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Challenges for VLBI Within an Integrated Global Geodetic Observing System

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Abstract

The Integrated Global Geodetic Observing System (IGGOS), proposed as a Project in the new structure of the International Association of Geodesy (IAG), is viewed as the essential contribution of geodesy to the interdisciplinary research of the System Earth. It will provide the basis for precise, reliable point positioning, the orientation of Earth in space, and the determination of the Earth's gravity field within a consistent reference system. All space geodetic techniques and their services have to be integrated into the IGGOS, and they shall take over their specific role according to their strengths and preferences. VLBI has some extraordinary capabilities which cannot be accomplished by other techniques. These are, in particular, the direct connection to the inertial celestial reference system, its high precision, and the independence from the Earth's gravity field. In addition, there is a very long VLBI time series for geodetic parameters (Earth rotation, station positions and velocities) which is not available from other techniques. Therefore, VLBI has to take a prominent role in the establishment of the Integrated Global Geodetic Observing System.

1. Introduction

Geodesy, as the science of the measurement and the mapping of the Earth's surface, provides precise information on the state and the temporal variations of the Earth's orientation in space, its geometric figure and shape, and its outer gravity field. The parameters describing the variations with time reflect the effects of mass displacements due to dynamic processes in the system Earth. They include the processes in the solid geosphere (motions of the core, mantle convection, plate tectonics, etc.), in the hydrosphere (ice mass exchange, ocean currents, sea level changes, etc.) and in the atmosphere (winds, pressure variations, global warming, etc.). By these means, geodetic observations and products contribute directly to Earth system research. To do this contribution efficiently, i.e., to provide unequivocal information, the efforts have to be strictly coordinated and to be integrated into one unique observing system with consistent constants, standards, reference frames, models and parameters.

At present, the geodetic observation systems providing the data for estimation of the geometric and gravimetric parameters are mainly based on space techniques (very long baseline interferometry, satellite positioning systems, satellite altimetry and satellite gravity missions). They are globally oriented and are subject to the same kind of environmental and physical influences. The evaluation and analysis of the data, however, is often done independently using different standards and models. The individual geodetic techniques have their particular strengths and weaknesses. To take maximum benefit of the advantages and to compensate the shortcomings as far as possible, they have to be combined in a proper way using one and the same fundamental reference system.

Both the generation of consistent products for Earth system research and the optimum use of the geodetic observations require thus the unification of all fundamentals (constants, standards, reference frames, models) underlying the geodetic techniques and methods. This leads to the establishment of an Integrated Global Geodetic Observing System (IGGOS).

2. Decisions of the IAG Concerning the Establishment of an IGGOS

During its Scientific Assembly in Budapest, Hungary, September 2001, the International Association of Geodesy (IAG) decided to install a new structure for the next legislature period starting in 2003. The basic scientific components of the new structure are the Commissions, the Services, the IAG Project(s), the Inter-Commission Committee(s) and the Communication and Outreach Branch.

The *Commissions* shall promote the advancement of science, technology and international cooperation in their fields. Four Commissions will be established to cover the entire field of geodesy:

1. Reference Frames,
2. Gravity Field,
3. Earth Rotation and Geodynamics,
4. Positioning and Applications.

The *Services* are part of the Association's work and generate products, using their own observations and/or observations of other services, relevant for geodesy and for other sciences and applications. At present the services of IAG are:

- International GPS Service,
- International VLBI Service,
- International Laser Ranging Service,
- International Earth Rotation Service,
- International Gravimetric Bureau,
- International Geoid Service,
- International Center for Earth Tides,
- Permanent Service for Mean Sea Level,
- International Bureau of Weights and Measures (Time Section).

Inter-Commission Committees shall handle well defined, important and permanent tasks involving all commissions. An example might be a committee for geodetic theory and methodology.

The *Communication and Outreach Branch* provides the Association with communication, educational/public information and outreach links to the membership, to other scientific associations and to the world as a whole.

IAG Projects are of a broad scope and of highest importance for the entire field of geodesy. These projects serve as the flagships of the Association for a long time period (decade or longer). To establish IAG Projects, the IAG Executive Committee (EC) shall appoint a planning group for the creation of each project. Each IAG Project shall have a Steering Committee consisting of the Project Chair, one member from each Commission, two members-at-large, and the chairs of the Project sub-groups (if any).

