 radar altimeter mission, the Gravity Recovery and Climate Experiment (GRACE) mission to measure the Earth's time variable gravity, and the ICES mission to measure ice sheet elevation all require orbits that are accurately referenced to the Earth at the centimeter level, which in turn requires the precise reference frame that the ITRF provides. The precise orbit knowledge required by these missions is a critical prerequisite to their ability to significantly contribute to hydrology, oceanography, and glaciology.

Maintaining Support for the Future

It is easy to overlook the importance of the terrestrial reference frame and take for granted that a well-determined frame will always be available. However, a considerable amount of analysis from a variety of institutions around the world is required to determine and maintain the modern terrestrial reference frame. This effort takes place quietly in the background but is nonetheless critical for much of today's high-accuracy geodesy-based results. Each technique brings unique contributions, and the past few decades have been devoted to improving the quality of the data and the analysis methods. As we approach, and hope to exceed, the part-per-billion level in knowledge of the Earth's shape, the importance of continuing the support of each of these techniques cannot be underestimated. Returning to our initial example, when we ask whether a tide gauge is sinking or the sea level is rising, and we want to know this better than the few millimeter-per-year level, only an accurate, stable global terrestrial reference frame will give the answer.

For more information on space geodesy and reference frames, refer to International Terrestrial Reference Frame, ITRF (<http://lareg.ensg.ign.fr/ITRF>); International Earth Rotation Service, IERS (<http://www.iers.org>); International GPS Service, IGS (<http://igs.cbl.jpl.nasa.gov>); International VLBI Service for Geodesy and Astrometry (<http://ivscc.gsfc.nasa.gov>); International DORIS Service, IDS (<http://ids.cls.fr/welcome.html>); and International Laser Ranging Service, ILRS (<http://ilrs.gsfc.nasa.gov>).

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