GGOS Bureau of Products and Standards

Inventory of Standards and Conventions used for the Generation of IAG Products

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Preface

The Global Geodetic Observing System (GGOS) released in 2008 a call for participation to complement the existing structure by additional components, such as the Coordinating Office and GGOS Portal, the Bureau for Standards and Conventions, and the Bureau for Networks and Communications. The proposal of the Forschungsgruppe Satellitengeodäsie (FGS) for the establishment and operation of the GGOS Bureau for Standards and Conventions (BSC) was accepted by the GGOS Steering Committee on December 14, 2008. Since 2009, the BSC is jointly operated by the Deutsches Geodätisches Forschungsinstitut (DGFI) and the Institut für Astronomische und Physikalische Geodäsie (IAPG) of the Technische Universität München, both in Munich, Germany, within the FGS.

The FGS group includes, beside DGFI and IAPG, the Forschungseinrichtung Satellitengeodäsie (FESG) of the Technische Universität München, the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany, and the Institut für Geodäsie und Geoinformation, University Bonn (IGG), Germany. The group operates the Geodetic Observatory Wettzell, Germany, and pursues various research projects in space geodesy. The FGS is prominently involved in the management of the international scientific organizations and it took over long-term commitments in the IAG Services as data, analysis and combination centers.

In 2014, a restructuring of the GGOS organization was performed. The existing components were kept and their responsibilities were partly redefined. The BSC has been renamed as GGOS Bureau of Products and Standards (BPS) and its tasks have been extended. The charter

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and implementation plan for the BPS was completed in 2015.

The BPS supports GGOS in its goal to obtain geodetic products of highest accuracy and consistency. In order to fully benefit from the ongoing technological improvements of the observing systems, it is essential that the analysis of the precise space geodetic observations is based on the definition and application of common standards and conventions and a consistent representation and parameterization of the relevant quantities. This is of crucial importance for the establishment of highly accurate and consistent geodetic reference frames, as the basis for a reliable monitoring of the time-varying shape, rotation and gravity field of the Earth. The BPS also concentrates on the integration of geometric and gravimetric parameters and the development of new products, required to address important geophysical questions and societal needs.

A key objective of the BPS is to keep track of adopted geodetic standards and conventions across all components of the International Association of Geodesy (IAG) as a fundamental basis for the generation of consistent geometric and gravimetric products. The work is primarily build on the IAG Service activities in the field of data analysis and combinations. The BPS shall act as contact and coordinating point regarding homogenization of standards and IAG products. More specifically, major tasks in this field are (i) to review and evaluate all standards, constants, resolutions and conventions adopted by IAG and its components, (ii) to identify gaps, inconsistencies and deficiencies, and (iii) to propose new standards if necessary. Following this task description, the former BSC has started with the compilation of an inventory based on the assessment of the standards and conventions currently in use by IAG and its components. This activity has been continued by the BPS and as a result this document was created.

During the GGOS Coordination Board meeting and IAG Executive Committee meeting in San Francisco (December 2014), the participants agreed on the procedure for the review of the inventory. It was decided that the document should be evaluated by an external review. The approved version of this document, which is published in the IAG Geodesist's Handbook 2016 reflects the status of January 15, 2016. A regularly updated version will be provided on the GGOS web site.

As a major outcome, this inventory presents the status regarding standards and conventions, identifies gaps and inconsistencies, and provides recommendations for improvements. This recommendations should be discussed with dedicated experts in the field and an action plan should be compiled, including a task description, specification of responsibilities, and a time schedule.

Scope of the document

The BPS has the task to keep track of adopted standards and conventions across all IAG components and to evaluate products of IAG with respect to the adequate use of standards and conventions. Based on this general task description, a major activity of the BPS was the compilation of an inventory regarding standards, constants, resolutions and conventions adopted and used by IAG and its components for the generation of IAG products.

The scope of this document is summarized as follows: Chapter 1 gives in the first section some general information about GGOS including its mission, goals and the organizational structure. The second part of this introductory chapter deals with standards and conventions from a general view along with some relevant nomenclature, and it presents current standards, standardized units, fundamental physical standards, resolutions and conventions that are relevant for geodesy. In the second chapter the mission and goals of the BPS are summarized, along with a description of its major tasks. It also presents the BPS staff and the associated members, representing the IAG Services, the International Astronomical Union (IAU) and other entities involved in standards and conventions. Chapter 3 focusses on numerical standards, including time and tide systems and the geopotential value W_0. Chapter 4 is the key element of this document and it contains the product-based inventory, addressing the following topics: Celestial reference systems and frames, terrestrial reference systems and frames, Earth Orientation Parameters (EOP), Global Navigation Satellite System (GNSS) satellite orbits, gravity and geoid, as well as height systems and their realizations. The structure of the corresponding sections was homogenized to a large extent, however, its character is partly different. This is a consequence of the current situation, that for some topics official IAG products exist (e.g., ITRF, EOP), whereas for others, like the gravity field and the height systems, no official IAG products are declared. In this product-based inventory, the BPS presents the current status, identifies gaps and inconsistencies as well as interactions between different products. In this context also open questions and recommendations regarding standards and conventions for the generation of IAG products are provided.

In addition to this printed version, the inventory will be regularly updated and will be published as a *living doc-*

ument on the GGOS web site. This is important to keep its contents up-to-date, since the standards and conventions are regularly updated and also the IAG products are evolving with time, e.g., the upcoming ITRF2014 will be released early 2016 by the International Terrestrial Reference System (ITRS) Centre.

According to its Terms of Reference, the BPS also works towards the development of new products derived from a combination of geometric and gravimetric observations and thus, such integrated products should be addressed in an updated version.

Acknowledgements

This document has been reviewed in a two step procedure as described below. The efforts of all reviewers and their constructive feedback and valuable comments on the inventory are greatfully acknowledged by the authors. The suggestions and comments helped a lot to improve the document and they are incorporated in this version.

The first (*internal*) review cycle was initiated by the BPS in April 2014. The document was distributed to the GGOS Coordinating Board members and to the BPS associated members. Additionally, some of these colleagues and other experts were contacted personally by the BPS to get feedback and detailed comments on particular topics (sections) of the document. Many of them responded and provided very important feedback and suggestions, which were incorporated in the first revision of the document. This first revision cycle was completed at the end of 2014. The colleagues who provided feedback are:

F. Barthelmes (Germany), S. Bettadpur (USA),
M. Bloßfeld (Germany), J. Böhm (Austria),
N. Donelly (Australia), J. Gipson (USA),
R. Gross (USA), J. Hassdyk (Australia),
B. Heck (Germany), T. Herring (USA),
C. Hohenkerk (United Kingdom), J. Ihde (Germany),
J. Kusche (Germany), F. Lemoine (USA),
E. Pavlis (USA), G. Petit (France),
C. Rizos (Australia), T. Schöne (Germany),
H. Schuh (Germany), M. Seitz (Germany),
R. Stanaway (Australia), D. Thaller (Germany).

The authors thank all these colleagues for their contributions.

During the GGOS Coordinating Board in San Francisco, USA in December 2014, it was decided that a second (*external*) review cycle should be conducted by IAG. Responsible for this official IAG review process was the IAG Bureau (Chris Rizos, Harald Schuh and Hermann Drewes). The IAG Secretary General, Hermann Drewes, took over the responsibility for the coordination of the review process. Each chapter/product of the inventory was reviewed (mostly) by two reviewers (see Table 1). Again, many fruitful comments and suggestions have been received from the reviewers, which were incorporated in the final version of this document. The contributions of all reviewers, the support of the IAG Bureau and the coordination of the review process by Hermann Drewes is gratefully acknowlegded by the authors.

Table 1: *Reviewers designated by IAG to evaluate this document.*

Chapter	Reviewers
Chapter 1.1	H. Kutterer (Germany), C. Rizos (Australia)
Chapter 1.2	H. Kremers (Germany), D. D. McCarthy, N. Stamatakos (USA)
Chapter 2	H. Drewes (Germany), H. Schuh (Germany)
Chapter 3	G. Petit (France), N. Sneuuw (Germany)
Chapter 4.1	A. Nothnagel (Germany), J. Souchay (France)
Chapter 4.2	Z. Altamimi (France), T. Herring (USA)
Chapter 4.3	D. Gambis (France), R. Gross (USA)
Chapter 4.4	A. Jäggi (Switzerland)
Chapter 4.5	R. Barzaghi (Italy), U. Marti (Switzerland)
Chapter 4.6	B. Heck (Germany), M. Sideris (Canada)

1 Introduction

1.1 Global Geodetic Observing System (GGOS): Mission, goals and structure

The GGOS was initially created as an IAG Project during the International Union of Geodesy and Geophysics (IUGG) meeting in 2003 in Sapporo, Japan, in response to developments in geodesy, the increasing requirements of Earth observations, and growing societal needs. Since 2004, GGOS represents IAG in the Group on Earth Observation (GEO) and contributes to the Global Earth Observation System of Systems (GEOSS) [GEO 2005]. After a preliminary development phase, the Executive Committee of the IAG decided to continue the Project at its meeting in August 2015 in Cairns, Australia. From 2005 to 2007, the GGOS Steering Committee, Executive Committee, Science Panel, Working Groups, and web pages were established. Finally, at the IUGG meeting in 2007 in Perugia, Italy, IAG evaluated GGOS to the status of a full component of IAG – as *the permanent observing system of the IAG.*

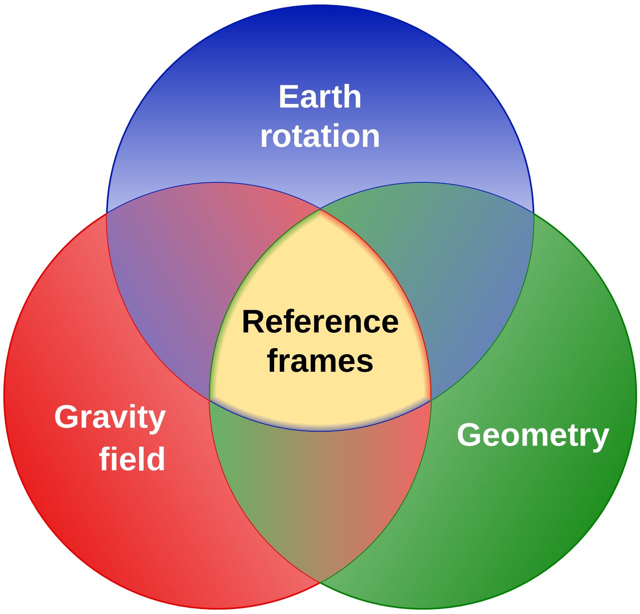


Fig. 1.1: *Integration of the "three pillars" geometry, Earth rotation and gravity field ([Rummel 2000], modified by [Plag et al. 2009]).*

The IAG Services and Commissions provide the geodetic infrastructure and products, as well as the expertise and support for scientific developments, which are the basis for monitoring the Earth system and for global change research. GGOS relies on the observing systems and analysis capabilities already in place in the IAG Services and envisions the continued development of innovative technologies, methods and models to improve our understanding of global change processes. IAG and GGOS provide a framework that ranges from the acquisition, transfer and processing of a tremendous amount of observational data to its consistent integration. Consistency among the data sets from the different (geometric and gravimetric) observation techniques is of crucial importance for the generation of IAG products, such as geodetic reference frames which are the basis for the integration of geometry, Earth rotation and the gravity field (see Figure 1.1).

GGOS as an organization is built upon the existing IAG Services as a unifying umbrella, and will continue to be developed for this purpose. Under this "unifying umbrella", all the products provided by the different IAG Services are considered GGOS products – as ratified at the IAG General Assembly in 2009 in Buenos Aires, Argentina.

The mission and the overarching strategic focus areas of GGOS are specified in its Terms of Reference (see `www.ggos.org`). They were officially adopted by the IAG Executive Committee (EC) at the IUGG XXV General Assembly, Melbourne, Australia, 2011. Its first revision was approved by the IAG EC during the IUGG XXVI General Assembly, Prague, Czech Republic, 2015.

The mission of GGOS is:

1. To provide the observations needed to monitor, map and understand changes in the Earth's shape, rotation, and mass distribution.
2. To provide the global geodetic frame of reference that is the fundamental backbone for measuring and consistently interpreting key global change processes and for many other scientific and societal applications.
3. To benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built.

The overarching strategic focus areas of GGOS goals and objectives are:

1. **Geodetic Information and Expertise**: GGOS outcomes will support the development and maintenance of organizational intangible assests, including geodetic information and expertise. The development of this strategic focus area will benefit all other goals and objectives.

2. **Global Geodetic Infrastructure**: Development of, advocacy for, and maintenance of existing global geodetic infrastructure is a direct support of each GGOS goal.
3. **Services, Standardization, and Support**: Optimal coordination, support, and utilization of IAG Services, as well as leveraging existing IAG resources, are critical to the progress of all GGOS goals and objectives.
4. **Communication, Education, Outreach**: Marketing, outreach, and engagement are critical elements for sustaining the organizational fabric of GGOS.

The organizational structure of GGOS is comprised of the following key components (see Figure 1.2):

GGOS Consortium – is the collective voice for all GGOS matters.

GGOS Coordinating Board – is the central oversight and decision-making body of GGOS, and represents the IAG Services, Commissions, Inter-Commission Committees, and other entities.

GGOS Executive Committee – serves at the direction of the Coordinating Board to accomplish day-today activities of GGOS tasks.

GGOS Science Panel – advises and provides recommendations relating to the scientific content of the GGOS 2020 to the Coordinating Board; and represents the geoscientific community at GGOS meetings.

GGOS Coordinating Office – coordinates the work within GGOS and supports the Chairs, the Executive Committee and the Coordinating Board.

Bureau of Products and Standards (former Bureau for Standards and Conventions) – tracks, reviews, examines, evaluates the standards, constants, resolutions and conventions adopted by IAG or its components and recommends their continued use or proposes necessary updates; works towards the developement of new products derived from a combination of geometric and gravimetric observations.

Bureau of Networks and Observations (former Bureau for Networks and Communications) – develops strategies and plans to design, integrate and maintain the fundamental geodetic infrastructure, including communications and data flows; monitors the networks and advovates for implementation of core and co-located network sites and improved network performance.

GGOS Working Groups and Focus Areas (former Themes) – address overarching issues common to several or all IAG components, and are a mechanism to bring the various activities of the Services, Commissions and Inter-Commission Committees together, or to link GGOS to external organizations. Focus areas are cross-disciplinary and address specific areas where GGOS contributors work together to address broader and critical issues.

IAG – promotes scientific cooperation and research in geodesy on a global scale and contributes to it through its various research bodies.

IAG Services, Commissions and relevant Inter-Commission Committees – are the fundamental supporting elements of GGOS.

GGOS Inter Agency Committee (GIAC) – a forum that seeks to generate a unified voice to communicate with Governments and Intergovernmental organizations (GEO, UN bodies) in all matters of global and regional spatial reference frames and GGOS research and applications.

1.2 Standards and conventions

Standards and conventions are used in a broad sense and various international organizations and entities are involved in this subject. This section gives general information and an overview about the standards and conventions that are currently in use within the geodetic community. According to Drewes [2008] and Angermann [2012] one shall distinguish standards, standardized units, fundamental physical standards, resolutions and conventions. Besides this, also background models used for the processing of the space geodetic observations are introduced in this section.

1.2.1 Standards

Standards are generally accepted specifications and measures for quantitative or qualitative values that define or represent under specific conditions the magnitude of a unit. A technical standard is an established norm or requirement, which is usually a formal document that provides uniform engineering or technical criteria, methods and processes or procedures.

Various international, regional and national organizations are involved in the development, coordination, revision, maintenance, etc. of standards that address the interests of a wide area of users. Important for geodesy is the International Organization for Standardization (ISO), an international standard-setting body composed of representatives from a network of national standards institutes of more than 150 countries. The Technical Committee ISO/TC211 (`www.isotc211.org`)

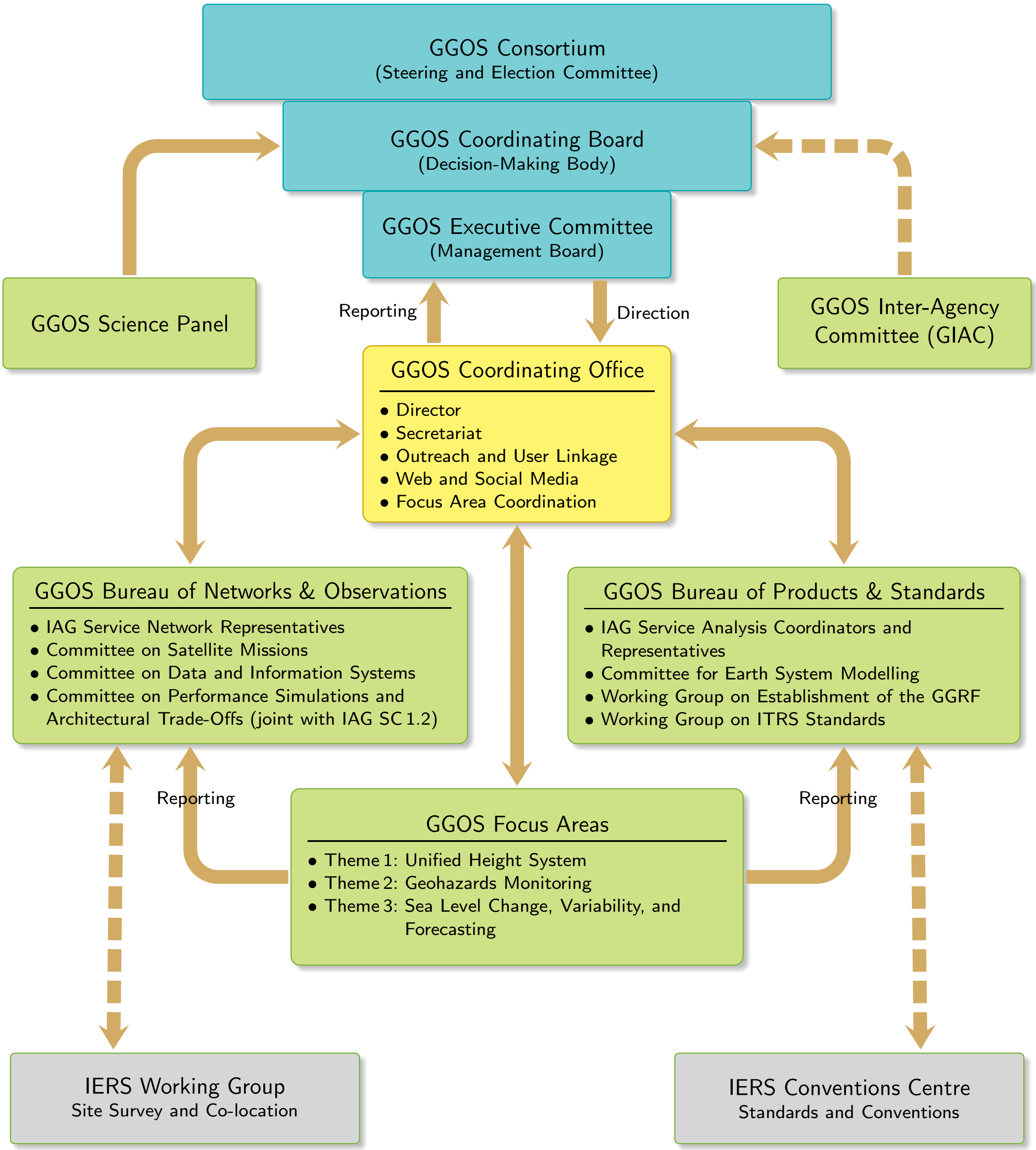


Fig. 1.2: *Organizational structure of GGOS as adopted in 2015. Its initial structure [Kutterer et al. 2012] was restructured in 2014. The former Bureau on Networks and Communications (BNC) was renamed the Bureau of Networks and Observations (BNO), and the former Bureau of Standards and Conventions (BSC) was renamed the Bureau of Products and Standards (BPS). "Focus Areas" were formerly called "Themes". Please also note that GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees.*

was formed within ISO to cover the areas of digital geographic information and geomatics. Also relevant for geodesy is the Open Geospatial Consortium (OGC), an international voluntary standards organization, originating in 1994. In OGC, more than 400 governmental, commercial, nonprofit and research organizations worldwide collaborate in a consensus process encouraging development and implementation of open standards for geospatial content and location-based services, Geographic Information System (GIS) data processing and data sharing. The ISO and OGC standards are applied in geo-referencing, spatial analysis, and communication (service specification). There is a close cooperation between OGC, ISO/TC211 and IAG components.

The standards and conventions that are relevant for geodesy are based primarily on decisions made by international organizations or bodies involved in this topic, such as

- the Bureau International de Poids et Mesures (BIPM),
- the Committee on Data for Science and Technology (CODATA)

and by resolutions related to standards and conventions adopted by the Councils of

- the International Union of Geodesy and Geophysics (IUGG),
- the International Astronomical Union (IAU) and
- the International Association of Geodesy (IAG).

Within IAU, the Commission A3 "Fundamental Standards" (`www.iau.org/science/scientific_bodies/commissions/A3`) and the IAU's Standards of Fundamental Astronomy (SOFA) service (`www.iausofa.org`) are directly involved in standards.