During the IAG Scientific Assembly, Budapest 2001, a candidate IAG Project "Integrated Global Geodetic Observing System (IGGOS)" was proposed by R. Rummel et al. (2002). It was discussed and approved by the "IAG Committee for the Realization of the New IAG Structure" on September 6, 2001. A planning committee for the project consisting of about ten persons will be installed soon. This committee has to take into account all the work performed by IAG in this area in order to design the objectives, the charter, and the structure of the project. It has to include a close cooperation with the IAG Services, relevant Commissions and Sub-Commissions.

3. Requirements and Interdisciplinary Position of IGGOS

The Integrated Global Geodetic Observing System (IGGOS) should be seen as geodesy's contribution to the study of the System Earth composed of the solid geosphere, the hydrosphere and the atmosphere. It will provide its findings to interdisciplinary research, governmental agencies and private sectors. In this context one has to consider the existing initiatives in this field.

In 1998, the *United Nations (UN)* released an Integrated Global Observing Strategy (IGOS: http://ioc.unesco.org/igospartners). The development and implementation of this IGOS is supported by a partnership of several groups of agencies, international research programs and other sponsors. The two major groups of agencies are the Committee on Earth Observation Satellites (CEOS) created in 1984 by the Economic Summit of Industrialized Nations (G-7) including some 20 national space agencies, and the International Group of Funding Agencies for Global Change Research (IGFA) grouping national research funding agencies. The major international research programs involved are the International Geosphere-Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP). Both programs are mainly driven by the International Council for Science (ICSU) and the United Nations Educational, Scientific and Cultural Organization (UNESCO).

The Global Observing Strategy comprises three Global Observing Systems (G3OS):

- The *Global Climate Observing System (GCOS)* signed on September 29, 1998 by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (ICO) of UNESCO, the United Nations Environment Programme (UNEP), and ICSU;
- The *Global Ocean Observing System (GOOS)* agreed upon by a new Memorandum of Understanding between IOC, WMO, UNEP and ICSU at the end of 1998;
- The *Global Terrestrial Observing System (GTOS)* established in January 1996 by the Food and Agriculture Organization (FAO) of the UN, ICSU, UNEP, WMO and UNESCO.

The purpose of these observing systems is mainly policy oriented rather than dealing with scientific objectives. Their "mission is to provide policy-makers, ... , with data they need to detect, locate, understand and warn of changes in the terrestrial ecosystems".

Geodesy, and in particular IAG, is very active in some of the interdisciplinary committees of ICSU. We just mention the

- Scientific Committee on Antarctic Research (SCAR),
- Committee on Space Research (COSPAR),
- Scientific Committee on the Lithosphere (SCL) with the International Lithosphere Programme (ILP),

where IAG has its representatives and common projects, commissions and other activities.

Thus we may summarize the IAG Project IGGOS being the interface between the IAG Commissions and Services and the ICSU, WMO and UN initiatives (Fig. 1).

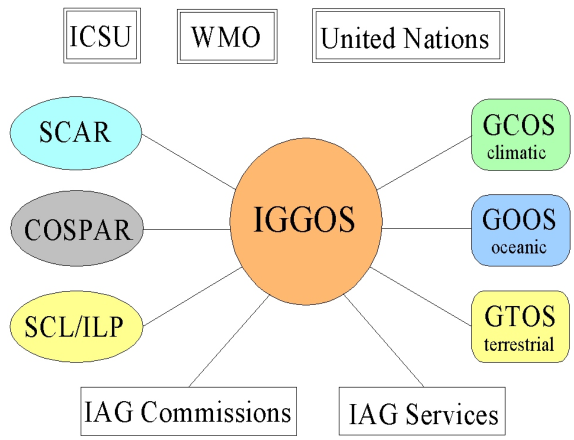

Figure 1. Interdisciplinary position of the IAG Project IGGOS

4. Requirements of IGGOS and Its Position in Geodetic Science

The Integrated Global Geodetic Observing System (IGGOS) shall provide a consistent reference system for all groups of fundamental geodetic parameters (Fig. 2):

- Earth rotation parameters (precession, nutation, rotational velocity, pole position),
- Terrestrial position parameters (point coordinates and velocities, surface models - DTM's - and deformations),
- Gravity field parameters (gravity anomalies, height anomalies, geoid, deflections of the vertical, "mean" sea level).

