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Consistent Georeferentiation for a Global Spatial Data Infrastructure

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Abstract

The realization of geodetic reference systems on different spatial scales, like global, continental, national, regional, and local is a necessity for different applications. Thanks to geodetic space techniques it is nowadays possible to establish consistency between all spatial scales by the introduction of a hierarchy of geodetic reference systems. The realization of a most precise global reference system depends on accurate measurements which permit the precise definition of origin, orientation and scale of its coordinate system. This is of fundamental importance for all subsequent spatial scales in the hierarchy depending on consistency on this global definition. Therefore the implementation of precise global reference systems relies on a global infrastructure of fundamental stations for geodesy. These are geodetic observatories contributing permanently with complementary and redundant measurements to different international services. Examples for fundamental stations for geodesy are the Fundamental Station Wettzell in Germany and its daughter, the Geodetic Observatory TIGO in Concepción, Chile. They operate all relevant geodetic space techniques together with local sensors at one location in order to monitor geometrical changes in different spatial and time scales. This globally oriented activity is important for georeferentiation throughout all hierarchy levels down to the local spatial scale. Applications like coordinate cadastre at the local spatial scale can be established in consistency with the superior hierarchy levels of geodetic reference systems.
A global spatial data infrastructure benefits from the hierarchy of consistent geodetic reference systems. Fundamental stations of geodesy are therefore also a necessary global infrastructure for a consistent global spatial data infrastructure.

Reference Systems

Spatially distributed objects or facts generate spatial data. Geodesy assigns a geodetic reference system to spatial data which allows for unambiguous identification of an object or fact. Geodetic reference systems are coordinate systems.

In Geodesy a number of different spatial coordinate systems are used – mainly depending on their application (and historical evolution):

- one dimensional, vertical reference system;
- two dimensional, horizontal reference system;
- three dimensional, spatial reference system.

The set of spatial parameters defining a geodetic reference system are called a geodetic datum. For a three dimensional reference system its geodetic datum has to contain three conditions to fix the origin, three conditions to fix the orientation of its axes in space and one parameter for the scale. There exists a unlimited number of possible geodetic reference systems.

Special attention needs to be given to the time domain. Just as the objects or facts to be georeferenced refer to a specific epoch or time interval, the geodetic reference system itself has to be referenced by an epoch in the time domain.

In other words: In addition to the three spatial coordinates we have to introduce time as the fourth coordinate. It is for this reason that the geodetic datum definitions contain a reference epoch in its name, e.g. GRS80, WGS84.

Hierarchy of Geodetic Reference Systems

Applications of reference systems range from orbit determination of space vehicles to coordinate cadastre. While orbit determination requires a global reference system, the administration of properties requires a more local reference system.

Traditionally geodesists are used to work with the principle “from the big to the small”, when they introduced different triangulation networks and classified them in first, second and third order. While the first order network allowed the coverage of a large area with few points the subsequent orders densified the triangulation network. Consistency among the different orders of networks was achieved by using reference points of the higher order network for the orientation of the densification network. However the method of triangulation was limited to the national or continental geodetic networks but not producing a global one.

Space geodesy finally allows the complementation in global geodetic networks. It provides three-dimensional geodesy to all applications. Hence, the question arises: How can consistency be achieved among the different geodetic networks?

We encounter global, continental, national, regional or local reference systems. Each of those systems requires its set of parameters to fix the reference system. Each reference system regardless of whether it has global, continental, national, regional or local scale will need to define origin, orientation and scale. This is a fundamental task.

With the introduction of a hierarchy of reference systems in which the global reference system resides on top and the local reference system at the bottom, we achieve consistency by defining origin, orientation and scale only once on the global level. Once the top hierarchy level reference system is established, the principle “from the big to the small” is applied to define the lower level reference systems.

Reference points of the global geodetic reference system provide the basis to orientate and scale densification networks with continental extension.

Subsequently those reference points of the continental reference system provide the basis to orientate and scale densification networks with national extension, and so forth.

Finally the local reference systems are related consistently to a frame of reference points of the superior levels.