1.2.2 Standardized units

In the International Vocabulary of Basic and General Terms in Metrology [BIPM 2006; ISO/IEC 2007] the terms *quantities* and *units* are defined. The value of a quantity is expressed as the combination of a number and a unit. In order to set up a system of units, it is necessary first to establish a system of quantities, including a set of equations relating those quantities. Binding for geodesy is the International System of Units (SI), which was adopted by the 11th General Conference on Weights and Measures (1960). It is maintained by the BIPM. The units are divided into two classes – base units and derived units. In a similar way the corresponding quantities are described as base quantities and derived quantities. In the SI there are seven base units representing different kinds of physical quantities. Three of them are applied in geodesy:

- *Time* (standardized unit second [s]): The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.
- *Length* (standardized unit metre [m]): The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
- *Mass* (standardized unit kilogram [kg]): The kilogram is the unit of mass. It is equal to the mass of the international prototype of the kilogram.

The number of derived units and derived quantities of interest in geosciences can be extended without limit. For example, the derived unit of speed is metre per second [m/s], or centimetre per second [cm/s] in the SI. Whereas the kilometre per hour [km/h] is a unit outside the SI but accepted for use with the SI. The same holds for the gal [cm/s^2] which is a special non-SI unit of acceleration due to gravity.

The realization of the SI at the BIPM constitutes a fundamental contribution to the tasks of the IAG. One of the five scientific departments of the BIPM, the "Time department", is a service of the IAG. The activities of this department are focused on the maintenance of the SI second and the formation of the international reference time scales.

1.2.3 Fundamental physical constants

The formulations of the basic theories of physics and their applications are based on fundamental physical constants. These quantities, which have specific and universally used symbols, are of such importance that they must be known as accurately as possible. A physical constant is generally believed to be both universal in nature and constant in time. In contrast, a mathematical constant is a fixed numerical value, which does not directly involve any physical measurement. A complete list of all fundamental physical constants is given by the National Institute of Standards and Technology (NIST). NIST publishes regularly a list of the constants.

The CODATA is an interdisciplinary Scientific Committee of the International Council for Science (ICSU). IUGG and IAU are member unions of CODATA. The Committee works to improve the quality, reliability, management and accessibility of data. CODATA is concerned with all types of data resulting from measurements and calculations in all fields of science and technology, including physical sciences, biology, geology, astronomy, engineering, environmental science, ecology and others.

The CODATA Committee (former Task Group) on Fundamental Physical Constants was established in 1969. Its purpose is to periodically provide the international scientific and technological communities with an internationally accepted set of values for the fundamental physical constants. The first such CODATA set was published in 1973, and later in 1986, 1998, 2002, 2006 and 2010, see, [Mohr et al. 2012], and the open accessible report at physics.nist.gov/cuu/Constants/Preprints/Isa2010.pdf. The latest version, the 2014 least-squares adjustment of the values of the set of fundamental physical constants was released in 2015. The 2014 set replaces the previously recommended 2010 CODATA set and may also be found on the World Wide Web at www.physics.nist.gov/Constants. The fundamental physical constants are classified in universal, electromagnetic, atomic and nuclear, physico-chemical constants as well as adopted values. The set of values provided by CODATA do not aim at covering all scientific fields. Only few of these fundamental constants are also relevant for geodesy. These are primarily two universal constants and two adopted values, which are given below:

a) Universal constants

- Newtonian constant of gravitation (G): $(6.674\,08 \pm 0.00031) \cdot 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}$
- Speed of light in vacuum (c, c_0): 299 792 458 m/s (exact)

b) adopted values (as mean values at sea level)

- Standard acceleration of gravity (g_n): $9.806\,65\,\mathrm{m/s^2}$ (exact)
- Standard atmosphere (atm): 101 325 Pa (exact)

It is obvious, that the astrogeodetic community needs, in addition to these fundamental physical constants, a set of suitable fundamental parameters as a basis for the definition and realization of reference systems as well as for the generation of geodetic products. The geodetic activities in this field are addressed in Section 3.1. It shall also be mentioned, that the Conventions of the International Earth Rotation and Reference Systems Service (IERS) provide in Section 1.2 a summary of numerical standards [Petit et al. 2010], as reflecting the situation in 2010. More information on the IERS Conventions and on fundamental parameters can be found in Sections 1.2.5 and 3.1.

1.2.4 Resolutions

A resolution is a written motion adopted by a deliberating body. The substance of the resolution can be anything that can normally be composed as a motion. In this context we refer to the motion for adopting standards, constants or any parameters to be used by institutions and persons affiliated with the adopting body. Most important resolutions for geodesy are those adopted by IUGG, IAG, and IAU.

The IUGG and IAG resolutions are adopted at the IUGG General Assemblies and published every four years in the corresponding IAG Geodesist's Handbooks [Drewes et al. 2012]. They are also available in electronic form at www.iugg.org/resolutions.

The IAU resolutions are adopted by General Assemblies held every 3 years. They are published regularly in the IERS Conventions along with detailed information for their implementation [e.g., Petit et al. 2010]. An electronic version can be obtained from www.iau.org/administration/resolutions.

Resolutions are non-binding laws of a legislature, but more binding than recommendations. In non-legal bodies, such as IUGG, IAG and IAU, which cannot pass laws, they form the highest level of commitment. Resolutions shall be respected by all institutions and persons affiliated with the adopting body.

The resolutions, which are relevant with respect to standards and conventions for geodesy, are summarized below in chronological order. Please note that only some major information is extracted from the original resolutions. For the full version follow the links above.

IUGG Resolution No. 7 (1979) and **IAG Resolution No. 1 (1980)** on the Geodetic Reference System 1980 (GRS80) [Moritz 2000]. It is recommended that the Geodetic Reference System 1967 shall be replaced by a new Geodetic Reference System 1980, also based on the theory of the geocentric equipotential ellipsoid.

IAG Resolution No. 16 (1983) on tide systems, recognizing the need for the uniform treatment of tidal corrections to various geodetic quantities such as gravity and station positions. It is recommended that the indirect effect due to the permanent yielding of the Earth shall not be removed [IAG 1984].

IUGG Resolution No. 2 (1991) on the Conventional Terrestrial Reference System (CTRS) recommends that:

- CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system,
- the geocentric non-rotating system to be identical to the Geodetic Reference System (GRS) as defined in the IAU resolutions,
- the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG),
- the origin of the system to be the geocenter of the Earth's masses including oceans and atmosphere, and
- the system to have no global residual rotation with respect to horizontal motions at the Earth's surface.

IAU Resolution A4 (1991) has set up a general relativistic framework to define reference systems centered at the barycenter of the solar system and at the geocenter.

IAU Resolution B2 (1997) on the International Celestial Reference System (ICRS). From January 1, 1998, the IAU celestial reference system shall be the ICRS. The corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on reference frames. The IERS should take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

IAU Resolution (2000) contains several specific resolutions (RES):

RES B1.1	Maintenance and establishment of reference frames and systems
RES B1.2	Hipparcos Celestial Reference Frame
RES B1.3	Definition of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS)
RES B1.4	Post-Newtonian Potential Coefficients
RES B1.5	Extended relativistic framework for time transformations and realization of coordinate times in the solar system
RES B1.6	IAU Precession-Nutation Model
RES B1.7	Definition of the Celestial Intermediate Pole
RES B1.8	Definition and use of Celestial and Terrestrial Ephemeris Origins
RES B1.9	Re-definition of the Terrestrial Time (TT)
RES B2	Coordinated Universal Time (UTC).

The Resolutions B1.1 through B1.8 of the IAU General Assembly 2000 have been adopted by IUGG at its General Assembly in 2003 (see Resolution No. 4). More information on these resolutions may be found in the "Proceedings of the IERS Workshop on the Implementation of the New IAU Resolutions" published in the IERS Technical Note No. 29 [Capitaine et al. 2002].

IUGG Resolution 3 (2003) strongly supports the establishment of the GGOS (former IGGOS) Project within the new IAG structure as geodesy's contribution to the wider field of geosciences and as the metrological basis for the Earth observation programs within IUGG.

IAU Resolution B1 (2006) on adopting the P03 precession theory and definition of the ecliptic. It accepts the conclusions of the IAU Division I Working Group on Precession and Ecliptic [J. L. Hilton et al. 2006], and recommends that the terms lunisolar precession and planetary precession be replaced by precession of the equator and precession of the ecliptic, respectively, and that, beginning on 1 January 2009, the precession component of the IAU 2000A precession-nutation model be replaced by the P03 precession theory [Capitaine et al. 2003] in order to be consistent with both dynamical theories and the IAU 2000 nutation.

IAU Resolution B2 (2006) is a supplement to the IAU 2000 resolutions on reference systems, containing primarily two recommendations, the first to harmonize the name of the pole and origin to "*intermediate*" and a second recommendation fixing the default orientation of the BCRS and GCRS, which are assumed to be oriented according to the ICRS axes (for more information see the IERS Conventions 2010 [Petit et al. 2010]).

IAU Resolution B3 (2006) is on the re-definition of Barycentric Dynamical Time (TDB) (for more information see the IERS Conventions 2010 [Petit et al. 2010]). This resolution has also been adopted by the IUGG in 2007 as written in Resolution 1.

IUGG Resolution No. 2 (2007) on the Geocentric and International Terrestrial Reference System (GTRS and ITRS) endorses the ITRS as the specific GTRS for which the orientation is operationally maintained in continuity with past international agreements (BIH orientation), and adopts the ITRS as the preferred GTRS for scientific and technical applications, and urges other communities, such as the geo-spatial information and navigation communities, to do the same.

IUGG Resolution No. 3 (2007) on the Global Geodetic Observing System (GGOS) of the IAG. The new structure of IAG reflected by the designation of GGOS as a permanent component, urges sponsoring organizations and institutions to continue their support of the elements of GGOS, which is crucial for sustaining long-term monitoring and understanding of the Earth system.

IAU Resolution B2 (2009) on IAU 2009 astronomical standards. It recommends that the list of previously published constants compiled in the report of the IAU Division A Working Group Numerical Standards for Fundamental Astronomy (NSFA) [Luzum et al. 2011] be adopted as the IAU (2009) System of Astronomical Constants, that Current Best Estimates (CBE) of astronomical constants be permanently maintained as an electronic document, and that the IAU establish a permanent body to maintain the CBEs for fundamental astronomy.

IAU Resolution B3 (2009) resolves that from 01 January 2010 the fundamental astronomic realization of the International Celestial Reference System (ICRS) shall be the Second Realization of the International Celestial Reference Frame (ICRF2) as constructed by the IERS/International VLBI Service for Geodesy and Astrometry (IVS) Working Group on the ICRF in conjunction with the IAU Division I Working Group on the International Celestial Reference Frame [Fey et al. 2009].

IUGG Resolution No. 3 (2011) on the ICRF2. This resolution urges that the ICRF2 shall be used as the standard for all future applications in geodesy and astrometry, and that the highest consistency between the ICRF, the ITRF, and the EOP as observed and realized by IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS.

IAU Resolution B2 (2012) on the re-definition of the astronomical unit of length. It is recommended that the astronomical unit be re-defined to be a conventional unit of length equal to 149 597 870 700 m exactly, in agreement with the value adopted in IAU 2009 Resolution B2 (see `www.iau.org/static/resolutions/IAU2012_English.pdf`).

IAG Resolution No. 1 (2015) for the definition and realization of an *International Height Reference System (IHRS)*. It outlines five fundamental conventions for the definition of the IHRS, including a conventional value for the reference potential $W_0 = 62\,636\,853.4\ \mathrm{m^2 s^{-2}}$, and stating the mean tidal system/mean crust as the standard for the generation of IHRS-related products (see `iag.dgfi.tum.de/index.php?id=330`).

IAG Resolution No. 2 (2015) for the establishment of a global absolute gravity reference system. It resolves, among other issues, to initiate the replacement of the International Gravity Standardization Net 1971 (IGSN71) by the new Global Absolute Gravity Reference System.

IUGG Resolution No. 3 (2015) on the Global Geodetic Reference Frame (GGRF) recognizing the adoption in February 2015 by the General Assembly of the United Nations (UN) of a resolution entitled “A Global Geodetic Reference Frame for Sustainable Development”. It urges the UN Global Geospatial Information Management (GGIM) GGRF Working Group to engage with IUGG and other concerned organizations such as the Committee of Earth Observation Satellities (CEOS) and the Group on Earth Observation (GEO), in order to promote the implementation of the UN GGIM GGRG RoadMap.

UN Resolution (2015) on a Global Geodetic Reference Frame (GGRF). The United Nations General Assembly adopted the resolution on a Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) on February 26, 2015.

1.2.5 Conventions

A convention is a set of agreed, stipulated or generally accepted norms, standards or criteria. In physical sciences, numerical values such as constants or quantities are called conventional if they do not represent a measured property of nature, but originate from a convention. A conventional value for a constant or a specific quantity (e.g., the potential of the geoid W_0) can be, for example, an average of measurements agreed between the scientists working with these values.

In geodesy, conventions may be adopted by IAG and its components (Services, Commissions, Inter-Commission Committees, and GGOS). Most established and common are the conventions of the IERS. These IERS conventions are regularly updated and they serve as the basis for the analysis of the geometric observations and for the generation of IERS products. The IERS conventions are based on the resolutions of the international scientific unions, namely the IUGG, IAU and IAG and they provide those constants, models, procedures, and software that have the most significance to IERS products (e.g., celestial and terrestrial reference frames, Earth orientation parameters).

The latest version are the IERS Conventions 2010 [Petit et al. 2010]. They consist of eleven chapters that focus on various topics, such as general definitions and numerical standards, the definition and realization of the celestial and terrestrial reference systems, transformations between both systems, the geopotential, displacement of reference points, tidal variations in the Earth's rotation, models for atmospheric propagation delays, general relativistic models for space-time coordinates and equations of motion and general relativistic models for propagation. The IERS conventions provide the basis for the work of the geometric Services of IAG, the International GNSS Service (IGS) [Dow et al. 2009], the International Laser Ranging Service (ILRS) [Pearlman et al. 2002], the International VLBI Service for Geodesy and Astrometry (IVS) [Schuh et al. 2012], and the International DORIS Service (IDS) [Willis et al. 2010], as well as for the definition and realization of geodetic reference systems and for the generation of IERS products.

For data and products related to the gravity field, equivalent conventions have to be established by the International Gravity Field Service (IGFS), but this is still an issue that needs to be solved. Instead, for satellite gravity field missions (e.g., CHAMP, GRACE, GOCE) different standards or conventions are in current use, e.g., EIGEN [Förste et al. 2012], GOCE [European GOCE gravity consortium 2012], EGM2008 [N. Pavlis et al. 2012].

Moreover, consistency between geometric and gravimetric standards has to be ensured, as a prerequisite for the major goal of GGOS, the integration of the geometry, rotation and gravity field of the Earth. A key objective of the BPS is to contribute to this important goal.

1.2.6 Physical and empirical background models

Besides the numerical standards and conventions, the background models that are applied for the processing of the geodetic observations shall be addressed in this inventory. These models need to be developed with a specific level of accuracy for various effects and phenomena that can be used to compute estimates of the space geodetic observations. Usually two different types of correction models are distinguished:

– Models to correct the effect of geophysical phenomena that affect the station positions, quasar positions and/or satellite orbits (e.g., solid Earth tides, ocean tides, pole tides, ...);
– Models to account for effects that directly influence the space geodetic observations such as signal propagation (ionosphere, troposphere) and technique-related instrumental effects, e.g. GNSS antenna phase center variations, thermal deformation of VLBI telescopes, and SLR range biases.

The first type of models is applied to the a-priori values for station coordinates, satellite orbits and quasar positions (in the case of VLBI), whereas the second type is mostly computed in observation space, but can also be applied to the a-priori values. The corrected a-priori values are then used to compute the theoretical geometry at the observation epoch. Finally, the values “o-c” (observed minus computed) are derived, and are an input for the adjustment procedure and the computation of geodetic products (see Figure 1.3).

Concerning the background models, a further type of discrimination may be mentioned: While some models refer to a-priori fixed, fully determined values, some others use parameterized expressions; the parameter values are estimated within the least squares adjustment process related to the adjustment of the observations. Examples of the second type are, e.g., parameters in the solar radiation pressure model or harmonic coefficients in the description of the Earth’s gravitational potential.

It is obvious, that for the processing of the geodetic observations all the models have to be applied consistently according to well-defined standards and conventions. This is important to get interpretable and consistent results, in particular if the data of the individual techniques are combined to generate geodetic products, such as the terrestrial reference frame and the EOP.

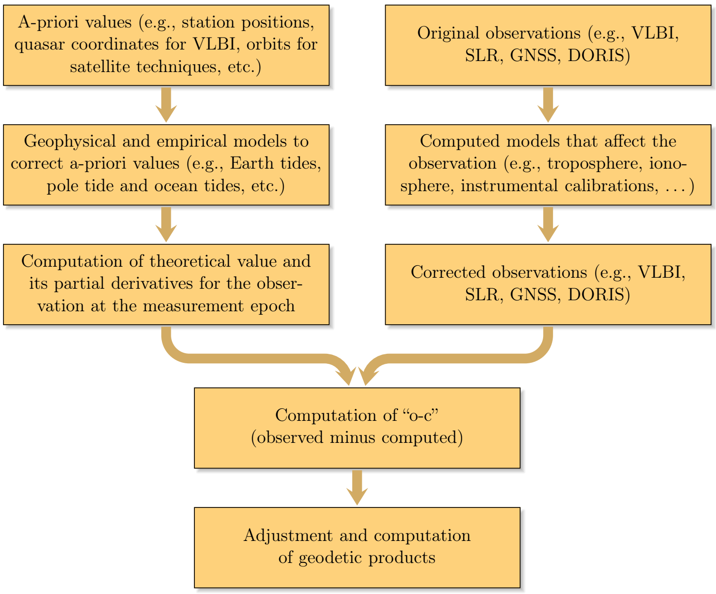


Fig. 1.3: *Procedure for applying geophysical and empirical background models in the processing of space geodetic observations. Please note that in some software packages the second type of models (that affect the observations) are applied to the a-priori values, which will lead to identical results.*

2 GGOS Bureau of Products and Standards

The GGOS Bureau of Products and Standards (BPS) is a recent reorganization of the former GGOS Bureau for Standards and Conventions (BSC), which was established in 2009. This resulted from a re-alignment of the GGOS organization during the GGOS Coordinating Board Meeting in Vienna (April 2014). It has been decided to keep the existing GGOS components, to redefine and clarify their responsibities, and to extend the tasks of both GGOS Bureaus. A new charter and implementation plan for the BPS was completed in 2015.

The BPS is hosted and supported by the Deutsches Geodätisches Forschungsinstitut (DGFI) and the Institut für Astronomische und Physikalische Geodäsie (IAPG) of the Technische Universität München, within the Forschungsgruppe Satellitengeodäsie (FGS) [Angermann et al. 2015; Hugentobler et al. 2012].

2.1 Mission and objectives

The work of the BPS is primarily built on the IAG Services and the products they derive on an operational basis for Earth monitoring making use of various space geodetic observation techniques such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR)/Lunar Laser Ranging (LLR), GNSS, Doppler Orbit Determination and Radiopositioning Integrated by Satellite (DORIS), altimetry, gravity satellite missions, gravimetry, etc. The purpose and major goal of the BPS is to ensure that common standards and conventions are adopted and implemented by the IAG components as a fundamental basis for the analysis of the different geodetic observations to ensure consistent results for the geometry, rotation and gravity field of the Earth along with its variations in time. The BPS supports GGOS in its goal to obtain products of highest accuracy, consistency, and temporal and spatial resolution, which refer to a unique reference frame, stable over decades in time.

The objectives are:

- To keep track of the strict observance of adopted geodetic standards, standardized units, fundamental physical constants, resolutions and conventions in the generation of IAG products.
- To review, examine and evaluate all standards, constants, resolutions and conventions adopted by IAG or its components and recommend their use or propose the necessary updates.
- To identify gaps, inconsistencies and deficiencies in standards and conventions and to initiate steps to remove them.
- To propose the adoption of new standards and conventions where necessary, and submit the corresponding resolutions for the approval by IAG, IUGG, IAU, and other international organizations.
- To propagate standards and conventions to the wider scientific community and promote their use.

2.2 Tasks

Main tasks related to standards and conventions are:

- The BPS assesses the geodetic standards and conventions currently in use by all the IAG Services for the generation of geodetic/geophysical products. It reviews official products of IAG with respect to the adequate use of standards and conventions.
- The BPS propagates all geodetic standards and conventions to geodetic and general scientific communities and urges their common use. If necessary, the BPS proposes the adoption of new standards and conventions, changes and revisions, and submits the corresponding resolutions for the approval by IAG, IUGG, IAU, and other international organizations.
- The BPS propagates most important standards to society in general and promotes their use. These outreach activities include the participation at relevant conferences and meetings and submission of papers to journals also in neighbouring fields.
- The BPS maintains regular contact with all internal and external institutions involved in the adoption of standards, resolutions and conventions. It thereby takes advantage of representations in IAG Services, IAG Commissions, IUGG and IAU, as well as in other bodies involved in standards and conventions (e.g., BIPM, ISO, CODATA).
- The Bureau is in charge of administrative tasks, communications, data base and web support. For these tasks a close cooperation with the GGOS Coordination Office and the GGOS Portal is established.
- For specific issues dealing with particular fields of geodesy the BPS may set up dedicated working groups. Regional or national members may be included in such working groups
- The BPS reports regularly to the GGOS Coordinating Board and to the IAG Executive Committee, and – if necessary or appropriate – to the IUGG Executive Committee.