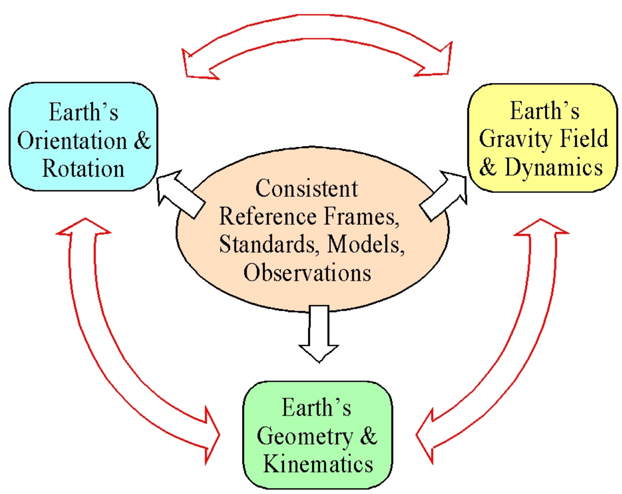

Figure 2. The IGGOS within geodetic science

Reference system in this sense means the definition of a set of geometric and physical parameters necessary for the measurement and the description of the geometry and physical processes within the Earth's system. It shall use hereby consistent standards in geometry (origins, orientations, scales, ...), in physics (speed of light in the media, geocentric gravitational constant, ...), and in dynamics (geopotential and other forces). It shall use consistent, coordinated observation techniques (e.g., within an Integrated Space Geodetic Network, ISGN) and unique data exchange formats (e.g., SINEX).

The accomplishment of these requirements will be the primary duty of the Services of the IAG. The interaction and coordination of the services' activities is the basic concept of the IGGOS. The three pillars of geodesy — geometry & kinematics, Earth orientation & rotation, gravity field & dynamics — shall be combined to a consistent, unified observing system. From this combination a series of new products for Earth sciences shall emerge, such as the feasibility of establishing a global mass balance.

While the scientific foundations will mainly come from the relevant IAG Commissions, the products to be given to the interdisciplinary community will be provided by the Services. However, IGGOS is not seen as a new "Super-Service" that generates the products or the scientific results, but it is to coordinate the scientific work and to serve as an interface to the non-geodetic scientific community and to society. It shall strive for the fulfillment of the requirements mentioned above. IGGOS will not be able to operate without the Services of IAG (Fig. 3).

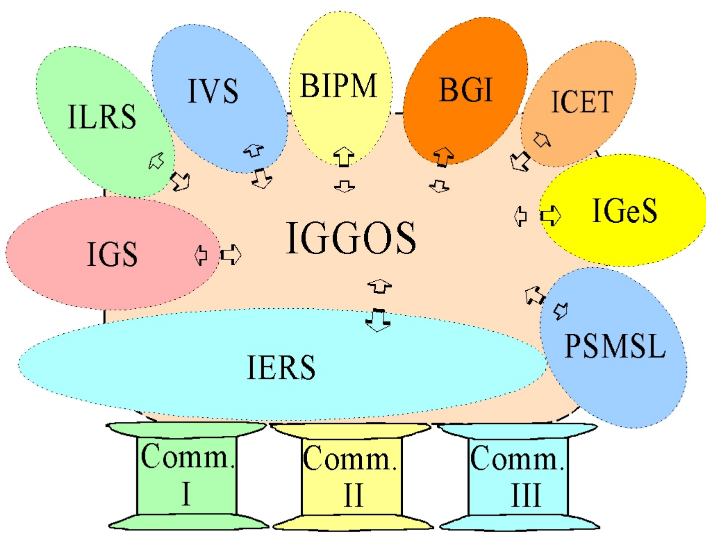

Figure 3. Interaction of IAG Commissions and Services with IGGOS (IERS: International Earth Rotation Service, IGS: International GPS Service, ILRS: International Laser Ranging Service, IVS: International VLBI Service for Geodesy and Astrometry, BIPM: Bureau International de Poids et Mesure (Time Section), BGI: Bureau Gravimetrique International, ICET: International Center of Earth Tides, IGeS: International Geoid Service, PSMSL: Permanent Service of Mean Sea Level).

5. Contribution of VLBI to IGGOS

Very Long Baseline Interferometry (VLBI) will contribute to two basic parameter groups of the IGGOS, the Earth Orientation Parameters (EOP) and parameters related to the Terrestrial Reference System (TRS). Both are of fundamental importance for the establishment of the Integrated

Global Geodetic Observing System.