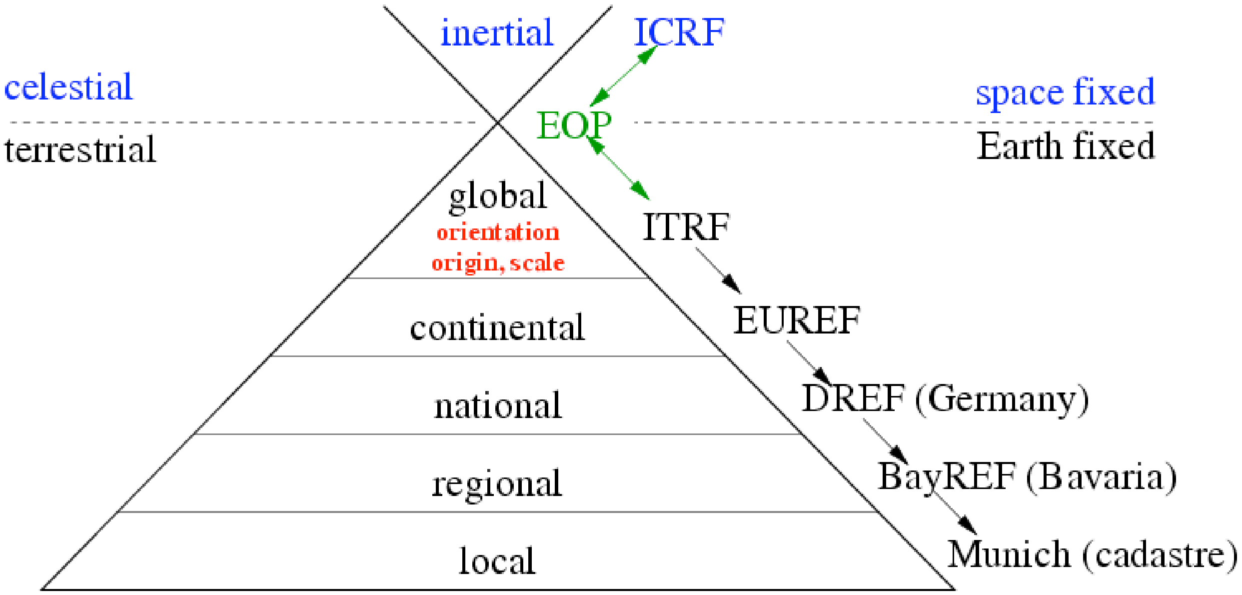

Figure 1: Hierarchy of reference systems: The Earth orientation parameters allow for the transformation between space fixed celestial and Earth fixed terrestrial reference frame. Once the ITRF is defined on the global level with its orientation, origin and scale all subsequent reference systems with smaller extension (e.g. European Reference System, German Reference System, Bavarian Reference System) can be fixed to the reference points of the superior reference network. A few fundamental stations at the global hierarchy level enable consistency to a huge number of

The consequence of the introduction of a hierarchy of three dimensional reference systems are the following:

- a need for globally distributed geodetic fundamental stations for the fixation of origin, orientation and scale;
- transformation of (traditionally two and/or one dimensional) national reference systems into the context of the superior continental and global reference systems.

Global Reference System

How do we define now a global reference system? For practical reasons and convenience in many civil engineering applications it is suggested to coincide the origin of the geodetic reference system with the center of mass of Earth (physical reference point). Consequently satellites orbiting the center of mass of Earth are adequate sensors for its determination.
The Earth rotational axis is steadily varying – although it is a naturally defined axis in space. For the definition of a global geodetic reference system it is convenient to fix one axis to the conventional pole (CIO) and permanently measure the deviation from it as polar motion. This requires a celestial quasi-inertial reference system (ICRF) based on quasars which permits to determine the position of Earth in space.
The metric scale has to be introduced by time interval measurements of traveling electromagnetic signals between reference points, as the meter is a secondary unit depending on the definition of the time second by cesium standards and the constance of the speed of light.

Fundamental Stations for Geodesy

The mission of fundamental stations for geodesy is to define a reference point in *time*, *space* and the *gravitational field* of Earth. A set of fundamental stations provide the global frame for all geodetic activities, because the definition of origin, orientation and scale of the global reference system is realized by the instrumentation operated at fundamental stations (Hase, 1999).

Today a fundamental station for geodesy consists of the instruments contributing information to its location in time, space and gravitation:

- time and frequency laboratory to generate Universal Time Coordinated,
- radio telescope for Very Long Baseline Interferometry (VLBI),
- satellite laser ranging system (SLR),
- permanent GNSS receiver (GPS, Glonass, Galileo),
- gravity meter,
- complementary instruments as such as meteorological station, seismometer, etc.

Fundamental stations for geodesy are characterized by:

- *permanency* in its operation,
- *complementarity* and
- *redundancy* in its instruments, which are geometrically tied by
- *local surveys*.

Why permanency in its operation? The geodetic instrumentation of a fundamental station has to consist of the most precise instruments for the most precise methods, because their errors will propagate to each subsequent level of geodetic reference networks within the hierarchy. From another point of view, once using the most precise instruments and methods with utmost resolution, a lot of geodynamical phenomena show their time variability. Nothing is fix. It this the variability in the time domain which requires permanent monitoring in order to know in which epoch which coordinates and which coordinate velocities are the correct ones.

Why complementary in its instruments? The instrumentation has to be complementary in order to be able to use the most precise methods. For the refraction correction while pointing to a target like a satellite or a quasar, local meteorological informations are a necessity.
Also for the correct interpretation of data it is essential to have additional information from complementary sensors. A superconducting gravity meter showing an unmodeled annual periodicity in its measurements calls for the installation of soil moisture sensors to evaluate whether rainy and dry seasons are causing it.