2.3 Staff and representation of IAG components and other entities

In 2009, when the BSC started its operation, the staff members of the Bureau were U. Hugentobler (Director), D. Angermann (Deputy Director), J. Bouman, M. Gerstl, T. Gruber, B. Richter, P. Steigenberger. In order to improve balance between members affiliated with geometric and gravimetric research fields and due to a few personnel changes, the present BPS staff is (status December 2015):

- Director: D. Angermann (successor of U. Hugentobler since April 2011)
- Deputy director: T. Gruber
- Geodetic fields covered by the BPS team:
  - Geometry, orbits, TRF: D. Angermann, U. Hugentobler, P. Steigenberger (as associated member)
  - Earth Orientation, CRF: M. Gerstl, R. Heinkelmann (as representative of IAU)
  - Gravity, height systems: T. Gruber, L. Sánchez

In its current structure the following GGOS entities are associated with the BPS:

- Committee "Contributions to Earth System Modelling", Chair: M. Thomas (Germany),
- Joint Working Group "Establishment of the Global Geodetic Reference Frame (GGRF)",
  Chair: U. Marti (Switzerland),
- Working Group "ITRS Standards for ISO TC211",
  Chair: C. Boucher (France).

As defined in its charter, the BPS serves as contact and coordinating point for the IAG Analysis and Combination Centers regarding the homogenization of IAG/GGOS standards and products. The IAG Services and the other entities involved in standards and geodetic products have chosen their representatives as associated members of the BPS. The Bureau comprises the staff members, the chairs of the associated GGOS components, the committee and two working groups as listed above, as well as representatives of the IAG Services and other entities. The status of December 2015 is summarized in Table 2.1. Regarding the development of standards, there is a link with the IERS Conventions Center, the IAU Working Group "*Numerical Standards for Fundamental Astronomy*", BIPM, CODATA, NIST and ISO/TC211.

This configuration of the BPS ensures a close interaction with the IAG Services and the other entities involved in standards. A communication plan has been setup for a regular exchange of information, in particular regarding the homogenization of standards and IAG products. Regular meetings of the BPS staff members take place in Munich every two months to perform the operational business. In addition regular telecons and face-to-face meetings (e.g., twice per year) with the BPS staff and the representatives (and invitees) take place to coordinate and manage the BPS work, to monitor progress against schedule, and to redefine tasks and responsibilites in case of need.

***Table 2.1:** Associated members of the BPS, representing the IAG Services, IAU and other entities (status: December 2015).*

T. Herring, USA, G. Petit, France	International Earth Rotation and Reference Systems Service (IERS)
U. Hugentobler, Germany	International GNSS Service (IGS)
E. Pavlis, USA	International Laser Ranging Service (ILRS)
J. Gipson, USA	International VLBI Service for Geodesy and Astrometry (IVS)
F. Lemoine, J. Ries, USA	International DORIS Service (IDS)
J.-M. Lemoine, H. Capdeville, France	International DORIS Service (IDS)
R. Barzaghi, Italy	International Gravity Field Service (IGFS)
F. Barthelmes, Germany	International Center for Global Gravity Field Models (ICGEM)
S. Bonvalot, France	Bureau Gravimetric International (BGI)
R. Heinkelmann, Germany	International Astronomical Union (IAU), Working Group "Numerical Standards for Fundamental Astronomy"
M. Craymer, Canada	Chair of Control Body for ISO Geodetic Registry Network
L. Hothem, USA	Vice-Chair of Control Body for ISO Geodetic Registry Network
J. Ádám, Hungary	Chair of the IAG Communication and Outreach Branch
J. Ihde, Germany	IAG representative to ISO/TC211
J. Kusche, Germany	Representative of gravity community
P. Steigenberger, Germany	Representative of GNSS community

3 Evaluation of numerical standards

3.1 Defining parameters of geodetic reference systems, time and tide systems

The IUGG resolution No. 7 (1979) and the IAG resolution No. 1 (1980) recommend that the Geodetic Reference System 1980 (GRS80) [Moritz 2000] shall be used as the official reference for geodetic work. The GRS80 is defined by four conventional constants GM, a, J_2, ω (see Table 3.1). The GRS80 is now more than 30 years old and thus these conventional constants are not anymore a good representation of a best-fitting set of Earth parameters. However, the IAG recommends the GRS80 parameters as a conventional ellipsoid, i.e. to convert Cartesian coordinates into ellipsoidal coordinates. It is used worldwide for many map projections and millions of coordinates are related to it.

The numerical standards and adopted constants may also change with time, and thus we would better speak about *fundamental parameters* instead of *constants* [Groten 2004]. In the last few years, substantial progress has been achieved in the estimation of these fundamental parameters and their temporal changes. Consequently, the introduction of a new Geodetic Reference System (i.e., GRS2000) was a key topic within the geodetic community, in particular in Special Commission 3 "*Fundamental Constants*" [Groten 2004] of the IAG (in its old structure). However, after lengthy discussion and consideration, it was decided not to propose any change of the existing GRS80 at that time. Nevertheless, some progress was made and a consistent set of fundamental parameters and current (2004) best estimates have been compiled [Groten 2004]. The paper lists several possible values for the parameters. A consistent set is defined in section III of that paper, which was used for the IERS Conventions 2010 [Petit et al. 2010]. Table 3.1 summarizes the numerical standards given in different sources, namely the conventional GRS80 constants [Moritz 2000], the fundamental parameters of [Groten 2004], the IERS Conventions 2010 and the Earth Gravitational Model 2008 (EGM 2008 [N. Pavlis et al. 2012]).

Various factors have to be considered for a comparison and interpretation of the values displayed in Table 3.1. The values are obtained from different sources aiming at different purposes. The GRS80 is still used as conventional ellipsoid (e.g., the IERS Conventions (2010), Chapter 4, recommend to use the GRS80 ellipsoid to express geographical coordinates), although the values are no longer truly representing reality. Except for the angular rotation velocity ω, all other GRS80 values differ from the consistent set of fundamental parameters published by Groten about 25 years later [Groten 2004]. For example, the difference for the equatorial radius a is about 0.4 m. The set of fundamental parameters of [Groten 2004] was kept for the IERS Conventions 2010. The adopted standards for the EGM 2008 were defined in the same geodetic reference system as adopted for EGM 96 [Lemoine et al. 1998] to ensure consistency between both gravity field models. For a comparison of the values displayed in Table 3.1 it has also to be considered, that they are partly expressed in different time and tide systems.

Without going into detail on time systems, it shall be mentioned that the IUGG Resolution No. 2 (1991) recommends that the Geocentric Coordinate Time (TCG) shall be used for the Geodetic Reference System (GRS). In practice, however, all analysis centers for the geometric space techniques use a scale consistent with the Terrestrial Time (TT). As described in the IERS Conventions the relation between both time scales is given by the equation

$$L_{\mathrm{G}} \;=\; 1 - d(\mathrm{TT})/d(\mathrm{TCG}) \;=\; 6.969290134 \cdot 10^{-10} \qquad (3.1)$$

Thus, the difference between both time scales and the corresponding length scales is about 0.7 ppb (parts per billion). Hence the value for the gravitational constant GM depends on the metric (see Table 3.1)

$$GM_{\mathrm{TT}} \;=\; GM_{\mathrm{TCG}}\,(1 - L_{\mathrm{G}})\,. \qquad (3.2)$$

It follows that the TT-compatible value of GM given for the EGM2008 standards is consistent with the TCG-compatible value given for the IERS Conventions 2010 (see Table 1.1 of the IERS Conventions [Petit et al. 2010]).

3.2 Solid Earth tide systems

Concerning the tide system the IAG resolution No. 16 (1983) states that for the uniform treatment of tidal corrections to various geodetic quantities such as gravity and station positions, the indirect effect due to the permanent yielding of the Earth shall not be removed [IAG 1984].

Table 3.1: *Numerical standards given in different sources. The fundamental parameters of [Groten 2004] give the equatorial radius not only in the mean-tide system, but also in the zero-tide and tide-free system (the corresponding values are displayed in brackets). Please note that various factors have to be considered for a comparison of the values (see explanations in this section).*

Quantity	**GRS80 (Moritz 2000)**	**Fundamental Parameters (Groten 2004)**	**IERS2010 (Petit and Luzum, 2010)**	**EGM2008 (Pavlis et al. 2012)**	**Unit**
Gravit. constant (GM)					
– TCG-compatible value	398.6005	398.6004418	398.6004418		$[10^{12}\mathrm{m}^3\mathrm{s}^{-2}]$
– TT-compatible value				398.6004415	
Equatorial radius (a)					
– zero-tide value		(6378136.62)	6378136.6		
– mean-tide value		6378136.7			[m]
– tide-free value	6378137.0	(6378136.59)		6378136.3	
Dyn. form factor (J_2)					
– zero-tide value	1082.63	1082.6359	1082.6359	1082.6361	$[10^{-6}]$
Mean angular rotation velocity (ω)	7.292115	7.292115	7.292115	7.292115	$[10^{-5}\mathrm{rad\ s}^{-1}]$

In the geodetic community the following different tidal systems are in use and have to be distinguished (see [Denker 2013; Mäkinen et al. 2009; Petit et al. 2010]:

- In the *mean-tide system* only the periodic tidal effects are removed from the positions, but the permanent parts (both direct and indirect) are retained.
- The *zero-tide system* is the one recommended by IAG. In this system, the periodic tidal effects and direct permanent effects are removed completely, but the indirect deformation effects associated with the permanent tide deformation are retained.
- In the *tide free system* (or *non-tidal system*), the total tidal effects (periodic and permanent, direct and indirect) have been removed with a model. In this case, the required (unobservable) fluid Love numbers have to be adopted by conventional values.
- The conventional routine for the evaluation of solid Earth tides computes tidal displacements as a sum of a frequency-independent closed form and a series of frequency-dependent corrections. The closed form includes a permanent tide which is wrongly multiplied with the nominal elastic Love number. Since for a long time the reduction of the wrong permanent part was disregarded, a separate tidal system was created which is now called *conventional tide free system.*

For geodetic products different tidal systems are being used. While the gravimetric services provide products mostly in the zero-tide system, in agreement with IAG resolution 16 of the 18^{th} General Assembly 1983, the geometric services provide their products, e.g., the ITRF, in the conventional tide free system. However, the ITRF has adopted, by convention, the same tide system as the technique analysis centers. If the users need another tide system representation, the IERS Conventions provide the necessary conversion formulas in Chapter 7. In applications involving satellite altimetry, the mean-tide system is commonly used.

3.3 Geopotential value W_0

Per definition, W_0 is understood as the value of the gravity potential of the Earth on a particular equipotential surface called *the geoid.* Since the Earth's gravity potential field contains an infinite number of equipotential surfaces, the geoid is to be defined arbitrarily by convention. The usual convention follows the definition given by Gauss [1876] and Listing [1873]: *The geoid is the equipotential surface that best fits (in a least square sense) the undisturbed mean sea level.* As this condition cannot be satisfied due to different causes (like existence of the continents, oceanic currents, atmospheric pressure effects, external gravity forces, etc.) an additional convention about the mean sea level is required. This convention shall consider not only the reductions applied to remove disturbing effects, but also the time span and the location where the sea surface level shall satisfy the Gauss-Listing definition. It can be realized over different time spans at a local tide gauge, or as average from several tide gauges, or over the ocean areas sampled globally [see, e.g., Ekman 1995; Heck 2004; Heck et al. 1990; Mather 1978].

As a reference level for the determination of vertical coordinates, W_0 defines the scale (size) of the reference (zero-height) surface with respect to the Earth's body (i.e., it defines the vertical datum of a height system). As a parameter of the gravity field, W_0 may be required for the transformation between the time scales TCG and TT (see equations 3.1 and 3.3); and it can be introduced as a primary parameter for the definition of a reference mean Earth ellipsoid; i.e., a level ellipsoid that best fits the geoid. Local realizations of W_0 (i.e. $W_0^{(i)}$) are enough for the determination of vertical coordinates referring to a local height system i. For the transformation between TCG and TT and in the case of a worldwide unified vertical reference system, a global estimation of W_0 is required. Usually, this was performed by assuming W_0 equivalent to the normal potential U_0 generated by a mean Earth ellipsoid (like the GRS80). Today, the estimation of a global W_0 is based on the combination of mean sea surface models derived from satellite altimetry observations and the Earth's gravity field modeling derived from space techniques, in particular low Earth orbiting satellites like GRACE, GOCE, and the satellites for laser ranging observations like LAGEOS, ETALON, etc. [e.g., Burša et al. 2007; Dayoub et al. 2012; Sánchez 2012; Sánchez et al. 2014].

At present, there are three different global reference geopotential values (see Table 3.2): the first one corresponds to the normal potential U_0 of the GRS80 ellipsoid [Moritz 2000], the second one is that value included in the IAU standards (and also in the IERS conventions), and the third one is the conventional W_0 value adopted by the IAG as the reference level for the definition and realization of the *International Height Reference System, IHRS* [IAG resolution No. 1, 2015]. The IAU standards [Luzum et al. 2011] and the IERS Conventions 2010 [Petit et al. 2010] include a W_0 value, since the initial definition of the constant L_{G} (see equations 3.1 and 3.2) was given by

$$L_{\mathrm{G}} = W_0/c^2 , \tag{3.3}$$

c beeing the speed of light (cf. IAU recommendation IV, 1991, and IAU resolution B 1.9, 2000). Consequently, after the introduction of the timescales TCG and TT in 1991, L_{G} was recomputed always when a new best estimate for W_0 was available (see Table 3.3). In the IAU General Assembly of 2000, it was decided to declare L_{G} as a defining constant (IAU resolution B1.9, 2000); i.e., it should not change with new estimations of W_0. A W_0 value was maintained as an IAU/IERS standard, although it is not more needed by the IAU or the IERS. As matter of fact, the L_{G} value applied at present by the IAU and the IERS is based on the W_0 value recommended by [Groten 1999] and further mentioned by [Groten 2004]. The primary reference for the computation of that W_0 value is dated in 1998 [Burša et al. 1998]; i.e., it corresponds to the best estimate available in 1998. This value (62 636 856.0 $\mathrm{m^2s^{-2}}$) is usually called the IERS W_0 value, although the IERS did not participate in its determination.

The IAG conventional W_0 value (62 636 853.4 $\mathrm{m^2s^{-2}}$) relies on the newest (as of 2013) gravity field and sea surface models and its computation is supported by detailed conventions considering [see Sánchez et al. 2015]: (1) sensitivity of W_0 to the Earth's gravity field modeling (especially omission and commission errors and time-dependent Earth's gravity field changes); (2) sensitivity of W_0 to the mean sea surface modeling (e.g. geographical coverage, time-dependent sea surface variations, accuracy of the mean sea surface heights); (3) dependence of W_0 on the tide system; and (4) weighted computation based on the input data quality. According to Ihde et al. [2015], W_0 is defined to be time-independent (i.e. quasi-stationary) and it shall remain fixed for a long-term period (e.g. 20 years). However, it has to have a clear relationship with the mean sea surface level as this is the convention for the realization of the geoid. Therefore, a main recommendation after adopting this conventional W_0 value is to monitor the changes of the mean potential value at the sea surface W_S. When large differences appear between W_0 and W_S (e.g. $> \pm 2$ $\mathrm{m^2s^{-2}}$), the adopted W_0 may be replaced by an updated (best estimate) value [Sánchez et al. 2015]. This monitoring shall consider not only sea level changes, but also mass redistribution effects associated to temporal variations of the gravity potential.

3.4 Open problems and recommendations

As outlined in Section 3.1, there are currently different numerical standards in use within the geodetic community. The GRS80 values are still used as official ellipsoid parameters, although they are not truly representing reality anymore. The numerical standards of the IERS Conventions 2010, which are based on the best estimates of [Groten 2004], are commonly used for the processing of the geometric observations and for the generation of IERS products. The fact that the semi-major axis between GRS80 and IERS Conventions 2010 differs by 0.4 m is critical and has to be considered correctly for users of geodetic products. Moreover, different standards are used within the gravity community, and they are also partly different from the numerical standards given in the IERS Conventions.

Table 3.2: *Global reference geopotential values.*

W_0 **[m^{2}s^{-2}]**	**Comments**	**References**
62 636 860.850	GRS80 ($W_0 = U_0$)	[Moritz 2000]
62 636 856.0	IERS Conventions 2010 (best W_0 estimate in 1998), Topex/Poseidon (1993–1996), EGM 96	[Petit et al. 2010]
62 636 853.4	Conventional IAG value (best W_0 estimate in 2015, mean sea surface (1993–2013) from multi-mission cross-calibration of several satellite altimeters, and gravity field modeling based on SLR, GRACE, and GOCE data	[Sánchez et al. 2015]

Table 3.3: *Values of the constant L_G according to new best estimates of W_0. In 2000 L_G was declared to be a defining constant.*

Year	W_0 **[m^{2}s^{-2}]**	L_G
1991	$62\,636\,860 \pm 30$ [Chovitz 1988]	$6.969\,291 \cdot 10^{-10} \pm 3 \cdot 10^{-16}$ (IAU recommendation IV, note 6, 1991)
1992	$62\,636\,856.5 \pm 3$ [Burša et al. 1992]	$6.969\,290\,19 \cdot 10^{-10} \pm 3 \cdot 10^{-17}$ [Fukushima 1995]
1995	$62\,636\,856.85 \pm 1$ [Burša 1995]	$6.969\,290\,3 \cdot 10^{-10} \pm 1 \cdot 10^{-17}$ [McCarthy 1996, Tab. 4.1]
1999	$62\,636\,856.0 \pm 0.5$ [Groten 1999]	$6.969\,290\,134 \cdot 10^{-10}$ (as defining constant) (IAU resolution B1.9, 2000)

The current situation concerning numerical standards and the different use of time and tide systems is a potential source for inconsistencies and even errors of geodetic products. Thus, it is essential for a correct interpretation and use of geodetic results and products that the underlying numerical standards be clearly documented. Moreover, if geodetic results are combined that are expressed in different time or tide systems, transformations have to be performed to get consistent results.

Another issue concerning time systems was brought up by J. Gipson during the last GGOS Unified Analysis Workshop in Pasadena (June 2014). At present, different space techniques and sometimes also different groups working within the same technique have different time systems, for example GPS time vs. UTC. The offset between the different systems does not affect the comparison of most geodetic parameters. However if the parameter is rapidly varying, such as ΔUT1, then it is important that the comparisons are done at the same epoch. Thus it is recommended at a minimum that all scientists are clear and explicit about what time-tags they are using. In a perfect world the same time-tags should be used by everyone.

Concerning the tide systems the foundations of the IAG Resolution No. 16 (1983) are still valid. The recommended zero tide system is the most adequate system for gravity acceleration and gravity potential of the rotating and deforming Earth. However, for the terrestrial reference system parameters the conventional tide free concept is used for decades, although the tide free crust is far away from the real Earth shape and it is unobservable. In the past, there have been several discussions on the tide system for the terrestrial reference frame. Due to practical reasons it was decided that it shall not be changed. But even if this conventional tide free concept is kept also in the future, the zero tide system shall be used for gravity and geopotential.

The IAG resolution No. 1 (2015) provides the basic conventions for the definition of an *International Height Reference System (IHRS)*, being the IAG conventional W_0 value a fundamental parameter. The IAG conventional W_0 value and the so-called IERS W_0 value differ by -2.6 m^{2}s^{-2}, corresponding to a level difference of about 27 cm. To avoid confusion among users of geodetic products, it is necessary to present only one W_0 global reference value. It is clear that the relationship between TCG and TT does not depend anymore on the geoid definition, since L_G was declared as a defining constant. However, it is desirable that the IAU Standards and the IERS Conventions include the IAG conventional W_0 value instead of the 1998 value recommended by [Groten 1999, 2004]. The main implication of a new W_0 value for the IAU/IERS timescales is related to the accuracy in the realization of the *International Atomic Time (TAI)*. It presently corresponds to *a coordinate timescale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit*. Therefore, TAI still has a reference to the geoid (W_0), while TT does not have it anymore. This is a potential source of inconsistency because it is usually considered that TAI is a realization of TT. However, a redefinition of the TAI scale considering the IAG conventional W_0 value will be required when the clock accuracy (i.e. timescale accuracy) reaches about $7 \cdot 10^{-17}$ to $9 \cdot 10^{-17}$. The best possible accuracy today is about $2 \cdot 10^{-16}$, which corresponds to a potential difference accuracy of about $20\,\mathrm{m}^2\mathrm{s}^{-2}$; i.e., ten times larger than the difference between the IAG conventional W_0 value and the IERS W_0 value [Petit, 2015, pers. communication]. In any case, the reformulation of the TAI definition is under the responsibility of the General Conference of Weights and Measures through the Consultative Committee on Time and Frequency.

In the future, the development of a new Geodetic Reference System based on a consistent system of best estimates of major parameters related to a geocentric level ellipsoid shall be considered. This should involve the collection of best estimates including uncertainties and a documentation of the parameter estimation, and the computation of derived parameters. According to its Terms of Reference, the BPS shall take the responsibility for this task involving all experts in the field.

Summary of recommendations on numerical standards:

Recommendation 0.1 : The used numerical standards including time and tide systems must be clearly documented for all geodetic products.

Recommendation 0.2 : Astronomical, geodetic or geophysical standards including or requiring a W_0 reference value should adopt the IAG conventional W_0 value issued by the IAG resolution No. 1 (2015), i.e. $W_0 = 62\,636\,853.4\,\mathrm{m}^2\mathrm{s}^{-2}$.

Recommendation 0.3 : A new Geodetic Reference System GRS20XX based on a consistent estimation of best estimates of the major parameters related to a geocentric level ellipsoid should be developed.

4 Product-based review of standards and conventions

This chapter focuses on the assessment of the standards and conventions currently adopted and used by IAG and its components for the generation of IAG products. With the compilation of such a *product-based inventory*, the BPS supports GGOS in its goal to obtain consistent geodetic products and it provides also a fundamental basis for the integration of geometric and gravimetric parameters, and for the development of new products.