5.1. Earth Orientation Parameters

Dynamic processes in the Earth's system cannot be observed directly but they have to be modeled from the observation of particular effects caused by those processes. Examples are the variations of the Earth's rotation or the deformation of the Earth's surface due to mass displacements in the solid, liquid or gaseous part of the Earth. To model the dynamic processes by adequate physical approaches we need an inertial reference system where the corresponding basic equations hold. In the case of modeling the Earth's motion in space we refer to the inertial system defined and realized by the Celestial Reference System (CRS). The connection between CRS and TRS is given by the EOP, i.e., precession, nutation, rotational velocity (UT1-UTC), and pole coordinates (X_p, Y_p). This chain of parameters can be provided completely only by VLBI because it is the only technique that has direct observational access to the CRS. The other space techniques are only able to refer to quasi-inertial systems. We just mention the problem of separating the variation of the longitude of the node of the satellites' orbits from the variations in UT1-UTC.

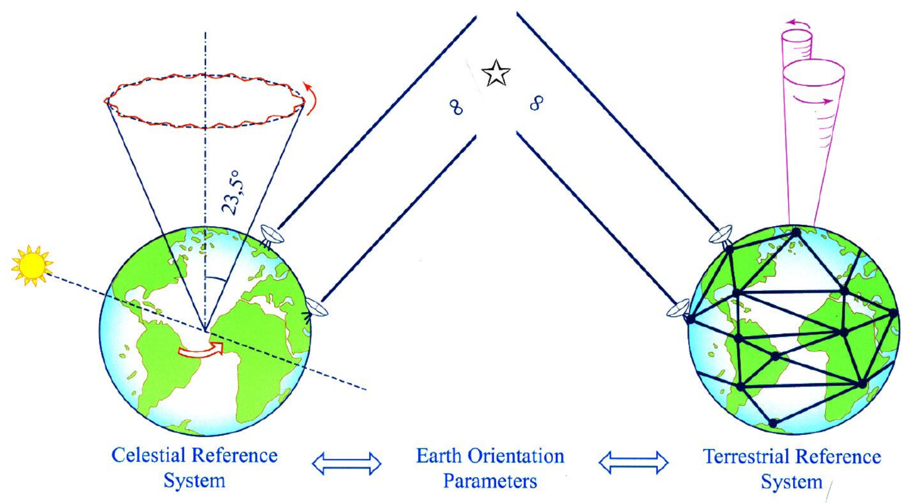

Figure 4. Connection of the Celestial System and the Terrestrial System can only be provided by VLBI.

The knowledge of the EOP and their variations with time is very important for many practical applications. Extraterrestrial space missions have to refer to the exact orientation of Earth in space to get the correct trace. Long period navigation of artificial spatial bodies has to consider the variation of Earth's orientation for its continuous positioning. Astronomical and astrometric research need the precise relation of the TRS with respect to the CRS given by the EOP.

The change of EOP, i.e., the variation of the Earth's rotation, is a fundamental tool for the interdisciplinary study of several processes in the Earth's system. Geology uses the methods of historical geology, paleo-climatology and paleo-magnetometry which refer directly or indirectly to the time dependent rotation axis of the Earth. In geophysics the parameters of the magnetic field and of core-dynamics are affected by the Earth's rotation. Global change research (atmospheric and oceanographic) gets important information from Earth rotation variations which reflect mass displacements in the atmosphere (pressure and winds) and in the oceans (currents, pressure, temperature).

How precisely do we need to know the variations of Earth orientation parameters? The answer depends on the application. The most evident requirements are certainly given by the realization of the celestial and terrestrial reference frames. If we ask for millimeter precision of terrestrial coordinates, then we need the pole coordinates better than ± 0.1 mas and the rotational velocity (UT1-UTC) better than ± 0.01 msec. This precision of pole coordinates can probably be provided by several space geodetic techniques (VLBI, SLR, GPS, DORIS). The corresponding precision of UT1-UTC, however, may hardly be provided by techniques other than VLBI. Figure 5 shows the comparison of the (formal) precision of VLBI (solution of Goddard Space Flight Center, GSFC) and GPS (IGS) from January 1994 to December 2000. VLBI is in general below ± 0.01 msec, with lower precision where only poorly configured observation sessions are available, while GPS varies around ± 0.02 msec.

Besides the internal precision we shall compare directly the estimated values of UT1-UTC. Here we find significant systematic and random differences. In 2000 there exists an offset of 0.26 msec between the solutions, and after its reduction there is a w.r.m.s. difference of ± 0.17 msec (Fig. 6). As GPS has no direct access to the inertial celestial reference system, it has to adjust its time series frequently to the VLBI data, i.e., it is only able to estimate relative values or rates of UT1-UTC.