Why redundancy in its instruments? The only possibility to control the most precise instruments if they function properly is to compare them among each other – as there is no superior standard for calibration available. This requires to have redundant equipment at the fundamental station (e.g. frequency normals). Redundancy is necessary to detect systematic errors of an instrument and also to evaluate the quality of data.
Concerning a permanent continuous operation – it is mandatory to have redundancy in the equipment in case of failures.

Why tie with a local survey? Different geodetic space techniques define by themselves a reference point in their technique-specific reference system. In order to use the synergy of the different space techniques like VLBI, SLR, GNSS it is necessary to tie the system immanent reference points. Therefore a local survey in the local control network has to be measured in order to determine the space vector between the reference points of VLBI, SLR, GNSS and the gravity meter. Only knowledge of the local space vector allows for coordinate transformations between the different techniques as it is done for the ITRF. This requires the collocation of instruments at one site.

Furthermore the local survey is also a measurement on site stability and has to be repeated periodically.

Examples of Fundamental Stations

The name “fundamental station” for geodesy has to be understood in analogy to the “fundamental stars” in astronomy. Likewise the former fundamental catalogs of fix stars (e.g. FK5) listing a position of a star and its proper motion at a certain epoch, the fundamental stations for geodesy are defining a terrestrial reference point position and velocity at a certain epoch.

The concept of fundamental stations was first rigorously realized during the 1980s in Wettzell, Germany. In the 1990s a Transportable Integrated Geodetic Observatory (TIGO) was developed at Wettzell designed for the realization of the characteristics of a fundamental station. TIGO is operated since 2002 at its final destination in Concepción, Chile. Both observatories operate all the relevant geodetic space techniques VLBI, SLR and GNSS as well as a time-keeping laboratory and gravity meter (Hase et al, 2003).

They are German resp. German/Chilean contributions to the international task of realizing the most precise global reference system.

Figure 1: Geodetic Observatory TIGO in Concepción, Chile. Collocated radiotelescope for VLBI, the SLR telescope (foreground) and the GNSS permanent station permit synergetic use of geodetic space techniques for the ITRF. TIGO is a fundamental station for geodesy and an example for the realization of the Global Geodetic Observing System (GGOS).

The presented characteristics of a fundamental station apply to about already eight observatories. For further improvements within the ITRF it would be ideal to have three fundamental stations on each continental plate in order to determine the plate kinematic.

Fundamental stations for geodesy are part of a global infrastructure, necessary for a wide range of applications from space navigation to the realization of land management with system of coordinate cadastre.

International Services

The operation of fundamental stations is determined by the demands of international services. The fundamental station TIGO in Chile is contributing to the:
- International VLBI Service (IVS),
- International Laser Ranging Service (ILRS),
- International GNSS Service (IGS)

whose products are incorporated into the:
- International Earth Rotation and Reference System Service (IERS).

The IERS products are IERS Terrestrial Reference Frame (ITRF) and the IERS Celestial Reference Frame (ICRF).

Furthermore TIGO features an approved time-keeping laboratory for the realization of Universal Time by the Bureau International de Poids et Mesures (BIPM) in Paris and as such currently the only laboratory in Chile.

The gravity meter data are included in the Global Geodynamic Project (GGP), which is a global initiative related to the global network of superconducting gravity meters.

The international services are providing a non-profit best-effort service based on the principle of subsidiarity. Each country participating is providing in the frame of their resources instruments or human resources dedicated to this infrastructural work.
No country on its own is able to achieve the same. Therefore data generated within the International Services are public data for the global spatial data infrastructure.

Global Geodetic Observing System (GGOS)

The activities of geodetic fundamental stations are crucial for the decade project of the International Association of Geodesy (IAG) called “Global Geodetic Observing System”.
GGOS intends to improve the accuracy of the global geodetic reference systems by integrating better the geometrical with the physical domain of geodesy.
Recent space mission dedicated to the gravitational field of Earth will provide better geoid models. Areas without permanent operated reference points have still to be equipped with appropiate instruments. The goal is to achieve a relative accuracy of 10^{-9} globally.
The GGOS project is the geodetic contribution to the global initiative “Global Earth Observing System of Systems” (GEOSS) of the Group on Earth of Observation (65 countries + 43 international organizations/institutions). GGOS will provide the base for georeferentiation of any other parameter to be observed within GEOSS.

Conclusion

The efforts towards a consistent global spatial data infrastructure require consistency of the geodetic reference systems. For their establishment fundamental stations for geodesy have a key role. For increased stability of terrestrial reference frames it would be desirable to have more fundamental stations in a more homogeneous distribution realized.

The global spatial data infrastructure benefits from consistent geodetic reference systems in such a way that localized objects or facts can be related to its context on each level in the hierarchy.

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