GGOS as an organization is built on the existing IAG Services, and under this "*unifying umbrella*", all the products provided by the different IAG Services are considered GGOS products. This declaration and also Section 7.5 "*Products available through GGOS*" from the GGOS publication [Plag et al. 2009] serve as the basis to specify the major products of IAG and GGOS, addressing the following topics:

Section 4.1	Celestial reference systems and frames,
Section 4.2	Terrestrial reference systems and frames,
Section 4.3	Earth orientation parameters,
Section 4.4	GNSS satellite orbits,
Section 4.5	Gravity and geoid,
Section 4.6	Height systems and their realizations.

The sections for each of these products (or topics) were organized in a similar structure. The first part gives a brief overview, followed by a description and discussion of the present status, and finally open issues are identified and recommendations are provided. Despite of this similar structure, the character of these sections is partly different as a consequence of the current situation regarding the availability of IAG products in the different fields and organizational issues of the IAG Services. IAG products exist for the celestial and terrestrial reference frame (Sections 4.1 and 4.2) as well as for the EOP (Section 4.3) which are provided by the responsible Product Centers of the IERS. The GNSS satellite orbits addressed in Section 4.4 are provided by the IGS. This technique-specific product was included in the inventory, since the GNSS orbits are used for a wide range of applications. For the gravity field and geoid (Section 4.5) as well as for the height systems and their realizations (Section 4.6), official IAG products still need to be defined and implemented. Due to this fact the character of these two corresponding sections differs from the others.

It should also be noted, that this list of topics and IAG products is by far not complete and it can be extended by adding other products in an updated version of this document. Furthermore, the ongoing GGOS activities towards the development of integrated products will have to be considered in a future version of such an inventory.

4.1 Celestial reference systems and frames

4.1.1 Overview

By the nature of this topic, the IAU has always been responsible for celestial reference systems and celestial reference frames. However, in the course of technological development many more organizations and working groups have been involved in the more recent past where observations in the radio frequency regime have superseded optical observations. Due to its dominating volume of observations, the International VLBI Service for Geodesy and Astrometry (IVS) [Schuh et al. 2012] was the key supplier of observations and analysis capability in the recent past. The IVS was established in 1999 as an international collaboration of organizations operating or supporting VLBI components to support geodetic and astrometric work on reference systems and Earth science research by operational activities. Due to the basics of its technique, the IVS is a joint service of IAG and IAU. On the IAG side, the IVS represents the VLBI technique in GGOS and interacts closely with the IERS, which is tasked by IAU and IUGG with maintaining the ICRF and ITRF, respectively.

As a result of this organizational structure, the IAG, through IVS, has an indirect responsibility for the celestial reference frame at radio frequencies. The VLBI data provide the direct link between the celestial and the terrestrial reference frame, and, at the same time, determines the Earth orientation parameters. Since the consistency between both frames is an important issue that should be addressed by the scientific community (see IUGG Resolution No. 3, 2011), the topic is subject of this inventory.

The IAU resolution No. B2 from the IAU General Assembly in 1997 resolved (a) that as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on reference frames and as defined by the IERS [Arias et al. 1995]; (b) that the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on reference frames; (c) that the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths; and (d) that the IERS shall take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths. According to this IAU resolution, the ICRS has been realized by the ICRF since January 1, 1998, which is based on the radio wavelength astrometric positions of compact extragalactic objects determined by VLBI.

The IERS has been charged with the responsibility of monitoring the ICRS, maintaining its realization, the ICRF, and improving the links with other celestial reference frames. Since 2001, these activities have been run jointly by the ICRS Center (at the Observatoire de Paris and the US Naval Observatory) of the IERS and the IVS, in conjunction with IAU (see e.g., IERS Annual Report 2010 [Souchay et al. 2013]).

4.1.2 International Celestial Reference System

Following the IAU Resolution B2 (1997), the ICRS replaced the Fifth Fundamental Star Catalogue (FK5) as the fundamental celestial reference system for astronomical applications. The ICRS is an idealized Barycentric Celestial Reference System (BCRS), with its axes kinematically non-rotating with respect to the distant objects in the universe [Petit et al. 2010]. These axes are defined implicitly through the set of coordinates of extragalactic objects, mostly quasars, BL Lac sources and a few Active Galactic Nuclei (AGN), as determined in the most precise realization of the ICRS, the ICRF (for more information see [Petit et al. 2010]).

The recommendations of the IAU Resolution A4 (1991) specify that the origin of the ICRF is to be at the barycenter of the solar system and the directions of its axes should be fixed with respect to the quasars. It is further recommended that the celestial reference system has its principal plane as close as possible to the mean equator at J2000.0 and the origin of this principal plane was close as possible to the dynamic equinox of J2000.0. The VLBI observations used to establish the extragalactic reference frame are used to monitor the motion of the celestial pole in space. In this way, the VLBI analyses provide corrections to the conventional IAU models for precession and nutation (see Section 4.3).

4.1.3 International Celestial Reference Frames

4.1.3.1 History of ICRS realizations

The initial realization of the IERS Celestial Reference System, RSC(IERS) 88 C01 [Arias et al. 1988] contained 228 extragalactic radio sources in total. This first catalogue was computed by combining the VLBI solutions of three US agencies (Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL) and National Geodetic Survey (NGS)). In the adjustment process the right ascension of the source 3C273B was fixed to its conventional FK5 value [Hazard et al. 1971]. 23 out of the 228 radio sources were chosen to define the axes directions of this first frame. This initial realization can be considered as the intangible basis of the celestial frame, since all subsequent realizations directly or indirectly refer to this initial set of coordinate axes. Between 1988 and 1994, several celestial reference frames were determined on a regular basis following the first one, all of which were referred to the respective previous realization of ICRS by No Net Rotation (NNR) constraints.

As specified in the IAU Resolution No. 2 (1997), the ICRF, i.e. the first realization of the ICRS, is based on the positions of extragalactic objects measured by VLBI. Adopted by the IAU Working Group on Reference Frames (WGRF), it was determined by the VLBI solution of the GSFC at National Aeronautics and Space Administration (NASA) [Ma et al. 1998, 1997]. The catalogue provides the positions and uncertainties of 608 radio sources, including 212 defining sources used for the global NNR condition, to realize the axes of the ICRF [Arias et al. 1990] with respect to previous IERS celestial reference frames [Arias et al. 1991; Ma et al. 1997].

There were two extensions of ICRF: ICRF-Ext. 1 [Gambis 1999] and ICRF-Ext. 2 [Fey et al. 2004]. For both extensions the original ICRF positions of the defining sources remained unchanged, thus preserving the initial ICRF orientation fixed.

4.1.3.2 The current realization, the ICRF2

Within the common IAU/IVS Working Group entitled "*The Second Realization of the International Celestial Reference Frame – ICRF2*" a new version of ICRF has been computed [Fey et al. 2009, 2015], which was accepted by the IAU at its General Assembly in Rio de Janeiro, Brazil, in August 2009 (see IAU Resolution No. B3, 2009) and by IUGG Resolution No. 3 (2011). It contains the positions of 3414 compact radio sources, including a selected set of 295 defining sources. The stability of the axes is approximately 10 μas, making ICRF2 nearly twice as stable as its predecessor, also accompanied by an improved noise level of about 40 μas and a more uniform sky distribution including more defining sources on the southern hemisphere.

The overall characteristics of the ICRF2 solution are described in [Fey et al. 2009, 2015]. The a-priori models for geophysical effects and precession/nutation used for the ICRF2 computations generally followed the IERS Conventions 2003 [McCarthy et al. 2003]. Specifically, corrections for solid Earth tides, the pole tide, ocean loading, and high frequency EOP variations were made using the IERS Conventions 2003. Other important effects were modeled using

- Atmosphere pressure loading corrections according to Petrov et al. [2004],
- The Vienna Mapping Function (VMF1) troposphere model of Böhm, Werl, et al. [2006],
- The antenna thermal deformation model of Nothnagel [2009],
- A-priori gradients model according to MacMillan et al. [1997].

4.1.3.3 Recent and future developments

Recently, the IAU Division A Working Group entitled "*Third Realization of the International Celestial Reference Frame (shortly ICRF 3)*" has been formed. The aim of the IAU WG is to compute and present the next ICRF3 to the IAU General Assembly in 2018. The developments are supported by the IAG Sub-Commission 1.4 "*Interaction of Celestial and Terrestrial Reference Frames*". Improvements are foreseen by the inclusion of observations at higher radio frequencies and a possible radio-optical link with ESA's optical astrometry mission Gaia.

4.1.4 Discussion of the present status

4.1.4.1 General issues

The organizational structure regarding the definition and realization of the celestial reference system is rather complex. Quite a large number of organizations, services and other entities are involved. Although the responsibilities for the definition of the ICRS and the maintenance of the ICRF are resolved in the IAU resolutions (see Sections 1.2.4 and 4.1.1), the complex structure in this field requires an efficient and regular exchange of information to ensure effectiveness of the work.

4.1.4.2 ICRS definition and its realization

The definition and realization of the ICRS are given in the IERS Conventions [Petit et al. 2010] on the basis of several IAU resolutions. The IAU Resolution A4 (recommendation VII, 1991) recommends under (1) "*that the prinicipal plane of the new conventional celestial reference frame be as near as possible to the mean equator at J2000.0 and that the origin of the principal plane be as near as possible to the dynamical equinox of J2000.0*". These rather imprecise definitions result from the fact that old realizations were usually not as precise as the current conventional definition. A series of ICRS realizations has been computed so far, and in each of those the datum has been defined with respect to the previous realization by applying NNR conditions. But this is depending on the quality, number and distribution of the defining radio-sources used in the NNR condition. By applying this procedure, inconsistencies of the predecessor can affect the reference frame definition (mainly the orientation) of new (more precise) frames.

4.1.4.3 ICRF computations

Both, ICRF and ICRF2, have been computed by only one IVS Analysis Center using a single software package and thus, this individual solution is not controlled through a combination process of several software packages and combination strategies. Currently, formal errors of the ICRF determined by VLBI are probably too optimistic since they do not take into account uncertainties of a number of technique-specific parameters. Examples are antenna axis offsets, thermal expansion modeling, influences of uncertain technique-specific model components and source structure effects. Moreover, the imbalance of VLBI observatories on the northern and the southern hemisphere is not quantified at all.

4.1.4.4 Consistent estimation of the ICRF, ITRF and EOP

The IUGG Resolution No. 3 (2011) recommends, that the highest consistency between the ICRF, the ITRF and the EOP as observed and realized by IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS. At present, both frames (the ICRF and ITRF) and their integral EOP solutions are not fully consistent with each other as they are computed independently by separate IERS Product Centers. Although the IUGG recommendation has not been fulfilled yet, studies in this direction have been initiated, e.g. DGFI has performed a simultaneous estimation of CRF, TRF and EOP series [M. Seitz et al. 2014].

On the international level, this topic is addressed by the IAU Working Group "*ICRF 3*" and by the IAG Sub-Commission 1.4 "*Interaction of celestial and terrestrial reference frames*". This topic was also addressed at the IERS Retreat in Paris 2013 (see `www.iers.org/IERS/EN/Organization/Workshops/Retreat2003.html`). The recommendations of this IERS Retreat provide some relevant questions related to this issue (see Section 4.1.6).

4.1.5 Interaction with other products

Through the VLBI observations there is a direct link of the celestial reference frame with

- Terrestrial reference frames and
- Earth orientation parameters.

The interactions of the ICRF with the ITRF and EOP also provide indirect links to the dynamic reference frames of satellite orbits and to other parameters, which are derived from the mentioned products.

4.1.6 Open problems and recommendations

4.1.6.1 General issue on ICRS/ICRF

As a consequence of the complex organizational interactions, the current ICRF has to be considered a joint IAU/IAG product. Therefore, this product is part of this inventory. It helps to address important scientific questions, like the consistency between the celestial and terrestrial frame. Moreover, the objectives and goals of GGOS require not only an Earth-fixed frame, but also the link to an inertial frame and the interactions between both described by the EOP. The responsible organizations are asked to clarify in which way the ICRS/ICRF may be labeled a GGOS product.

4.1.6.2 ICRF computations

It remains to be considered whether the next ICRS realization shall be estimated from a combination of different analysis center solutions computed with different software packages to ensure redundancy and a reliable quality control of the final product. The precision of the coordinates of radio sources forming the ICRF steadily gets better due to more accurate observations and improved analysis methods. Therefore, it shall be investigated if source position instabilities must be included.

4.1.6.3 Consistency of ICRF, ITRF and EOP

Important questions taken from the recommendations of the IERS Retreat 2013 are: (1) How consistent is the ICRF with the ITRF and EOP? (2) Is the ICRF decoupled enough from the ITRF so that radio sources do not need to be included in the ITRF computations and vice versa? (3) What is the gain if ICRF, ITRF and EOP are estimated in a common adjustment? It is recommended that these questions should be addressed to the IAU WG "*ICRF 3*" and to the IAG Sub-Commission 1.4 "*Interaction of celestial and terrestrial reference frames*". Moreover groups that can do these studies are encouraged to contribute.

Summary of recommendations on ICRS/ICRF:

Recommendation 1.1 : The responsible organizations are asked to clarify in which way the ICRS/ICRF may be labeled a GGOS product.

Recommendation 1.2 : It should be considered by the organizations and their responsible working groups, whether the next ICRS realization, the ICRF3, should be estimated from a combination of different analysis center solutions, as well as of different observing frequencies.

Recommendation 1.3 : Research groups are encouraged to perform the previously mentioned studies regarding the consistency of ICRF, ITRF and EOP.

4.2 Terrestrial reference systems and frames

4.2.1 Overview

A Terrestrial Reference System (TRS), also denoted as Earth-fixed global reference system, is a spatial reference system co-rotating with the Earth, in which points at the solid Earth's surface undergo only small variations with time. These variations are mainly due to geophysical effects caused by various dynamic processes and forces from external bodies. In the nomenclature, we distinguish between a *reference system*, which is based on theoretical considerations and conventions, and its realization, which is called the *reference frame* (see, e.g., [Kovalevsky et al. 1989], IERS Conventions 2010 [Petit et al. 2010]).

Terrestrial reference frames (TRF) are needed to refer the geodetic observations and estimated parameters to a unique global basis. High accuracy, consistency and long-term stability is required for precisely monitoring global change phenomena as well as for precise positioning applications on and near the Earth's surface.

The importance of geodetic reference frames for many societal and economic benefit areas has been recognized by the United Nations too. In February 2015, the UN General Assembly adopted its first geospatial resolution *"A Global Geodetic Reference Frame for Sustainable Development"* (see `www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/69/266` and `www.unggrf.org/`).

The ITRS has been formally adopted and recommended for Earth science applications [IUGG 2007]. The IERS is in charge of defining, realizing and promoting the ITRS. Definition, realization and promotion of the ITRS is the responsibility of the IERS. The regularly updated IERS Conventions (latest version [Petit et al. 2010]) serve as the necessary basis for the mathematical representation of geometric and physical quantities.

The International Terrestrial Reference Frame (ITRF) is a realization of the ITRS, consisting of three-dimensional positions and time variations (e.g., constant velocities) of IERS network stations observed by space geodetic techniques. Currently the contributing space techniques are VLBI, SLR, GNSS and DORIS.

Realizations of the ITRS are published by the ITRS Center hosted at the Institut National de l'Information Géographique et Forestiere, France (IGN). Within the re-organised IERS structure (since 2001), the ITRS Center (formally called ITRS Terrestrial Reference Frame Section) is supplemented by ITRS Combination Centers which were included as additional IERS components to ensure redundancy for ITRF computations and to allow for a decisive validation and quality control of the combination results. ITRS Combination Centers are established at DGFI, IGN, and since 2012 at the JPL in Pasadena (USA).

Until now, twelve releases of the ITRF were published by the IERS, starting with ITRF 88 and ending with ITRF 2008, each of which superseded its predecessor (see Chapter 4 of the IERS Conventions 2010, [Petit et al. 2010]). An updating of ITRS realizations was performed every few years, since the tracking networks of space techniques are evolving, the period of data extends, and also the modeling and data analysis strategies as well as the combination methods were improved with time. Furthermore, large earthquakes can affect station positions and velocities over large regions. Up to ITRF 2000, long-term global solutions (comprising station positions and velocities) from four techniques (VLBI, SLR, GNSS and DORIS) were used as input for the ITRF generation. Starting with ITRF 2005, the ITRF computations were based on time series of station positions and EOP including variance-covariance information from each of the techniques' combination centers.

The next section provides a brief summary about the current ITRS realization, the ITRF 2008. Please note, at the time when this document was prepared for publication in the IAG's geodesists handbook (status: January 15, 2016), the computations for the ITRF 2014 were almost finalized. It is expected that the ITRF 2014 will be released by the ITRS Center early 2016 and it will then replace the ITRF 2008.

4.2.2 The current ITRS realization, the ITRF 2008

The ITRF 2008 is the current realization of the ITRS based on reprocessed solutions of the four space techniques VLBI, SLR, GNSS and DORIS [Altamimi et al. 2011]. The input data used for its elaboration are time series of station positions and daily EOP. The data were reprocessed by several individual analysis centers for the different space techniques according to the specifications given in the ITRF 2008 call for participation. It was specified that the input data shall conform to the IERS Conventions 2003 (the up-to-date version at that time) [McCarthy et al. 2003]. The individual time series were combined per-technique by the four responsible technique-specific combination centers, namely the National Ressources Canada (NRCan) for the IGS [Ferland 2010; Ferland et al. 2008], the IGG of the University Bonn, Germany, for the IVS [Böckmann et al. 2010], the Agenzia Spaziale Italiana (ASI) for the ILRS [Bianco et al. 2000; E. Pavlis et al. 2010] and the Collecte Localisation par Satellite (CLS) in cooperation with the Center National d'Etudes Spatiales (CNES), France, and GSFC at NASA, USA, for the IDS [Valette et al. 2010]. A summary of the input files is given on the ITRF web site: `http://itrf.ensg.ign.fr/ITRF_solutions/2008/input_data.php`.

Table 4.1 summarizes the major characteristics of the ITRF 2008 input data. We should recall that the ITRF 2008 input data are resulting from an intra-technique combination of individual solutions provided by 11 ACs in the case of GNSS and 7 ACs for the other techniques. To ensure consistency of the ITRF 2008 input data, all contributing ACs are supposed to use common processing standards and models for the data analysis.

Two solutions were computed by the ITRS Combination Centers at IGN and DGFI. The method of the

Table 4.1: *Input data sets for ITRF 2008 (TC: Techniques' Combination Center, NEQ: constraint-free normal equation, AC: Analysis Center). In addition also geodetic local tie information is used as input for the ITRF computations.*

Technique	Service / TC	# ACs per technique	Data	Time period
GNSS	IGS/NRCan	11	Weekly solutions	1997.0 – 2009.0
VLBI	IVS/IGG	7	24 h session NEQ	1980.0 – 2009.0
SLR	ILRS/ASI	7	14/7 day solutions	1983.0 – 2009.0
DORIS	IDS/CLS-CNES-GSFC	7	Weekly solutions	1993.0 – 2009.0

IGN works on the solution level by a simultaneous estimation of similarity transformation parameters with respect to the combined frame along with the adjustment of station positions, velocities and EOP [Altamimi et al. 2011]. The strategy applied at DGFI is based on the normal equation level. The station positions, velocities and EOP are estimated in a common adjustment [Angermann et al. 2009; M. Seitz et al. 2012]. Despite some differences between both strategies, the general procedure for the ITRF 2008 computation is very similar.

The procedure is based on two main steps:

- The accumulation (stacking) of the time series per technique to generate technique-specific solutions or normal equations.
- The combination of the per-technique solutions or normal equations.

The ITRF 2008 solution computed at IGN was released by the ITRS Center as the official ITRF2008 [Altamimi et al. 2011]. All ITRF 2008 data files and results are available at the ITRF web site `itrf.ign.fr/ITRF_solutions/2008/`.

The ITRF 2008 solution computed at DGFI is labelled as DTRF 2008 [M. Seitz et al. 2012]. This solution is available at the anonymous ftp server of DGFI `ftp.dgfi.tum.de/pub/DTRF2008`.

A comparison between the DTRF 2008 and ITRF 2008 has been performed by DGFI to quantify the difference between these two realizations [M. Seitz et al. 2012, 2013]. The comparisons were done technique-wise by performing similarity transformations in order to investigate the level of agreement for the datum parameters as well as for the station positions and velocities. With respect to the datum parameters, the two realizations show an overall agreement in the order of 5–6 mm. The RMS differences for the station positions and velocities are given in Table 4.2. However, the results of this comparison do not fully reflect the overall accuracy of the terrestrial reference frame, since both realizations are based on identical input data and the impact of various effects (e.g., non-linear station motions) is not considered. The current ITRF results indicate that the GGOS requirements are not achieved yet. According to [Plag et al. 2009] the terrestrial reference frame should to be accurate at a level of 1 mm and to be stable with time at a level of 0.1 mm/yr.

The topic of an external evaluation of the terrestrial reference frames is mainly studied within a specific Working Group of IAG Sub-Commission 1.2, the WG 1.2.1 "*External Evaluation of Terrestrial Reference Frames*" [Collilieux et al. 2014]. The aim of this task force is to review all methods that allow evaluating the accuracy of a TRF. Methods that involve data sets that have not been used in the TRF computation will be especially emphasized (e.g., tide gauges, gravity, geophysical models).