This example proves again the need for VLBI for the determination of the Earth rotation parameters. Without any doubt, the long-term stability can only be achieved by VLBI observations with its direct connection between CRS and TRS.

5.2. Station Positions and Velocities for Realization of the Terrestrial Reference Frame

VLBI contributes essentially to the realization of the terrestrial reference frame (TRF) by providing precise station coordinates and velocities. In the latest realization of the IERS TRF (ITRF2000, http://lareg.ensg.ign.fr/ITRF/ITRF2000/) the individual VLBI solutions showed w.r.m.s. errors in position of about ± 4 mm and in velocity of about ± 0.6 mm/a. The other techniques' solutions were significantly less precise (SLR about ± 10 mm and ± 2.0 mm/a; GPS about ± 4 mm and ± 1.4 mm/a, respectively).

Comparing the velocities of the combined VLBI solution, which entered into the ITRF2000 with the combined solutions of the other techniques, we see the best relative adaptation of VLBI results (Table 1). In particular for the height component (Up) this may be surprising, because the satellite techniques (GPS, SLR) refer to the geocenter by means of the gravity field models used for orbit determination and provide herewith “absolute” heights. The scale of the ITRF2000, however, is derived with high weight from VLBI due to its extreme stability (see ITRF2000). As the scale affects mainly the radial component of the station coordinates, the VLBI heights are obviously more reliable than those derived from satellite techniques.

An accurate terrestrial reference frame is essential for an Integrated Global Geodetic Observing System (IGGOS) in its interdisciplinary role and for many practical application:

- Geo-referencing for geographic information systems;
- Precise positioning in engineering, cadastre, rural and urban planning, etc.;
- Navigation in air, on land and sea;

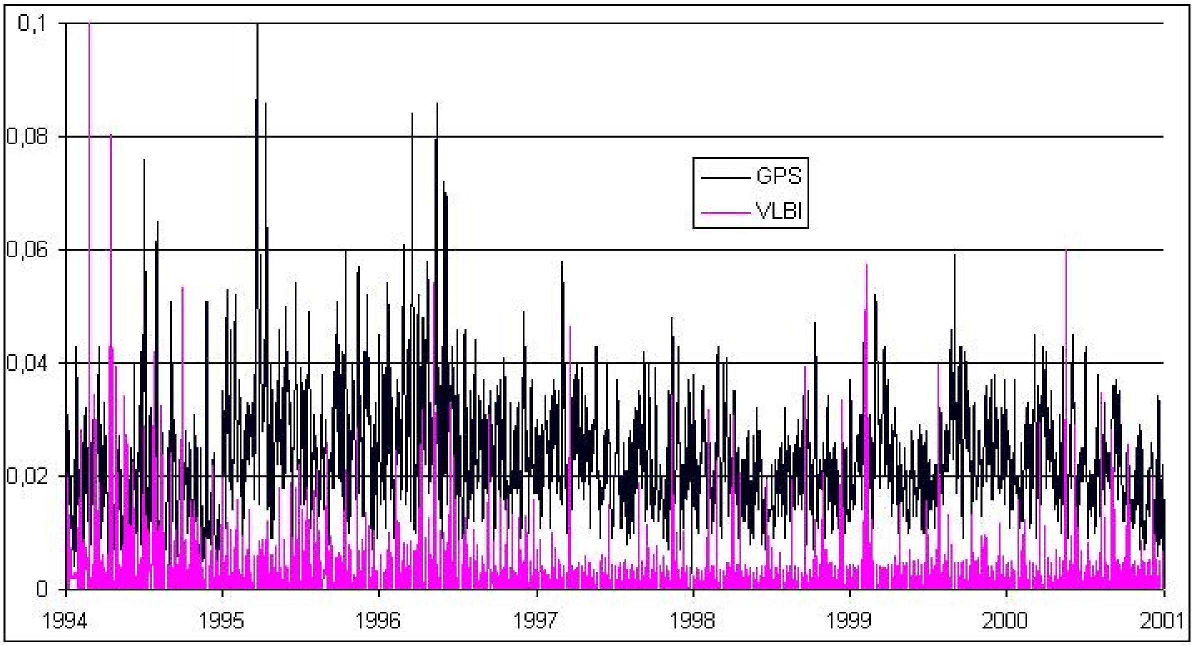

Figure 5. Comparison of UT1-UTC precision estimated from VLBI and GPS [msec]