4.2.3 Discussion of the present status

4.2.3.1 ITRS definition vs. its realization

According to the IERS Conventions [Petit et al. 2010] the ITRS definition fulfils the following principles:

- It is geocentric, the center of mass being defined for the whole Earth, including oceans and atmosphere;
- The unit 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;

Table 4.2: *RMS values of the similarity transformation between DTRF 2008 and ITRF 2008 at the reference epoch 2005.0.*

Technique	positions [mm]	velocities [mm/yr]
GNSS	1.33	0.19
VLBI	0.38	0.09
SLR	2.02	0.82
DORIS	3.22	0.98

- Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation of the BIH Terrestrial System (BTS) at epoch 1984.0;
- The time evolution of the orientation is realized by using a no net rotation (NNR) condition with regard to horizontal tectonic motions over the whole Earth.

In the following we compare the ITRS definition with its realization:

Origin: The ITRF origin is realized by SLR observations. Through the orbit dynamics SLR determines the Center of Mass (CM). According to the IERS Conventions 2010 [Petit et al. 2010] the ITRF origin should be considered as the mean Earth center of mass, averaged over the time span of SLR observations used and modeled as a secular (linear) function in time. It can be regarded as a *crust-based* TRF with the origin realized as a mean CM [Blewitt 2003; Dong et al. 2003; Petit et al. 2010; X. Wu et al. 2015]. In a truly *CM-based* frame, the SLR origin coincides with CM not only in mean but at any epoch, if the station coordinates and the satellite orbits are adjusted together and if the first degree gravity field coefficients are fixed to zero. However, accessible for the user are at present only mean (linear) geocentric station coordinates due to the linear ITRF station motion model. If an instantaneous geocentric position is required, it is recommended in the IERS Conventions [Petit et al. 2010] (see Section 4.2.5) to substract the so-called geocenter motion (i.e. the *vector from the crust-based ITRF origin to the instanteneous center of mass*) from the ITRF position vector. However, the expression "*geocenter motion*" is defined differently in the geodetic literature [e.g., Dong et al. 2003], and moreover a commonly accepted model available to account for this effect is not available yet. Although SLR is the most precise observation technique to realize the ITRS origin, it has to be considered that the SLR results may be affected by the so-called *network effect* due to a relatively sparse network and due to the blue-sky effect if atmospheric loading is not considered [Collilieux et al. 2009].

Scale: The ITRS scale is specified to be consistent with the TCG time coordinate (IAU and IUGG resolutions, 1991), whereas its realization is consistent with the terrestrial time (TT). The difference between both time scales is about $0.7 \cdot 10^{-9}$ (see Section 3.1), equivalent to a height difference of 4.5 mm at the surface of the Earth. The ITRS scale is realized by SLR and VLBI observations and similar as for the origin the results are affected by relatively sparse networks. As a result of the ITRF2008 combinations, IGN found a scale difference between VLBI and SLR of 1.05 ppb at epoch 2005.0 [Altamimi et al. 2011]. This result could not be confirmed by the DTRF2008 computations of DGFI [M. Seitz et al. 2012], that resulted in a scale difference between 0.09 and 0.55 ppb. The authors argued that this uncertainty mainly arises from the sensitivity of the scale realization with respect to the handling of the local ties.

Orientation and its time evolution: The orientation of the coordinate axes of the reference frame could, theoretically, also be defined by the Earth's gravity field, namely the second degree spherical harmonic coefficients which are related to the orientation of the principal axes of inertia. This definition of the orientation is not used in practice because its determination is not as precise as for the origin, and the satellite orbits are not so sensitive with respect to its variations. Instead, these reference frame parameters are realized by external NNR conditions. This is done by successive transformations with respect to the previous ITRF realization. Thus, its realization depends on the network geometries and the stations used for the definition, including the weighting. The orientation rate of the ITRF2000 was aligned to that of the geological model NNR-NUVEL-1A [Argus et al. 1991; DeMets et al. 1990, 1994], which is also the reference for the succeeding realizations, i.e., the ITRF2005 and ITRF2008. As deformation zones are neglected in the geological model and plate motions are averaged over long time periods (up to 1 Myr), there are differences with respect to present-day motions (see next paragraph).

Various studies have been performed on the NNR reference frame and its implication for the ITRF [Altamimi et al. 2012; Argus et al. 2011; DeMets et al. 2010; Drewes 2009; Kreemer et al. 2006]. As an example, Figure 4.1 shows the discrepancies between the Actual Plate KInematic Model (APKIM) [Drewes 2009] and the geophysical NNR-NUVEL-1A model. The station velocities differ with a rate of 1.1 mm/yr around a rotation pole with a latitude of about −60° and a longitude of about 120° [Drewes 2012] and the differences show a systematic pattern. However, their size is in the same order of magnitude as the discrepancies between different models that are presently available [Altamimi et al. 2012].

Some notes on the definition of the kinematic frame: The NNR frames mentioned above are a useful geodetic construct but not that useful for geophysical considerations because it is clear that the plates rotate relative to the mantle and geophysical models (Earth rotation, Glacial Isostatic Adjustment (GIA), etc.) are mostly based on mean-mantle frames. Various studies have been performed to define "absolute" plate motions

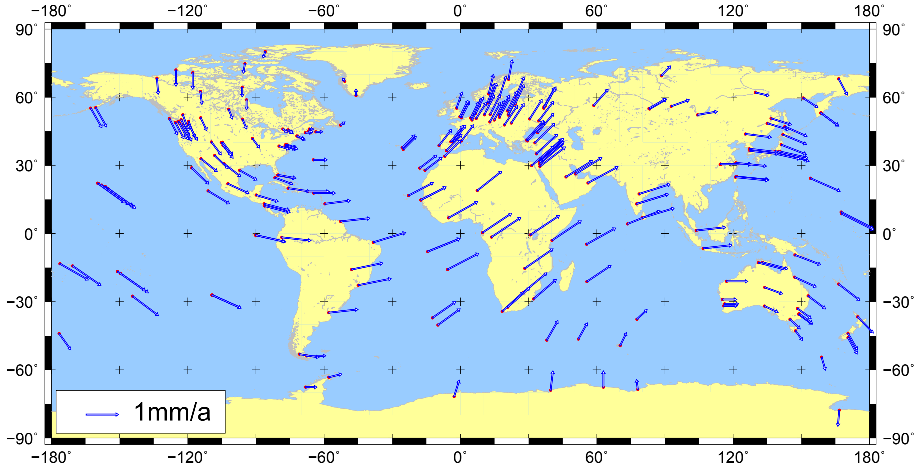


Fig. 4.1: *Differences of horizontal station velocities between APKIM 2005 and NNR-NUVEL-1A model.*

with respect to the Earth's mantle by moving hot spots [e.g., Doubrovine et al. 2012; Torsvik et al. 2008, 2010]. The results published by Doubrovine et al. [2012] provide a net lithosphere rotation with respect to the mantle described by a rotation pole at latitude −41.36°, longitude 65.89° with a rate of 0.185°/Myr, which is slightly higher than those of Torsvik et al. [2008, 2010] (0.165°/Myr and 0.14°/Myr, respectively). The published velocity vectors will have rates at the level of about 15 to 20 mm/yr. For example, if the secular drift of the pole is to be interpreted, a mantle fixed frame is the appropriate one to compare to GIA models. The observed drift of the pole is about 0.9°/Myr, and thus the contribution from the difference between the NNR and mantle fixed frame is not negligible.

4.2.3.2 Modelling of station positions and displacements

The instantaneous position of a station $X(t)$, which is fixed to the Earth's crust, is defined in Chapter 4 of the IERS Conventions 2010 [Petit et al. 2010] as the sum of a regularized station position $X_R(t)$ and conventional corrections $\sum_n \Delta X_n(t)$,

$$X\,(t) \;=\; X_R\,(t) \;+\; \sum_n \Delta X_n(t)\,. \tag{4.1}$$

In the conventional secular approach, the regularized station position itself is parameterized by a linear model describing the position at any epoch t_i by the position at the reference epoch t_0 plus a constant velocity multiplied by the time difference $(t_i - t_0)$

$$X_R(t_i) \;=\; X_R(t_0) \;+\; \dot{X}(t_0)\cdot(t_i - t_0). \tag{4.2}$$

Taking into account today's high accuracy of the space geodetic observations, non-linear station motions caused by various geohysical phenomena (e.g., postseismic deformations, volcanic activities, atmospheric or hydrological loading effects) become significant [e.g., Bevis et al. 2014; Blossfeld et al. 2014; X. Wu et al. 2015]. Below we discuss the consequences of the conventional linear approach in the context with non-linear station motions:

- The displacements of reference markers on the crust are modeled by conventional correction models (4.1), considering the effects on stations due to solid Earth tides, ocean loading, rotational deformation due to polar motion and ocean pole tide loading [Petit et al. 2010]. Even if these various effects are conventionally modeled, one has to keep in mind that model uncertainties, and possible model errors could affect the corrections of the instantaneous station position. Geophysical effects that are not considered in the conventional corrections will become visible as residuals in the position time series.
- For the non-conventional displacements due to e.g. non-tidal atmospheric or hydrological environmental loads, the IERS Conventions 2010 do not recommend any correction model at the moment (e.g. due to the fact that the current models are not accurate enough). Various investigations [e.g., van Dam et al. 2012; Davis et al. 2012] have shown that periodic variations in the time series of station positions with amplitudes up to several centimeters are caused by neglected corrections such as surface loading. As an example Figure 4.2 shows the time series of the *residual* non-linear station motions for GNSS station Irkutsk (Russia) in comparison with the loading signal. In case of SLR solutions, atmospheric loading can even cause a bias due to the so-called *blue-sky effect* [Sośnica et al. 2013].

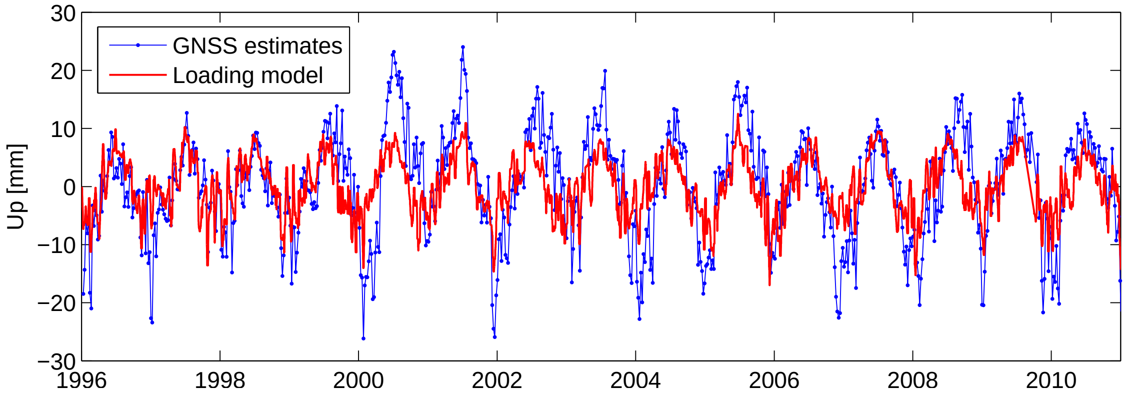


Fig. 4.2: *Time series of GNSS height estimations for station Irkutsk, Russia. The atmospheric pressure loading time series provided by the Goddard VLBI group were used (see* `gemini.gsfc.nasa.gov/aplo`*; [Petrov et al. 2004]).*

- Other issues are non-linear station motions caused by post-seismic behaviour after an earthquake [e.g., Freymueller 2010; Sánchez et al. 2013], which are currently modeled by piece-wise linear functions (*segments*) with positions and constant velocites. Besides the mentioned geophysical phenomena, also anthropogenic effects like, e.g. yearly groundwater withdrawal [Bawden et al. 2001] may affect ITRF stations in some regions.

  Other possibilities are modeling discrepancies of the technique-dependent internal reference points, such as GNSS phase center offsets and variation models for satellites and stations [Schmid et al. 2009] and corrections for radio antenna thermal deformations [Nothnagel 2009].
- It should be noted that in the upcoming ITRF2014 realization non-tidal loading signals derived from geophysical models will be considered and an extended parameterization has been implemented for the station motions.

Below some ongoing studies and research activities concerning the modeling of station motions and the handling of non-linear effects are shortly summarized:

Improved geophysical modeling: The Joint Working Group (JWG) 1.2 of the IAG and the IERS "*Modeling environmental loading effects for reference frame realizations*" investigates approaches to model the remaining effects (e.g., atmospheric and hydrological loading) and to validate the results.

New parameterization: Additionally to the current linear model, parameters of trigonometric functions or splines can be estimated to account for the observed seasonal station position variations. For a better description of post-seismic displacements a new parameterization is needed (e.g., logarithmic post-seismic functions).

Combined epoch solutions: As supplement to classical multi-year reference frames, the combination of the space-geodetic data can be also performed epoch-wise (e.g., weekly). In these so-called Epoch Reference Frames (ERFs), the non-linear station motions are directly estimated [Blossfeld et al. 2014]. These combined epoch solutions are called ERF. The IAG/IERS JWG 1.4 "*Strategies for epoch reference frames*" investigates strategies for the computation of ERFs.

4.2.3.3 Input data for ITRF computations

For a particular ITRS realization, the specifications for the input data, i.e. solutions and/or normal equations in SINEX format, are given in the call for participation of the IERS, which is released by the ITRS Center. Such a call specifies which parts of the IERS conventions should be obeyed, including updates. It is also stated that, whenever departures from the recommendations of the IERS Conventions are preferred, it is requested that the effects of those deviations were documented.

Each intra-technique solution is a combination of several Analysis Center (AC) solutions as shown in Table 4.1 (11 individual GNSS solutions and 7 individual solutions for the three other space techniques). Moreover, different software packages are in use by the ACs for processing space geodetic observations. The current status is that the standards and conventions used by all these ACs are not always clearly (or fully) documented and the corresponding AC log-files are not up to date in some cases. In order to achieve consistent results for the ITRF it must be ensured that the data provided by all contributing individual ACs are based on unified standards and conventions.

So far, only a selected subset of available data are used by the services for generating the ITRF input data, e.g.,: In case of GNSS some ACs only use GPS and some use GPS and GLONASS, but other GNSS are not considered by the IGS so far. For SLR low spherical satellites and SLR data to GNSS satellites are not used in International Laser Ranging Service (ILRS) computations.

4.2.4 Interaction with other products

The ITRF is a key geodetic product, that provides the basis for precise positioning on the Earth's surface and for Earth orbiters as well as for many practical applications (e.g., navigation, surveying, mapping) and global change research in Earth sciences. How well the reference frame can be realized has important implications for Earth system studies and for the monitoring of global change phenomena. There is an interaction between the terrestrial reference frame and all the other products addressed in this inventory, such as

- Celestial reference frames
- Earth orientation parameters
- Satellite orbits
- Gravity field models
- Heights

4.2.5 Open problems and recommendations

In this section we summarize the issues that were discussed in Section 4.2.3 and some recommendations are provided. Open issues were identified in particular in the following fields:

Reference frame definition

The origin of the ITRS is defined in the CM of the whole Earth system, including oceans and atmosphere, whereas it is realized as a mean CM, averaged over the time span of the SLR observations used and modeled as a secular (linear) function of time [Petit et al. 2010]. The problem is that over shorter time scales (e.g., annual or interannual), the realized origin moves with respect to the CM by a few millimeters. According to the IERS Conventions 2010 [Petit et al. 2010], the so-called "*geocenter motion*" should be substracted from the ITRF origin (realized as mean CM) if an instantaneous geocentric position is required. However, as mentioned in Section 4.2.3 the expression "*geocenter motion*" is defined differently in the geodetic literature and a commonly accepted geocenter motion model does not exist yet.

Concerning the scale of the ITRS, it is defined in TCG time scale (consistent with IAU and IUGG (1991) resolutions), whereas its realization refers to TT. To avoid inconsistencies, the relation between both time scales (see equation 3.1) must always be considered correctly if observations and/or products refer to different time systems. Concerning the realization of the scale, the ITRF2008 shows a significant scale offset between VLBI and SLR [Altamimi et al. 2011], which is not visible in the DTRF2008 solution of DGFI [M. Seitz et al. 2012]. This scale issue needs to be further studied by taking into account the new ITRF2014 computations.

The orientation of the ITRS is realized by external NNR conditions, whereas for each particular realization successive transformations with respect to the previous ITRF realization are performed, and thus this procedure depends on the network geometries and the stations used for the transformations. The orientation rate is aligned to that of the geological model NNR-NUVEL-1A. Although this method has several shortcomings (see Section 4.2.3), it is used as it ensures continuity with prior ITRFs. The present results show that the uncertainties related to the reference frame definition are a major error source for the ITRS realization, and further improvements should be achieved to fulfil the GGOS requirements.

Integration of space techniques

A major limiting factor for the integration of the different space geodetic techniques, the inter-technique combination, is the rather inhomogeneous distribution of stations and the sparse distribution of *high quality* co-location sites with reliable local tie vectors. Current ITRF results indicate that the discrepancies between intra-technique solutions and the local tie vectors are too large for many co-location sites. For about half of the co-locations, the differences are above 1 cm, which indicates that the GGOS goals for the accuracy of the terrestrial reference frame are not fulfilled yet. Thus, it is obvious that the long-term maintenance of co-location sites, their spatial distribution, and the quality of the local tie measurements need to be improved. In addition to the *classical* co-location on Earth, a challenge for the future would be the co-location of sensors in space.

Handling of non-linear station motions

The different approaches for the handling of non-linear station motions (see Section 4.2.3) should be studied in detail by making use of the upcoming ITRF2014 results and other suitable data. The IAG and IERS JWG 1.2 "*Modeling environmental loading effects for* *reference frame realizations*" is encouraged to investigate approaches to model these effects and to validate the results. An extended parameterization to estimate the "residual" non-linear station motions has been implemented for the ITRF2014 computations and the respective results should be studied in detail. Also the IAG/IERS JWG 1.4 "*Strategies for epoch reference frames*" (ERF) is encouraged to investigate strategies for the computation of ERFs. The ERFs should not replace the classical secular frames, but may be considered as a useful supplement.

Input data for ITRF computations

In practice it is questionable, whether all partial solutions for the ITRF are based on exactly the same standards and conventions. To get an overview about the current situation it is recommended that the Services (IGS, ILRS, IVS, IDS) together with all contributing ACs compile documentation of the present status of the standards and conventions currently applied in the software packages used for the data processing. Such a compilation of the processing standards has been performed already by the IDS, which is given as an example. A table summarizing the standards that are used by the IDS Analysis Centers with respect to their ITRF2014 submissions is available at `ids-doris.org/combination/contribution-itrf2014.html`. The efforts of the IGS to tabulate models used by its Analysis Centers should also be mentioned. For this purpose the corresponding information is summarized on a Google docs spreadsheat and can be updated by the IGS Analysis Centers to reflect model updates. These efforts should be continued (and strengthened) by the IAG Services to ensure that the processing standards are consistently applied by all Analysis Centers as a prerequisite for consistent products.

Summary of recommentations on ITRS/ITRF:

Recommendation 2.1 : The realization of the geodetic datum should be consistent with its definition. The orgin of the ITRS should be unambigously defined. It is highly recommended to perform further studies related to the SLR and VLBI scale issue.

Recommendation 2.2 : The station networks and the spatial distribution of high quality co-location sites should be improved. This recommendation is fundamental to achieve the GGOS accuracy requirements for the terrestrial reference frame and to ensure its long-term stability.

Recommendation 2.3 : The handling of non-linear station motions should be further studied by also taking into account the new results of the ITRF2014. Recommendations how to deal with this topic for future ITRS realizations should be provided.

Recommendation 2.4 : To ensure consisent ITRF results the conventions and processing standards should be consistently applied by the Services (IGS, ILRS, IVS, IDS) and their ACs.

4.3 Earth Orientation Parameters (EOP)

4.3.1 Overview

Earth orientation and Earth rotation are two aspects of the same physical effect. Earth rotation describes the change of the orientation of the Earth's body with respect to a space fixed reference frame. Astronomy, satellite geodesy, or precise navigation require an accurate knowledge of the orientation of the Earth in a quasi inertial reference frame. Various disciplines of geosciences depend on the gravitational and geodynamic impact of rotation. Earth rotation is one of the impulses of the dynamics of the Earth system and the interactions between individual components, such as the exchange of angular momentum between atmosphere, ocean and solid Earth, or the coupling mechanism between the Earth's core and mantle [Plag et al. 2009; F. Seitz et al. 2010]. Both requirements, orientation and rotation, will be fulfilled if the Earth Orientation Parameters (EOP) are given as functions of time, usually as a combination of diurnal time series with analytic models.

Practically, the EOP are the parameters representing the rotation part of the transformation between two reference frames, a terrestrial and a celestial frame. According to the definition by the IERS, these two frames are actual realizations of the geocentric International Terrestrial Reference System (ITRS) and the Geocentric Celestial Reference System (GCRS) or the Barycentric Celestial Reference System (BCRS):

$$\text{ITRS} \xrightarrow{\text{rotation}} \text{GCRS} \xrightarrow{\text{translation}} \text{BCRS}.$$

The ITRS orientation is given by the IUGG Resolution 2 (2007). It is operationally maintained in continuity with past international agreements (BIH orientation). The initial orientation at 1984.0 is the orientation given by the Bureau International de l'Heure (BIH) Terrestrial System (BTS84).

The GCRS specification (IAU Resolution A4, 1991, and update: IAU Resolution B1.3, 2000) follows a geocentric celestial relativistic metric. The orientation of the

GCRS is derived from the BCRS (IAU Resolution B2, 2006). The different metrics of GCRS and BCRS imply a slight difference of the respective orientations, which are called geodesic precession and geodesic nutation [Fukushima 1991].

The BCRS is assumed to be oriented according to the ICRS (IAU Resolution B2, 2006). The latter is recommended to show no global rotation with respect to a set of distant extragalactic objects. According to IAU Resolution B2 (1997) the initial orientation of the ICRS is given through the IERS celestial reference frame of the year 1995 (IERS95) as described by the ICRS Product Center [Arias et al. 1995] within the IERS.