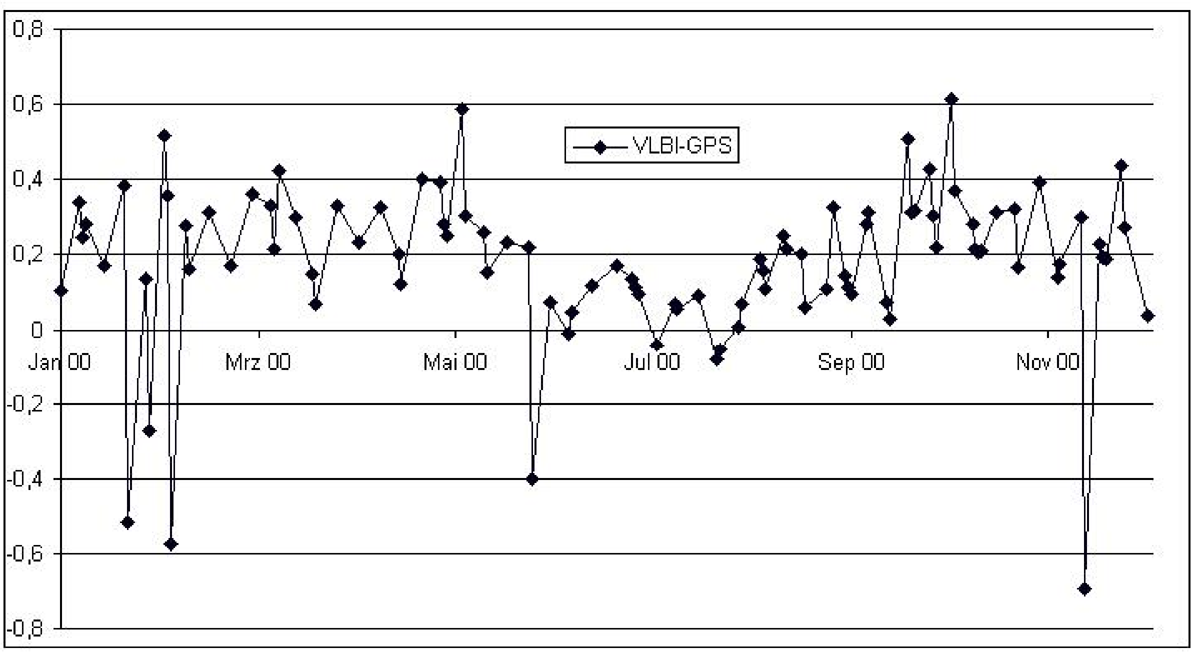

Figure 6. Differences of UT1-UTC in 2000 estimated from VLBI and GPS [msec]

- Disaster research: earthquakes, inundations, volcanoes, etc.;
- Geophysics: geodynamics, plate tectonics, geocenter variations, etc.;
- Oceanography: currents (buoys positioning), tide gauge control, ice surface control, etc.

The various needs and uses of terrestrial reference frames in practice and in society seem not to be sufficiently well known in geodesy. On the other hand, the role of geodesy for the definition, establishment and maintenance of terrestrial reference frames seems not to be sufficiently well known and appreciated in practice and in society.

Table 1. Comparison of station velocities derived from different techniques (combined solutions) and w.r.t. ITRF2000 (w.r.m.s. deviations in mm/a)

		vs. SLR	vs. GPS	vs. ITRF
VLBI	No. of sites	13	29	69
	North	± 2.4	± 1.0	± 1.4
	East	± 1.0	± 2.1	± 0.8
	Up	± 2.6	± 3.7	± 1.1
SLR	No. of sites		24	64
	North		± 2.7	± 1.8
	East		± 2.5	± 1.2
	Up		± 3.2	± 3.5
GPS	No. of sites			151
	North			± 1.5
	East			± 0.9
	Up			± 2.7

6. Conclusions

The Integrated Global Geodetic Observing System (IGGOS) is a fundamental requirement for geodesy, for the other Earth sciences, for interdisciplinary research, and for many practical applications. The Services of the International Association of Geodesy (IAG) play an important role in the realization of the IGGOS in its geometrical and gravimetrical components. Only the cooperation between Services and Commissions of the IAG will guarantee the success of IGGOS.

The International VLBI Service for Geodesy and Astrometry (IVS) is an indispensable partner in the establishment of the IGGOS because it provides unique and fundamental parameters to realize and maintain the global reference frames (celestial and terrestrial) and gives important information for monitoring the System Earth.

References

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