Since the EOP depend on the actual realizations of the conventional terrestrial and celestial reference frames, the EOP system should be readjusted as soon as a new release of ITRF or ICRF is adopted.

The transformation of cartesian coordinates from ITRS to GCRS at the date t is split into three segments

$$\begin{tikzcd}
\text{ITRS} \arrow[dr, "W(t)", "\text{polar motion}"'] & & & \text{GCRS} \\
& \text{TIRS} \arrow[r, "R(t)", "\text{Earth rotation}"'] & \text{CIRS} \arrow[ur, "Q(t)", "\text{precession-nutation}"'] &
\end{tikzcd}$$

where $Q(t)$, $R(t)$, and $W(t)$ are rotation matrices and $R(t)$ fits to the mean physical rotation of the Earth. The meaning of "mean" still has to be specified. The choice of the intermediate systems TIRS (Terrestrial Intermediate Reference System) and CIRS (Celestial Intermediate Reference System) is delaminated by the convention on $R(t)$ being an elementary rotation around the z-axis. Hence TIRS and CIRS have a common z-axis, called the **celestial pole**, which approximates a mean rotation axis of the Earth. $Q(t)$ and $W(t)^{-1}$ represent the motion of that celestial pole in the GCRS and ITRS respectively. If the celestial pole is choosen according to the IAU 2000/2006 resolutions, it will be called **Celestial Intermediate Pole (CIP)**.

According to IAU 2000 Resolution B1.7, the CIP separates the motion of the rotation axis of the ITRS in the GCRS into a celestial and a terrestrial part. The convention is such that [Capitaine 2013; Petit et al. 2010]:

- the celestial motion of the CIP includes the part of precession-nutation with periods greater than 2 days in the GCRS and the retrograde diurnal part of polar motion (including the Free Core Nutation (FCN)),
- the terrestrial motion of the CIP includes the part of polar motion which is outside the retrograde diurnal band in the ITRS and the motion in the ITRS corresponding to nutations with periods smaller than 2 days.

As outlined in the IERS Conventions 2010 [Petit et al. 2010], the motion $Q(t)$ of the CIP in the GCRS is realized by the IAU 2006/2000A precession-nutation model [Wallace et al. 2006] plus additional time-dependent corrections derived by the IERS from space geodetic observations. The motion $W(t)^{-1}$ of the CIP in the ITRS is provided by the IERS through time series derived from space geodetic observations and models including variations with frequencies outside the retrograde diurnal band. The implementation of the IAU 2000 and IAU 2006 resolutions for the transformation is detailed in the IERS Conventions 2010 [Petit et al. 2010].

In 2013, IAG and IAU set up a new Joint Working Group "Theory of Earth Rotation" [Ferrándiz et al. 2015]. The purpose of this JWG is promoting the development of theories of Earth rotation that are fully consistent and that agree with observations and provide predictions of the EOP with the accuracy required to meet future needs as recommended by, e.g., GGOS.

Concerning the realization of EOP products, the EOP are represented by the five following quantities (as specified the latest IAU 2000/2006 version of the terrestrial-celestial transformation):

- $\delta X = X - X_{\mathrm{model}}$, $\delta Y = Y - Y_{\mathrm{model}}$: corrections to the x- and y-coordinates of the CIP unit vector in the celestial system GCRS using the model IAU 2000/2006,
- $\Delta\mathrm{UT1} = \mathrm{UT1} - \mathrm{UTC}$: difference of mean solar time (Universal Time UT1) and Coordinated Universal Time (UTC) vice the averaged atomic time,
- x_{p}, y_{p}: Cardan angles of the polar wobble $W(t) = R_3(-s')R_2(x_{\mathrm{p}})R_1(y_{\mathrm{p}})$, traditionally called "pole coordinates". The x- and y-coordinates of the CIP unit vector in the terrestrial system ITRS are $\sin(x_{\mathrm{p}})$ and $\cos(x_{\mathrm{p}})\sin(-y_{\mathrm{p}})$.

The IERS is responsible for providing the time series of x_{p}, y_{p}, ΔUT1, δX, δY on an operational basis derived from the various space geodetic techniques (VLBI, SLR/LLR, GNSS and DORIS). The EOP products are available from the database of the IERS (see www.iers.org). Two Product Centers are responsible for the EOP generation, namely the IERS Earth Orientation Center and the IERS Rapid Service/Prediction Center [see Gambis et al. 2014; IERS 2014; Luzum et al. 2014].

4.3.2 IERS Earth Orientation Center

The IERS Earth Orientation Center is responsible for monitoring of long-term EOP, publications for time dissemination and leap second announcements. It is located at the Observatoire de Paris in France (see hpiers.obspm.fr/eop-pc). The general procedure for the generation of the EOP series is described in various publications [e.g., Bizouard et al. 2009b; Gambis 2004; Gambis et al. 2003, 2011].

The Earth Orientation Center provides the following main products:

Bulletin B contains final daily Earth orientation data for one month (see ftp://hpiers.obspm.fr/iers/bul/bulb_new/bulletinb.pdf)

Bulletin C contains announcements of leap seconds in UTC (see ftp://hpiers.obspm.fr/iers/bul/bulc/BULLETINC.GUIDE)

Bulletin D contains an announcement of the value ΔUT1 = UT1 − UTC (see ftp://hpiers.obspm.fr/iers/bul/buld/BULLETIND.GUIDE)

EOP 08 C04 contains long term Earth orientation data (see ftp://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf)

In the next section the EOP 08 C04 long term series is addressed in more detail.

4.3.2.1 Realisation of EOP time series

The Earth Orientation Center of the IERS, located at Paris Observatory, SYRTE, has the task to provide the international reference time series for the EOPs, referred as “IERS C04” (Combined C04), resulting from a combination of EOP series derived from individual space geodetic techniques. The latest C04 solution, referred as EOP 08 C04, became the official C04 solution since February 2010. The EOP 08 C04 time series is available from 1962 to the present and it contains smoothed values of x_p, y_p, UT1-UTC, LOD, δX, δY at 1-day intervals w.r.t. IAU 2006/2000A precession-nutation model and consistent with ITRF2008. EOP 08 C04 is updated twice a week with a latency of 30 days and the data are stored in yearly files since 1962 and in one file 1962–now. A documentation for this EOP series is given by [Bizouard et al. 2009b] and in the Annual Reports of the IERS (see [IERS 2014]).

In the past, EOP combined series were based on individual solutions derived by the analysis centers for the different space techniques, i.e., VLBI, SLR/LLR and GNSS. Nowadays, Technique Centers, i.e. IVS, ILRS, IGS and IDS are providing combined solutions based on individual analysis center contributions. The solutions used for the computation of the EOP 08 C04 series are shown in Table 4.3. More information on these input solutions along with their accuracies is provided in the IERS Annual Reports (see [Gambis et al. 2014]).

Table 4.3: *EOP series used in the computation of the EOP 08 C04 series (see [Gambis et al. 2014] for more details).*

EOP component	**EOP series used in the combination**
Pole coordinates and LOD	IGS Final Combined IGS Rapid Combined IVS Combined ILRS Combined
ΔUT1	IVS Combined Intensive VLBI solutions
Celestial pole offsets	IVS Combined

As described by Bizouard et al. [2009b] the computation of the EOP 08 C04 series is based on several processing steps.

- Each given EOP series (see Table 4.3) is transformed to the choosen ITRF/ICRF pair by removing an estimated linear drift.
- UT1−UTC is regularized (by removing zonal tides) and replaced by UT1−TAI to remove leap second jumps, whereas TAI denotes *International Atomic Time*.
- For each given series an intermediate reference solution is computed from the former combined solution by four-point window Lagrange interpolation and extrapolation; the reference series, which should contain the main part of the signal, is then subtracted from the input series; the difference is used in the combination.
- The trends of LOD in GNSS and SLR series, which are usually induced by non-modeled orbit errors and high correlations between LOD and orbit parameters, are determined by Vondrak filtering [Vondrak 1977] of ($\mathrm{LOD}_{\mathrm{GNSS/SLR}} - \mathrm{LOD}_{\mathrm{VLBI}}$) and removed.
- The resulting series are combined with the “combined smoothing method” [e.g., Vondrak et al. 2000] including weighting, outliers search and high frequency filtering.
- The final values are obtained by interpolating the filtered series at 1 day intervals, adding back the intermediate reference series, reconstructing UT1−UTC and adding back the zonal tides.

By applying the above described procedure, the EOP series is determined separately from the terrestrial and celestial reference frame. In the past, this has caused discrepancies at the level of 300 μas between the IERS C04 series and current ITRF realizations [see Bizouard et al. 2009b]. In the latest ITRF realizations, the ITRF 2005 [Altamimi et al. 2007], ITRF2008 [Altamimi et al. 2011; M. Seitz et al. 2012] and the upcoming ITRF2014 realization, the time series of station positions have been estimated simultaneously with the EOP. It is essential for many applications to ensure the consistency between the C04 series and the ITRF with a good accuracy. For that purpose, the EOP Product Center has developed together with the ITRS Product Center a strategy for the alignment of the EOP results to the latest ITRF realization. As described in [Bizouard et al. 2009a] this is done in two ways: using (1) the upgraded procedure of the EOP Product Center and (2) CATREF combination of IGN, France, incorporating the routinely available SINEX files by the technique services. The procedure of the EOP Product Center at Paris Observatory is routinely performed where the CATREF combination is to be done at regular intervals (e.g., every 6 months).

The following accuracy for the C04 series has been reported by Bizouard et al. [2009b]: The EOP 08 C04 series has been compared with the preceding version EOP 05 C04. The differences between both series are $21 \pm 30\,\mu$as and $-58 \pm 34\,\mu$as for the x_p and y_p, respectively. For UT1, LOD and the celestial pole offsets the differences are very small and much below their standard deviations. For the latest EOP 08 C04 series the authors give an accuracy of about 30 μas for the pole coordinates and about 15 μs for LOD, which is as good as the official IGS combined series.

Besides the EOP 08 C04 series, other combined Earth-orientation series (e.g., SPACE2008, COMB2008, POLE 2008) have been computed [Ratcliff et al. 2010]. These series are available from JPL's Geodynamics and Space Geodesy Group via anonymous ftp: `ftp://euler.jpl.nasa.gov/keof/combinations/2008`.

4.3.3 IERS Rapid Service/Prediction Center

The IERS Rapid Service/Prediction Center is responsible for providing predicted EOP and measured EOP on a rapid turnaround basis, primarily for real-time users and others needing EOP information sooner than that available in the final series published by the IERS Earth Orientation Center. It is located at the United States Naval Observatory (USNO) in Washington, D.C., USA (see `www.usno.navy.mil/USNO/earth-orientation`). The general procedure for the generation of the real-time EOP and predictions is described in various publications [e.g., Luzum et al. 2014; McCarthy et al. 1991; Stamatakos et al. 2007].

The IERS Rapid Service/Prediction Center provides the following main products:

Bulletin A contains x_p, y_p and UT1-UTC including their errors at daily intervals and predictions for one year into the future (see `ftp://maia.usno.navy.mil/ser7/readme.bulla`).

Standard Rapid EOP Data contain quick-look weekly estimates of the EOP since 1973-01-02 (file `finals.all`) or since 1992-01-01 (file `finals.data`) and predictions for the next 365 days (see `ftp://maia.usno.navy.mil/ser7/readme.finals`).

Daily Rapid EOP Data contain quick-look daily estimates of the EOP (file `finals.daily`) for the last 90 days and predictions for the next 90 days (see `ftp://maia.usno.navy.mil/ser7/readme.finals`).

GPS Daily Rapid EOP Data contain quick-look daily estimates of the EOP (file `gpsrapid.daily`) for the last 90 days and predictions for the next 15 days (see `ftp://maia.usno.navy.mil/ser7/readme.gpsrapid`).

4.3.3.1 Realisation of real-time EOP and predictions

The algorithm used by the IERS Rapid Service/Prediction Center for the determination of the quick-look Earth Orientation Parameters is based on a smoothing (weighting) cubic spline interpolation with adjustable smoothing fit to contributed observational data [Luzum et al. 2014; McCarthy et al. 1991]. Biases and rates with respect to the EOP 08 C04 series are determined using a robust linear estimator. The data contributing to the determination of the quick-lock Earth orientation parameter are displayed in Table 4.4. More information on these input solutions along with their accuracies is given in [Luzum et al. 2014]. The authors also provide the accuracy of the EOP predictions. As an example, the differences between the EOP predictions produced by the daily solutions and the EOP 08 C04 series are shown in Table 4.5.

4.3.4 Discussion of the present status

4.3.4.1 Input data

As shown in Tables 4.3 and 4.4, individual and intra-technique combined solutions are used as input data for the computation of the EOP series and predictions.

Table 4.4: *EOP series used in the determination of the quick-lock Earth orientation parameter. The IGS and USNO GPS results provide LOD, the derivative of UT1. (see [Luzum et al. 2014] for more details).*

EOP component	**EOP series used in the combination**
Pole coordinates	IGS Final Combined IGS Rapid Combined IGS Ultra Combined IVS Combined ILRS Combined Individual SLR and VLBI series
ΔUT1	IVS Combined Individual VLBI solutions IGS Ultra Combined USNO GPS UT
Celestial pole offsets	IVS Combined Individual VLBI solutions

Table 4.5: *Root mean square of the differences between the EOP time series predictions produced by the daily solutions and the 08 C04 combination solutions for 2013 (the values are extracted from Table 3a of [Luzum et al. 2014]). Note that the prediction length starts counting from the day after the date of the solution epoch.*

Days in future	x_p μas	x_p μas	**UT1-UTC** μs
1	0.327	0.228	0.058
5	1.81	1.22	0.214
10	3.46	1.94	0.525
20	6.75	2.66	1.88
40	12.9	4.12	2.82
90	23.8	16.5	8.49

The intra-technique combinations have been performed by the Technique Centers (i.e., IGS, ILRS, IVS) from several individual analysis center (AC) solutions by using various software packages. Although the standards and conventions used by all these ACs should follow the IERS Conventions as close as possible, the current status is that they are not always clearly (or fully) documented and in some cases the corresponding AC log-files are not up to date. Thus, it is difficult to exactly know the underlying standards and models for the processing of the input data. In order to achieve consistent EOP results it must be ensured that the data provided by all contributing ACs are based on identical standards and conventions.

4.3.4.2 Combination procedure

As described in Section 4.3.2, the combination procedure for the determination of the EOP 08 C04 series consists of several processing steps. The relevant publications [see Bizouard et al. 2009a,b] give some more information on the general procedure, but an overall documentation of the mathematical foundations is missing. Thus, it is difficult to evaluate the present combination procedure and to assess their impact on the EOP results. The same holds for the description of the combination procedure for the generation of real-time EOP and predictions, where some general information is available (see the references given in Section 4.3.3), but a detailed documentation of the mathematical foundations is missing.

4.3.4.3 Consistency between EOP and ITRF

Consistency between ITRF and EOP has been achieved for the two latest ITRS realizations, the ITRF2005 and ITRF2008, by simultaneously estimating the relevant parameters in a common adjustment. However, the procedure of the alignment between the combined EOP XX C04 series and the ITRF results is not described in much detail [see Bizouard et al. 2009a].

4.3.5 Interaction with other products

The space geodetic observations provide a direct link of the EOP with

- Celestial reference frames
- Terrestrial reference frames
- Low degree gravity field coefficients (i.e., C_{21}/S_{21})
- Satellite orbits

In addition there is a link to those parameters, that are derived from the above mentioned products.

4.3.6 Open problems and recommendations

4.3.6.1 Input data

In practice it is not clear, if all solutions contributing to the EOP combinations are based on exactly the same standards and conventions. To get an overview about the current situation it is recommended that the Services (IGS, ILRS, IVS, IDS) together with all contributing ACs compile documentation of the present status of the standards and conventions currently applied in the software packages used for the data processing. Based on the outcome of such an inventory, the Services should initiate steps to ensure that the processing standards are consistently applied by all ACs as a prerequisite for consistent EOP results. See also the recommendations for the input data used for the ITRF computations.

4.3.6.2 Combination procedure and consistency

The combination procedures, which are currently applied for both the determination of the long-term EOP series and for near-real time and predicted EOP should be described in more detail, including the mathematical foundations. This holds also for the alignment of the EOP series with the ITRF realizations. This would be the basis to evaluate the present methodology and to address important questions, e.g.,: (1) How are the EOP series aligned with the ITRF and ICRF? (2) How are the EOP determined beyond the epochs of the observations used for the ITRF2008? (3) How is the regular updating of the series performed? (4) What are the major limitations for the accuracy of the near-real time and predicted EOP? As discussed during the IERS Retreat in Paris in June 2013 (`www.iers.org/IERS/EN/Organization/Workshops/Retreat2013.html`), it should be investigated how the EOP predictions could be improved by reducing the latency of the last data point and by improved AAM and OAM update schedules, i.e., updates with 6 hour versus 24 hour latency. An important issue is also the consistency between TRF, CRF and EOP (see IUGG Resolution No. 2, 2011) as already discussed in Sections 4.1 and 4.2.

Summary of recommendations on EOP:

Recommendation 3.1 : The Services should document the present status of the standards and conventions implemented in their software packages used for determining EOP results.

Recommendation 3.2 : The procedures used for generating the EOP series and the near-real time and predicted EOP should be described in more detail, including mathematical foundations.

Recommendation 3.3 : Concerning the EOP predictions, it is recommended to investigate how the results can be improved by reducing the latency of the last data point and by more frequently updating the AAM and OAM data.

Recommendation 3.4 : Methodologies and procedures for the generation of consistent TRF, CRF and EOP should be investigated.

4.4 GNSS satellite orbits

Global Navigation Satellite Systems (GNSS) like the US American GPS and the Russian GLONASS are the most popular space geodetic techniques with a wide range of applications. Precise GNSS satellite orbits and clocks provide the basis for mm-level positioning for realizing global and regional reference systems, geophysical studies, surveying, deformation monitoring, and cadastre.

The Analysis Centers of the IGS process observations of global GNSS tracking networks on a regular basis in order to provide a variety of products. One of the IGS core products are the final orbits. These orbits are generated by the IGS Analysis Center Coordinator (ACC) as a weighted mean of the individual AC orbits [Beutler et al. 1995; Griffiths et al. 2009], see Figure 4.3. They are provided with a latency of 12 – 18 days.

Due to advances in observation modeling and processing strategies since the establishment of the IGS in 1994, the orbit quality has steadily improved. In order to achieve the highest product quality also for the orbits of the early years and to achieve consistency with current operational orbits, the IGS conducted a first reprocessing campaign covering the time period 1996 – 2008. These data were also used for the computation of ITRF2008. A second reprocessing covering 1994 – 2014 provides the input for ITRF2014. Users are advised to use the latest generation of reprocessed products to achieve the highest level of accuracy as well as consistency with the operational products for time periods where the reprocessed products are not available.

The individual analysis centers contributing to the final orbit combination are:

COD	Center for Orbit Determination in Europe, Switzerland
EMR	Natural Resources Canada, Canada
ESA	European Space Agency, Germany
GFZ	Deutsches GeoForschungsZentrum, Germany
GRG	GRGS-CNES/CLS, France
JPL	Jet Propulsion Laboratory, USA
MIT	Massachusetts Institute of Technology, USA
NGS	National Geodetic Survey, USA
SIO	Scripps Institution of Oceanography, USA

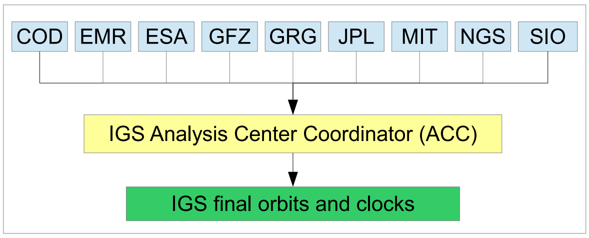


Fig. 4.3: *Generation of the IGS final orbit and clock products.*

4.4.1 Summary of standards

The standards listed in Table 4.6 are based on the recommendations for the 2nd IGS reprocessing campaign, see acc.igs.org/reprocess2.html. Due to mostly outdated analysis log files, the compliance of the ACs with these standards could not be verified.

4.4.2 Discussion and deficiencies

4.4.2.1 Solar radiation pressure modeling

Modeling of the Solar Radiation Pressure (SRP) is probably the largest error source of today's GNSS orbits. Deficiencies in the SRP modeling are visible as harmonics of the draconitic year in orbital [Griffiths et al. 2013] and other parameters: station positions [Amiri-Simkooei 2013; J. Ray et al. 2008], geocenter [Hugentobler et al. 2005], and Earth Rotation Parameters (ERP) [Steigenberger 2009]. A comparison of different SRP models can be found in Sibthorpe et al. 2011.

Recent developments that at least partly reduce these systematic errors include an adjustable box-wing model [Rodriguez-Solano et al. 2014], the extended Empirical CODE Orbit Model [Arnold et al. 2015], a cuboid box model for the Galileo IOV satellites [Montenbruck et al. 2015], and a box-plate model for GIOVE-B [Steigenberger et al. 2015].

4.4.2.2 Albedo

Earth radiation pressure or albedo in particular affects the scale of the orbits. Although several authors [e.g., Rodriguez-Solano et al. 2011; Ziebart et al. 2007] have shown the benefits of including albedo, this effect is not yet considered by all ACs.

4.4.2.3 Antenna thrust

When transmitting navigation signals, GNSS satellites experience an acceleration in radial direction depending on the power of the emitted signals called antenna thrust. Rodriguez-Solano et al. [2012] report a 5 mm radial orbit change when considering antenna thrust in GPS orbit determination. Transmit power levels for the GPS satellites are available at acc.igs.org/orbits/thrust-power.txt but no information is available for GLONASS and the emerging GNSS.

4.4.2.4 Attitude

The basic attitude condition of a GNSS satellite is that the navigation antenna points to the center of the Earth and the solar panels are oriented perpendicular to the Sun. To fulfil these conditions, the satellite has to rotate around its z-axis. The speed of this rotation depends on the elevation of the Sun above the orbital plane. Due to technical restrictions, the implementation of the attitude control deviates from this ideal case. Several models for the attitude of GNSS satellites are available but these models are not widely used at the moment.

- GPS block II, IIA, IIR satellites [Kouba 2009a]
- GPS block IIA satellites [Rodriguez-Solano et al. 2013]
- GPS block IIF satellites [Dilssner 2010]
- GLONASS-M satellites [Dilssner et al. 2010]

4.4.2.5 Satellite antenna model

GNSS measurements refer to the electrical phase center of the transmission and receiving antennas. The mean differences between the mechanically well-defined antenna reference point of the receiver antennas and the center of mass for the satellite antennas are called Phase Center Offsets (PCOs). Variations of the actual phase center depending on azimuth and elevation of the transmitted/received signal are called Phase Center Variations (PCVs). As usually no ground calibrations are available for the transmitting antennas, satellite antenna phase center offsets and variations were estimated from global GNSS data to derive antenna models for GPS and GLONASS.

The current model `igs08.atx` [Rebischung et al. 2012] considers only block-specific PCVs and satellite-specific PCOs. Satellite antenna phase center variations for nadir angles larger than 14° (important for Low Earth Orbiter (LEO) processing) were recently determined by the Center for Orbit Determination in Europe (CODE) [Jäggi et al. 2012] and added to `igs08.atx` [Schmid et al. 2013].

In the current model, azimuthal variations of the GNSS satellite antennas [Schmid et al. 2005] are not yet considered. One could also think of estimating satellite-specific antenna PCVs to account for deviations of the individual transmitting antennas from the block-specific mean values. In view of the emerging GNSS it is a critical issue that the satellite antenna offsets and phase center variations of Galileo satellites are unknown. For BeiDou and QZSS only the antenna offsets are known.

Table 4.6: *Selected standards of the IGS for its second reprocessing campaign.*

General Standards	IERS 2010 Conventions [Petit et al. 2010]
Reference Frame	IGS08 [Rebischung et al. 2012]
Antenna Model	igs08.atx [Rebischung et al. 2012]
P1C1 Code Biases	`ftp://ftp.unibe.ch/aiub/bcwg/cc2noncc`
Phase Wind-Up	according to J. Wu et al. [1993]
Gravity Field	EGM2008 [N. Pavlis et al. 2012]
Non-Tidal Loading	not applied
Higher-order Ionosphere	2nd and 3rd order applied [Fritsche et al. 2005; Hernández-Pajares et al. 2011]
A Priori Troposphere Delay	Local meteorological measurements or Global Pressure and Temperature (GPT) model [Böhm et al. 2007] to compute hydrostatic delays according to [Davis et al. 1985]
Troposphere Mapping	Global Mapping Function (GMF) [Böhm, Niell, et al. 2006] or Vienna Mapping Function 1 (VMF1) [Böhm, Werl, et al. 2006]

4.4.2.6 Non-tidal loading

It is currently not recommended to apply non-tidal loading corrections at the observations level. However, aliasing effects can be introduced by this procedure [Dach et al. 2011]. In addition, one should be aware that atmospheric loading is partly compensated when using GMF/GPT [Kouba 2009b; Steigenberger et al. 2009].

4.4.2.7 Subdaily ERP model

Griffiths et al. [2013] found subdaily alias errors in IGS orbit, coordinate, geocenter, and ERP products. They attribute these errors to deficiencies of the IERS subdaily ERP model and conclude that an improved model is needed to mitigate these errors.

4.4.3 Links to other products

Changes in the orbit modeling directly affect the following geodetic products:

- Terrestrial Reference Frame (TRF)
- TRF densification, e.g., IAG Reference Frame Sub–Commission for Europe (EUREF)
- GNSS satellite orbits and clocks
- Earth Orientation Parameters (EOP)
- Time-dependent Total Electron Content (TEC) maps
- Troposphere Zenith Total Delay (ZTD) time series

Changes in the orbit modeling affect the following products utilizing GNSS satellite orbits:

- LEO satellite orbits
- Static gravity field
- Time-dependent gravity field
- Time series of sea surface heights
- Time series of ice sheet and glacier elevations

4.4.4 Open problems and recommendations

The BPS has identified open problems in the field of GNSS orbit modeling and recommendations for further studies. These include:

- The consistency of the orbit solutions submitted by the IGS Analysis Centers has to be assured.
- An improved model for subdaily variations in Earth's rotation is required.
- Radiation pressure modeling and aliasing of orbital errors into geodetic parameters needs to be further studied.
- The impact of different arc lengths (1-day vs. 3-day) on geodetic parameters needs to be assessed.
- Satellite antenna offsets are required for Galileo, IRNSS, and SBAS satellites.
- Satellite antenna phase center variations are required for BeiDou, Galileo, IRNSS, QZSS, and SBAS.
- Attitude models are required for BeiDou, Galileo, IRNSS, and SBAS satellites.
- Transmit power level is required for BeiDou, Galileo, GLONASS, IRNSS, QZSS, and SBAS satellites.

Summary of recommendations on GNSS orbits:

Recommendation 4.1 : The impact of analysis strategies such as radiation pressure modeling and orbit arc length on derived geodetic parameters should be investigated in detail.

Recommendation 4.2 : An improved model for subdaily variations in Earth's rotation should be developed.

Recommendation 4.3 : Satellite operators should be urged to provide detailed information about satellite dimensions, surface properties, attitude models, antenna offsets, antenna phase patterns, and radio emission power.

4.5 Gravity and geoid

Gravity and geoid related products are collected by several IAG Services, which all together compose the International Gravity Field Service (IGFS). The overall goal of the IGFS is to coordinate the servicing of the geodetic and geophysical community with gravity field-related data, software and information. The combined data of the IGFS entities should include satellite-derived global models, terrestrial, airborne, satellite and marine gravity observations, Earth tide data, GNSS leveling data, digital models of terrain and bathymetry, as well as ocean gravity field and geoid from satellite altimetry. Both the static components and the temporal variations of the gravity field will be covered by the IGFS. The organizational structure of the IGFS is shown in Figure 4.4.

The IGFS is not handling gravity field data distribution directly – IGFS functions as a unifying service for the following gravity-field related IAG Services – “IGFS Centers”:

ICGEM	International Center for Global Gravity Field Models – distribution of satellite and surface spherical harmonic models;
BGI	Bureau Gravimétrique International – collection, archiving and distribution of gravity data;
ISG	International Service for the Geoid – collection and distribution of geoid models, collection and distribution of software for geoid computation, and organization of technical schools on geoid determinations;
ICET	International Center for Earth Tides – collection and archiving of global Earth tide data;
IDEMS	International Digital Elevation Model Service – Global Digital Terrain Models.

The general character of the products offered by the IGFS Services is slightly different from products of other IAG Services. While, for example, the ITRF is generated by a combination of products or observations provided by various other IAG Services, IGFS products are singular products either representing observations or geophysical models. Geophysical models usually are based on various data or observations, which are taken from a number of sources (e.g. satellite mission data, terrestrial observations). This implies that products from the IGFS as a minimum should indicate the standards applied for their generation. In many cases this can be guaranteed, but there are also other products for which this hardly is possible. Often huge software packages are used for product generation, in which specific standards and conventions have been implemented. These standards and conventions often are unknown or not specified together with the product.

In the following sections the products offered by the IGFS Services are briefly described and references for these products are provided. In the subsequent tables for each identified product an inventory of the standards applied for the generation of these products is given (on a best knowledge basis). This information is extracted from the available information provided on the services web sites or the related documentation.

4.5.1 ICGEM – International Center for Global Earth Models

The International Center for Global Earth Models collects and distributes historical and actual global gravity field models of the Earth and offers calculation service for derived quantities. In particular the tasks include: Collecting and archiving of all existing global gravity field models, maintaining an online archive for getting access to global gravity field models, providing web based visualization of the gravity field models, their differences and their time variation, offering a service for calculating different functionals of the gravity field models, and providing tutorials on spherical harmonics and the theory used by the calculation service.

The products of ICGEM are:

- Global gravity field model spherical harmonic series in ICGEM format (static and time series);
- Global topography model spherical harmonic series in ICGEM format (topography heights and gravitational potential);
- Gravity functionals and topography on freely selectable grids by calculation service: height anomaly, geoid height, gravity disturbance, gravity anomaly, Bouguer anomaly, gravity, gravitation, radial gravity gradient, equivalent water height.

More details about tasks and products can be found at the service web site `icgem.gfz-potsdam.de/ICGEM/ICGEM.html` and within the following references:

- Description of the ICGEM format: `icgem.gfz-potsdam.de/ICGEM/documents/ICGEM-Format-2011.pdf`;
- [Barthelmes 2013], `icgem.gfz-potsdam.de/ICGEM/theory/str-0902-revised.pdf`.

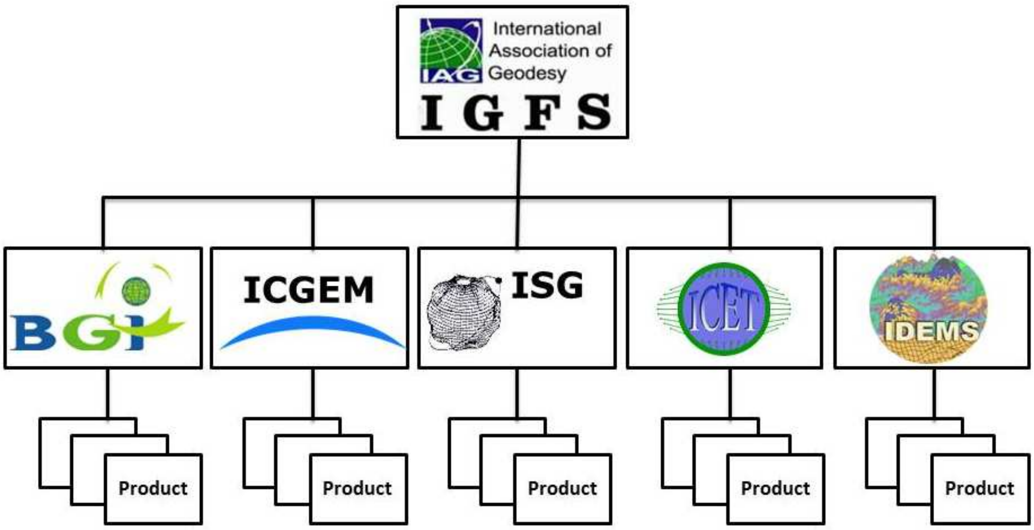


Fig. 4.4: *Organizational structure of the IGFS*

4.5.2 BGI – Bureau Gravimétrique International

The overall task of the Bureau Gravimetric International (BGI) is to collect, on a world-wide basis, all measurements and pertinent information about the Earth gravity field, to compile them and store them in a computerized data base in order to redistribute them on request to a large variety of users for scientific purposes.

The products of the BGI are:

- Collection of land, marine gravity data and reference gravity stations;
- Data from absolute gravity stations (see mirror site: `agrav.bkg.bund.de`);
- High resolution grids and maps of the Earth's gravity anomalies (Bouguer, isostatic and surface free-air), computed at global scale in spherical geometry (World Gravity Map (WGM) 2012);
- Regional gravity anomaly grids (derived from EGM 2008);
- Gridded estimates of (i) gravity accelerations, (ii) gravity disturbances, (iii) quasi-geoid undulations, and (iv) deflection of the vertical components from the ultra high resolution global gravity field model GGMplus [Hirt et al. 2013];
- Predicted gravity values – normal gravity is computed using Somigliana formula in the GRS80 system.

More details about tasks and products can be found at the service web site `bgi.omp.obs-mip.fr/` and in the following references:

- Land gravity data format (EOL) / Sea gravity data format (EOS): `bgi.omp.obs-mip.fr/content/download/720/4949/file/BGI_EOL_EOS_Data_format.pdf`;
- Fortran routine to extract [Longitude / Latitude / Bouguer] fields from EOL data file: `bgi.omp.obs-mip.fr/content/download/721/4952/file/conveol2xyz.pdf`;
- Determination of normal gravity (BGI document): `bgi.omp.obs-mip.fr/content/download/723/4969/file/BGI_Formules_Pesanteur_Normale.pdf`;
- Définition des anomalies gravimétriques (in French): `bgi.omp.obs-mip.fr/content/download/724/4972/file/FORMUL00.pdf`;
- Gravity definitions & anomaly computations (National Geospatial-Intelligence Center (NGA) document): `bgi.omp.obs-mip.fr/content/download/725/4975/file/computations.pdf`.

4.5.3 ISG – International Service for the Geoid

The activities of the International Service for the Geoid (ISG) are on educational, research, and data collection: Main tasks of the ISG are to collect geoid data on a worldwide scale (geoid repository), to collect and distribute software for geoid determination (software download), to conduct research on procedure for geoid determination (projects), to organize geoid schools, and to edit and distribute the Newton's Bulletin.

The products of the ISG are:

- Regional geoid models;
- Geoid software (local geoid estimation; harmonic manipulator; ellipsoidal gravity model manipulator; computation of terrain effects on gravimetric quantities);
- International schools on geoid determination and thematic schools.

More details about tasks and products can be found at the service web site: www.isgeoid.polimi.it/index.html. No product related references are available at the ISG web site. For regional geoid models the related reference in many cases is indicated.

4.5.4 ICET – International Center for Earth Tides

The terms of reference of the International Center for Earth Tides (ICET) can be summarized as follows:

- Collection of all available measurements related to Earth tides;
- Evaluation of these data by convenient methods of analysis in order to reduce the very large amount of measurements to a limited number of parameters which should contain all the desired and needed geophysical information;
- Comparison of the data from different instruments and different stations distributed all over the world, evaluating their precision and accuracy from the point of view of internal errors as well as external errors;
- Help solving the basic problem of calibration by organizing reference stations or realizing calibration devices;
- Filling gaps in information and data;
- Building a data bank allowing immediate and easy comparison of earth tides parameters with different Earth models and other geodetic and geophysical parameters;
- Ensuring a broad diffusion of the results and information to all interested laboratories and individual scientists.

The products of the ICET are:

- Tidal analysis results for gravimetric stations: For a large number of stations tidal loading computations can be downloaded. A detailed description of these files in order to identify the standards and conventions applied for these products is missing. Results for tilt stations, strain stations, barometric stations and wells are not available from the web site (link error);
- Ocean tides loading computation: There are available computations for a number of tide models and for a set of stations. There is missing a detailed description of these files in order to identify the standards and conventions applied for these products.

More details about tasks and products can be found at the service web site: www.upf.pf/ICET/. No product related descriptions are available at the ICET web site, but an extensive bibliography related to Earth tides is available. In general it seems that the web sites are outdated.

4.5.5 IDEMS – International Digital Elevation Model Service

This service currently is not active and will be reconfigured. The following paragraphs reflect the status until 2014 and shall provide some flavour about the tasks of this service. The International Digital Elevation Model Service (IDEMS) web site provides a focus for distribution of data and information about Digital Elevation Models (DEMs), relevant software and related datasets (including representation of inland water within DEMs) which are available in the public domain. Currently, this site has links to a number of Global Digital Elevation Models (GDEM) and hosts the ACE GDEM. Information on analysis of the SRTM dataset will be added as it becomes available.

The service does not provide products via its web site. It provides links to other project or satellite mission web sites where digital elevation models are made available. Some of the links are not active (web site outdated). As this service does not provide digital products no inventory of standards and conventions can be generated. The following digital elevation data bases are addressed via the web site: SRTM, ACE, ACE2, ASTER, GLOBE, GTOPO30, NED.

Some information on tasks and products can be found at the service site www.cse.dmu.ac.uk/EAPRS/iag/. The web site provides a bibliography for relevant publications, which should be helpful for those who want to make use of global digital elevation models.

4.5.6 IGFS Products Inventory of Standards

From the descriptions of products provided in the previous sections the following products of the IGFS, which need to follow certain standards and conventions can be identified:

- Global gravity field model as static and time variable spherical harmonic series (ICGEM 1);
- Gravity field functionals on a grid (ICGEM 2);
- Land and marine gravity data (BGI 1);
- Absolute gravity stations (BGI 2);
- Regional geoid solutions (ISG 1).

Those products which are not mentioned above either shall not be regarded as a data product (e.g. geoid software, schools) or are not specified in sufficient detail in order to identify if standards and conventions play a role.

Table 4.7 provides a summary of the identified standards and conventions of the above mentioned products for different classes of standards. In order to keep a complete overview and later on to identify dependencies between other product classes (e.g. geometric products defined in Sections 4.1 to 4.4) we intentionally left in all standards, even if there is no dependency at all for the gravimetric products.

4.5.7 Open problems and recommendations

The IGFS web site should act as an umbrella for all its services. It is strongly recommended to renew this web site and to provide descriptive documentation about the services and its products. Ideally, a document describing the products of the IGFS Services and the standards and conventions applied shall be made available there. More detailed information can be provided at the individual services web sites.

The services of the IGFS shall ensure that all metadata required to make use of their products are delivered together with the products. In order to make product conversions to different representations or reference systems the required algorithms could be described in the IGFS Services documentation. For this purpose it is recommended to create a unique document per service (or even better for the IGFS), where these algorithms are described in detail.

Some services of the IGFS provide poorly structured and sometimes outdated information about their products. In order to keep these services alive an update of the services web sites is strongly recommended. This specifically addresses the ICET and IDEMS.

Further remark on BGI and IDEMS: Much of the collected data of these services is not in the public domain. Although they appear as IAG Services, these data are not available for research within IAG, i.e. they are not delivered even to researchers working in IAG projects. This fact is unacceptable and should be addressed (and solved) within GGOS.

Summary of recommendations on gravity field:

Recommendation 5.1 : A centralized web access to all IGFS products and services maintained by the IGFS should be established. This shall include descriptions of the various products provided under the IGFS.

Recommendation 5.2 : IGFS products need to be clearly specified in terms of standards and conventions as well as algorithms applied.

Recommendation 5.3 : Inactive services and/or outdated information should not be considered anymore as inherent part of the IGFS.

Recommendation 5.4 : All IGFS products to be delivered under the umbrella of GGOS should be publicly available for research applications. Otherwise these products should not be advertised anymore as GGOS supported products. The IGFS should provide a list of its products, which are declared as GGOS products.

4.6 Height systems and their realizations

4.6.1 Overview

Currently, a formal *GGOS height systems product* or an *IAG Height Systems Service* does not exist. However, the availability of geodetic space techniques, especially GNSS and dedicated-gravity field missions (i.e., CHAMP, GRACE, GOCE), motivates the combination of current geodetic products to determine gravity field-related heights. This combination is normally performed following the relation $h - H - N = 0$. The ellipsoidal heights (h) are derived from GNSS positioning while the geoid or quasi-geoid models (N) are computed combining satellite and terrestrial (aerial, marine) gravity data. The physical heights (H) are usually obtained from spirit levelling (+ gravity reductions) referring to local vertical datums.

The determination of ellipsoidal heights is expected to conform to the IERS and IGS standards, since these heights depend on the geocentric Cartesian coordinates and on the size, orientation, and position of the reference ellipsoid used for their transformation into ellipsoidal coordinates. For the computation of the (quasi-) geoid, a compilation of standards (like the IERS conventions) is not available. The processing of CHAMP, GRACE and GOCE data is well-documented in the

Table 4.7: *Summary of the identified standards and conventions for gravity and geoid related products. The acronym n/a denotes "not applicable for this product". This means that according to our assessment there is no dependency between the product and the standard. If "unknown" is stated, it means that according to our assessment that there is or might be a dependency of the product on this standard, but that no information could be found in the available product descriptions.*

General Standards & Conventions	**ICGEM 1**	**ICGEM 2**	**BGI 1**	**BGI 2**	**ISG 1**
Speed of light	n/a	n/a	n/a	n/a	n/a
Time System	n/a	n/a	n/a	n/a	n/a
Gravitational constant of the Earth	Newton's gravitational constant	Reference ellipsoid chosen by user	FA and Bouguer anomalies based on GRS67	n/a	Reference ellipsoid indicated in product
Equatorial radius of the Earth	Reference radius provided in product.	Reference ellipsoid chosen by user.	FA and Bouguer anomalies based on GRS67	n/a	Reference ellipsoid indicated in product
Flattening of the Earth	n/a	Reference ellipsoid chosen by user	FA and Bouguer anomalies based on GRS67	n/a	Reference ellipsoid indicated in product
Terrestrial reference frame	n/a	n/a	n/a	n/a	Reference frame indicated in product
Celestial reference frame	n/a	n/a	n/a	n/a	n/a

Earth's Gravity Field	**ICGEM 1**	**ICGEM 2**	**BGI 1**	**BGI 2**	**ISG 1**
A priori model	n/a	n/a	n/a	n/a	n/a
Permanent tide system	Permanent tide system indicated in product	Permanent tide system chosen by user	unknown	unknown	Permanent tide system indicated in product

Earth Orientation Parameters	**ICGEM 1**	**ICGEM 2**	**BGI 1**	**BGI 2**	**ISG 1**
A priori information	n/a	Reference ellipsoid chosen by user	n/a	IERS polar motion coordinates	Reference ellipsoid indicated in product
Interpolation of a priori values	n/a	n/a	n/a	n/a	n/a
Subdaily ocean tidal effects	n/a	n/a	n/a	n/a	n/a
Atmospheric tidal effects	n/a	n/a	n/a	n/a	n/a
Nutation model	n/a	n/a	n/a	n/a	n/a
Precession model	n/a	n/a	n/a	n/a	n/a
Subdaily nutation	n/a	n/a	n/a	n/a	n/a
UT1 libration	n/a	n/a	n/a	n/a	n/a

***Table 4.7** continued*

Station Coordinates	**ICGEM 1**	**ICGEM 2**	**BGI 1**	**BGI 2**	**ISG 1**
Solid Earth tides	n/a	n/a	n/a	Potential, wave groups, delta factors	n/a
Permanent tide	n/a	n/a	n/a	unknown	n/a
Solid Earth pole tide	n/a	n/a	n/a	unknown	n/a
Oceanic pole tide	n/a	n/a	n/a	unknown	n/a
Tidal Ocean Loading	n/a	n/a	n/a	Wave groups, amplitudes, phases	n/a
Non-tidal ocean loading	n/a	n/a	n/a	unknown	n/a
Tidal atmospheric loading	n/a	n/a	n/a	unknown	n/a
Non-tidal atmospheric loading	n/a	n/a	n/a	unknown	n/a

IGFS Specific Standards	**ICGEM 1**	**ICGEM 2**	**BGI 1**	**BGI 2**	**ISG 1**
Horizontal coordinates (latitude/ longitude) reference	n/a	Ellipsoidal coordinates for reference ellipsoid	unknown	GRS80	Coordinate reference indicated in product
Vertical coordinates (height) reference	n/a	Height above reference ellipsoid	Indicated per data point	Physical height	Height above indicated reference ellipsoid
Spherical harmonic series truncation	n/a	Truncation degree defined by user	n/a	n/a	n/a
Gaussian filter (filter length, filter degree)	n/a	Filter parameters defined by user	n/a	n/a	n/a
Standard density of Earth crust	n/a	2670 kg/m^3	2670 kg/m^3	n/a	unknown
Air pressure correction	n/a	n/a	unknown	Standard atmosphere & barometric admittance	n/a

specific guidelines [Dahle et al. 2007; T. Gruber et al. 2010; Lühr et al. 2002]. However, the computation of the long-wavelength constituents of the (quasi-)geoid (degree $n \leq 180$ in a spherical harmonic expansion) produces different results depending on the combination of satellite-based gravity data and the processing strategy used for the estimation of the spherical harmonic coefficients. The medium to short-wavelength components of the (quasi-)geoid ($n > 180$) are usually estimated by combining terrestrial (airborne, marine) gravity data and the gravitational effects of the topography derived from digital terrain models. In this case, information about the mass density (either by digital density models or density hypotheses) is also necessary.

For the treatment of the terrestrial gravity, the standards published with the International Gravity Standardization Net 1971 (IGSN71) [Morelli et al. 1974] and the International Absolute Gravity Basestation Network (IAGBN) [Boedecker 1988] are available. Nevertheless, there are still large data bases referring to the old gravity reference called Potsdam system [Borrass 1911]. Gravity surveys with geophysical purposes (e.g., oil exploration) are in general not freely available and the standards applied to their processing are not clear.

The determination of the existing physical heights initially follows two basic conventions: (1) the geoid coincides with the mean sea level and (2) the corresponding vertical coordinate must be the orthometric height. The realization of these conditions was carried out by estimating the local mean sea level at selected tide gauges and by means of geodetic levelling in combination with gravity reductions. It should be stressed that orthometric heights depend on the mass density distribution in the Earth's interior which is not known at a sufficient degree. Any hypothesis about the density distribution creates a different realization of the orthometric height system, but also of the geoid as a level surface running in the Earth's interior over the continents. Currently, some height systems are based on normal heights and the quasi-geoid as the reference surface. Geoid and quasi-geoid are practically identical in marine areas, and the realization of the quasi-geoid is also given by the local mean sea level at the reference tide gauges. In general, the existing physical heights not only refer to different (unconnected) levels but are also static (without considering variations in time) and contain large uncertainties caused primary by systematic errors in levelling, omission or different approximations in the gravity reductions, and non-modeled effects in the height determination (more details in Table 4.8).

Considering these characteristics, it is clear that the state-of-the-art allows the combination of ellipsoidal and physical heights with (quasi-)geoid models with an accuracy varying from some cm up to 2 m. This may satisfy some practical applications, but measuring, understanding and modeling global change effects with magnitudes at cm- or mm-level is not possible. The solution of these deficiencies requires the establishment of a gravity field-related global vertical reference system, capable of supporting the standardization (unification) of the existing height systems and the precise combination of physical and geometric heights globally. The implementation of such a vertical reference system is a main objective of GGOS (see GGOS Focus Area 1: *Unified Height System* in GGOS 2020 Action Plans 2011 –2015, unpublished) and the success of this initiative has to be necessarily supported by a clear statement of standards and conventions.

4.6.2 Summary of standards

As a first attempt, the inventory of the standards used in height systems concentrates on the effects removed or retained in the different coordinates associated with vertical positioning; i.e., those corrections (or reductions) applied to the instantaneous station positions to generate *regularized* or *quasi-static* coordinates. The coordinates considered are: geometry on land (station positions derived from GNSS positioning), terrestrial gravity (relative and absolute gravity values measured on the Earth's surface), geopotential numbers (derived from levelling in combination with gravity reductions), and (quasi-)geoid models. To identify which standards have to be taken into account in this inventory, Table 4.9 summarizes the magnitude of the main effects currently considered.

Apart from the effects caused by secular changes (represented by the so-called *station velocities*), the largest magnitudes are related to the treatment of the permanent tide (see Section 3.2). In the case of the geometrical coordinates (i.e., ITRS/ITRF), the realization of the tide-free system is based on the elastic response of the Earth to the semidiurnal components of the tidal potential (cf. nominal Love numbers [Petit et al. 2010, Chapters 6 and 7]). This approximation is called *conventional tide-free system.* In the terrestrial gravity and spirit levelling processing, the tide-free system assumes the Earth in a hydrostatic equilibrium (cf. secular or fluid limit Love numbers [Munk et al. 1960]). This approximation is called *tide-free system.* These two different approximations cause discrepancies up to 0.16 m in the *tide-free vertical coordinates.* The computation of the (quasi-)geoid is done in tide-free or zero-tide system. However, some models apply the elastic response approximation and others apply the hydrostatic equilibrium condition. In this way:

- the geometric coordinates are given in the conventional tide-free system;
- the terrestrial gravity data are given in general in the zero-tide system (following the IAG Resolution No. 16, 1983), but some values determined before 1983 refer to the tide-free system;
- the geopotential numbers are given in the tide-free, zero-tide or mean-tide system. This depends on the application of the so-called *astronomical reduction to levelling.* This reduction produces coordinates in the tide-free system. If the indirect effect of the permanent tide is restored, they are given in the zero-tide system. If the astronomical reduction is not taken into account, the geopotential numbers are assumed to be in the mean-tide system;
- the global gravity models and the derived (quasi-) geoid models are published in conventional tide-free or zero-tide system. The mean-tide system is also used especially for oceanographic applications.

Table 4.8: *Characteristics and present status of the existing physical height systems.*

Characteristics	Present status
Reference level and vertical datum	
– **Definition**: the geoid according to Gauss 1876 and Listing 1873. – **Basic convention**: the geoid coincides with the undisturbed mean sea level. – **Realization**: mean sea level averaged over a certain period of time at an arbitrarily selected tide gauge. – **Remark**: The interpretation of this convention has changed over the years depending on the type and quality of geodetic observations and analysis strategies available for modeling both the mean sea surface and the geoid, e.g., [Ekman 1995; Heck 2004; Heck et al. 1990; Mather 1978; Sánchez 2012].	– There are as many vertical datums as reference tide gauges (at present more than 100 worldwide) and the reference levels relate to different determination epochs. – Height systems based on the quasi-geoid realize the reference level and the vertical datum in the same manner because geoid and quasi-geoid are practically identical in ocean areas and at the coast lines (where the tide gauges are established).
Vertical coordinates	
– **Definition**: orthometric heights (as *tacit* consequence of introducing the geoid as the reference surface). – **Realization**: levelling with gravity reductions (often using normal gravity instead of observed surface gravity). – **No convention** about the gravity reduction (sometimes no reduction). – **Remark**: Normal heights and quasi-geoid are preferred in some countries/regions.	– Vertical coordinates realize different orthometric height types depending on the applied hypothesis. – There is no unique relation between reference surface and vertical coordinates if the geoid is not computed using the same hypotheses applied for the orthometric heights. – The determination of normal heights does not depend on any hypothesis, but only on the parameters of the reference ellipsoid. The same holds for the quasi-geoid.
Reference frames	
– The **vertical control** over continental areas has been extended by means of spirit levelling along vertical networks. – **Drawbacks**: levelling is very time-consuming and the systematic errors significantly grow with the distance from the reference tide gauge.	– Most of the vertical networks have been measured piece-wise over very long time periods and the vertical coordinates refer to different epochs. – The estimation of vertical displacements at levelling points by spirit levelling is very difficult (expensive) and in most cases they are neglected. – The accuracy of the heights is limited regionally by the error propagation of spirit levelling to dm-level in remote areas and globally by the datum realization to m-level.

The tide-generating potential is modeled according to:

- for the geometric coordinates (IERS Conventions): Cartwright et al. [1973, 1971]. Transformation parameters to the models of Doodson [1921] and Hartmann et al. [1995] are also provided;
- for the CHAMP, GRACE, and GOCE data: the same as the IERS Conventions;
- for the terrestrial gravity: in addition to Cartwright [Cartwright et al. 1973, 1971], the Longman [1959] formulation was also widely applied before IGSN71. In recent years, the model of Hartmann et al. [1995] is also used.

The changes induced by the solid Earth tides (estimated by means of Love numbers) in the IERS Conventions are computed following the models of Wahr [1981] and Mathews et al. [1995] in combination with the model Preliminary Reference Earth Model (PREM) [Dziewonski et al. 1981]. Further corrections for the anelasticity of the mantle and resonance effects caused by oceanic currents and tides, and the Chandler wobble, the retrograde Free Core Nutation (FCN) and the prograde Free Inner Core Nutation (FICN) are also included. The estimation of the pole tide and ocean pole tide effects is based on [Wahr 1985], but using the so-called *fluid Love numbers* [Munk et al. 1960], i.e., the deformation for an Earth in hydrostatic equilibrium. Here it should be mentioned again that the direct deformation of the Earth's surface caused by the tide-generating potential is estimated applying (frequency-dependent) Love numbers for an elastic Earth. The ocean pole tide loading is computed using the model of equilibrium of Desai [2002]. The pole tide and ocean pole tide loading effects in GRACE and GOCE and in terrestrial gravity data of high-precision (absolute and superconducting gravimetry) are computed as in the IERS Conventions.

The ocean loading effects in the geometric coordinates are modeled according to Farrell [1972] and using the *conventional computation routine* of Scherneck [1991] described in the IERS Conventions. The ocean tide models preferred by the IERS are TPXO 7.2 [Egbert et al. 1994] and FES2004 [Letellier et al. 2005], while in the analysis of GRACE and GOCE data the model FES2004 is used.

Non-tidal effects (from ocean, atmosphere and hydrology) are not removed from the geometrical coordinates; i.e., these effects are included in the station positions. In the IERS Conventions, the atmospheric tidal effects caused by the solar diurnal and semidiurnal components are modeled according to [R. D. Ray et al. 2003], while in the GRACE data processing the model of Biancale et al. [2006] is used. GOCE data processing does not reduce this effect directly; it is modeled together with non-tidal effects.

The non-tidal effects in the case of GRACE and GOCE are understood as short-term mass variations of the atmosphere-ocean system. The corresponding effects are reduced from the spherical harmonic coefficients directly to get a quasi-stationary representation of the Earth's gravity field. The estimation of this reduction is based on the Ocean Model for Circulation and Tides (OMCT) [Thomas 2002] combined with the numerical weather models produced by the European Center for Medium-Range Weather Forecasts (ECMWF). Hydrological effects are assumed to be contained in the epoch-gravity models computed from GRACE.

In the computation of terrestrial gravity anomalies, the atmospheric effects are modeled by means of a standard atmosphere, i.e., a spherical model considering radial density changes only. In some cases, this approximation is refined by taking into account the perturbations caused by the terrain irregularities in the atmosphere-Earth surface coupling. The estimation of this reduction is based on an inverse Bouguer plate with the mean density of the atmosphere.

Regarding the level differences measured by geodetic levelling, the only applied reduction is the astronomical correction; the other effects (like pole tide, ocean pole tide, non-tidal loading, etc.) are considered insignificant [Heck 1984].

4.6.3 Discussion and deficiencies

According to the summary presented in the previous sections, the largest discrepancies of the existing height systems and their combination with geometrical heights and (quasi-)geoid models are caused by:

- different reference levels (i.e., zero-height surfaces) in the local height systems;
- datum inconsistencies associated with the individual vertical coordinates, e.g., no coincidence between the zero-height level of the vertical networks and the level of the (quasi-)geoid models;
- omission or different approximations in the computation of gravity reductions in the levelling data; i.e., different types of physical heights (orthometric, normal, normal-orthometric, etc.);
- vertical coordinates associated with different reference epochs (in general, dH/dt is unknown and therefore omitted);

Table 4.9: *Summary of geophysical effects and their magnitudes.*

Effect	**Geometry on land**	**Terrestrial gravity**	**Geopotential numbers**	**Geoid**
Solid Earth permanent tide	elastic response of the Earth −0.12 m at pole, +0.06 m at equator, or hydrostatic equilibrium −0.28 m at pole, +0.14 m at equator	hydrostatic equilibrium at pole: $+0.61\,\mu\mathrm{m\,s^{-2}}$ at equator: $-0.30\,\mu\mathrm{m\,s^{-2}}$	equipotential surfaces move as the geoid, but simultaneously	anelastic response of the Earth −0.19 m at pole, +0.10 m at equator
Periodic components of the Solid Earth tide (modeled as elastic response of the Earth)	at pole: −0.18 m (Moon), −0.08 m (Sun), at equator: +0.36 m (Moon), +0.16 m (Sun)	Moon: -1.1 to $+0.5\ \frac{\mu\mathrm{m}}{\mathrm{s}^2}$, Sun: -0.5 to $+0.3\ \frac{\mu\mathrm{m}}{\mathrm{s}^2}$	Moon: ±0.056 mm per km of levelling, Sun: ±0.026 mm per km of levelling	as undisturbed sea level −0.26 m at pole, +0.52 cm at equator
Solid Earth pole tide (modeled as hydrostatic equilibrium)	±0.0270 m (vert), ±0.0070 m (hz)	$< +0.082\,\mu\mathrm{m\,s^{-2}}$ (at latitude 45°)	±3 cm in 430 days	±0.0270 m
Oceanic pole tide (modeled as hydrostatic equilibrium)	±0.0018 m (vert), ±0.0005 m (hz)	unknown	negligible	±0.0018 m
LOD variations (modeled as hydrostatic equilibrium)	up to 1 m	0.0007 to 0.007 $\frac{\mu\mathrm{m}}{\mathrm{s}^2}$	negligible	negligible
Tidal ocean loading	±0.10 m	±(0.01 to 0.02) $\frac{\mu\mathrm{m}}{\mathrm{s}^2}$	negligible	unknown
Non-tidal ocean loading	unknown	unknown	unknown	10 mm in 100 to 1000 km
Tidal atmospheric loading	±0.0015 m	$< 0.003\,\mu\mathrm{m\,s^{-2}}$	negligible	unknown
Non-tidal atmospheric loading	unknown	-0.003 to -0.004 $\mu\mathrm{m\,s^{-2}}$/hPa	unknown	15 mm in 20 to 2000 km
Tidal hydrologic loading (groundwater)	±0.050 m	unknown	negligible	unknown
Non-tidal hydrologic loading (groundwater, snow, ice)	±0.050 m	0.05 to 0.1 $\mu\mathrm{m\,s^{-2}}$	unknown	10 to 12 mm in 10 to 8000 km
Secular changes (like tectonics, GIA, subsidence, etc.)	up to 0.1 m/yr	unknown	up to 0.1 m/yr	unknown

– systematic effects and distortions, e.g., long-wavelength (quasi-)geoid errors, poorly modeled radial effects in GNSS positioning, over-constrained levelling network adjustments, systematic errors in levelling, etc.;

– assumptions and theoretical approximations taken into account for the data processing; e.g., hypotheses in geoid and orthometric height computation, atmospheric delay in GNSS, neglecting ocean dynamic topography at tide gauges, etc.;

– dissimilar approaches to reduce the same effect in the different height types, in particular, the treatment of the luni-solar permanent tide;

– systematic and random errors in the different height types h, H, and N.

To overcome these deficiencies, it is necessary, among other tasks,

– to unify (standardize) the existing height systems; i.e., to refer all physical heights to one and the same reference level (defined and realized globally);
– to introduce geopotential numbers as the primary vertical coordinate in order to avoid inconsistencies caused by different gravity reductions in the height determination;
– to guarantee that geometrical and physical heights represent the same Earth's surface geometry; i.e., the

so-called regularized station positions should include consistent reductions, especially the treatment of the permanent tide. In the same way, the secular changes should be included in both representations: geometrical (dh/dt) and physical (dH/dt) heights;

- to adopt a conventional global gravity model to be used as the long-wavelength component in the estimation of (quasi-)geoid models of high resolution.

Table 4.10 shows some examples about the requirements and present limitations concerning the combination of physical and geometric heights.

4.6.4 Links to other products

To best exploit the advantages offered by space geodetic techniques, especially in the combination of GNSS positioning and satellite-based (quasi-)geoid models, modern height systems should support with high precision the integration of physical and geometrical coordinates. For that purpose the interaction of the following IAG/GGOS components and products is necessary

GGOS Focus Area 1 Unified Height System: to assess its requirements for the definition and realization of a unified global vertical reference system.

IAG Commission 1 (Reference Frames): to identify strategies, standards and conventions needed to increase the accuracy of the geometrical heights.

IAG Commission 2 (Gravity Field) and **ISG (International Service for the Geoid)**: to identify strategies, standards and conventions needed to increase the accuracy of the (quasi-)geoid modeling.

IAG Sub-commissions 1.3 (Regional Reference Frames), 2.1 (Gravimetry and Gravity Networks) and 2.4 (Regional Geoid Determination): to assess the detailed characteristics of the existing height systems in order to extent the global vertical reference frame activities to national and regional level.

IERS and IGS: to recognize the standards applied for the computation of the geometric vertical coordinates and to align (if necessary) these standards with those outlined/applied by the gravity community.

IGS Working Group Tide Gauge Benchmark Monitoring (TIGA) and **Permanent Service for Mean Sea Level (PSMSL)**: to connect the local height-zero levels to the terrestrial reference frame and to model the sea surface topography at the reference tide gauges.

IGFS and ICGEM: to identify the most appropriate global gravity model to compute the long-wavelength components of the global reference surface.

BGI and **IAG Sub-commissions 2.1 (Gravimetry and Gravity Networks) and 2.4 (Regional Geoid Determination)**: to improve the availability of terrestrial (shipborne and airborne) gravity data for the computation of the medium-wavelength components of the global reference surface.

IDEMS: to identify the most appropriate elevation models to estimate the terrain effects in the (quasi-) geoid modeling (short-wavelength components of the global reference surface).

This list is far from being complete and it includes *expected* products, which currently do not exist or have not been considered by some IAG/GGOS components.

4.6.5 The IAG resolution for the definition and realization of an *International Height Reference System (IHRS)*

A first concrete step oriented to the establishment of a worldwide unified (standardized) vertical reference system is the release of an IAG resolution for the *definition and realization of an International Height Reference System (IHRS)*. This resolution was issued during the IUGG 2015 General Assembly and outlines five basic conventions for the definition of the IHRS. The definition is given in terms of potential parameters: the vertical coordinates are geopotential numbers ($-\Delta W_P = C_P = W_0 - W_P$) referring to an equipotential surface of the Earth's gravity field realized by the IAG conventional value $W_0 = 62\ 636\ 853.4\ \mathrm{m^2 s^{-2}}$. The spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is given by coordinates $\mathbf{X}$ of the ITRF. This resolution also states that parameters, observations, and data should be related to the mean tidal system/mean crust. This is in contradiction with the IAG resolution No. 16 (1983); however, the mean tidal system is necessary to support oceanographic applications, especially in coastal areas. In this way, a clear statement for the transformation of the IHRS products from one tide system to the others is required. More details about the foundations of this IAG resolution can be found in [Ihde et al. 2015] and [Sánchez et al. 2015].

At present, the main challenge is the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). It is expected that the IHRF follows the same structure as the ITRF: a global network with regional and national densifications, whose geopotential numbers referring to the global IHRS are

Table 4.10: *Requirements and present limitations concerning the combination of physical and geometric heights (taken from [Sánchez 2012]).*

Requirement	Present status

Ellipsoidal heights h and (quasi-)geoid heights N must be given with respect to the same ellipsoid; i.e., the same ellipsoidal parameters have to be used
– for the transformation of geocentric Cartesian coordinates into ellipsoidal coordinates,
– as reference field for the solution of the geodetic boundary value problem,
– for scaling global gravity models, etc.
	– Different ellipsoidal parameters (a, GM) are applied in geometry and gravity.
	– h and N are given in different tide systems; e.g,
	  – mean-tide system in oceanography, satellite altimetry, levelling,
	  – conventional tide-free system in ITRF positions, GRS80, some (quasi-)geoid models,
	  – zero-tide system in some (quasi-)geoid models, terrestrial gravity data.

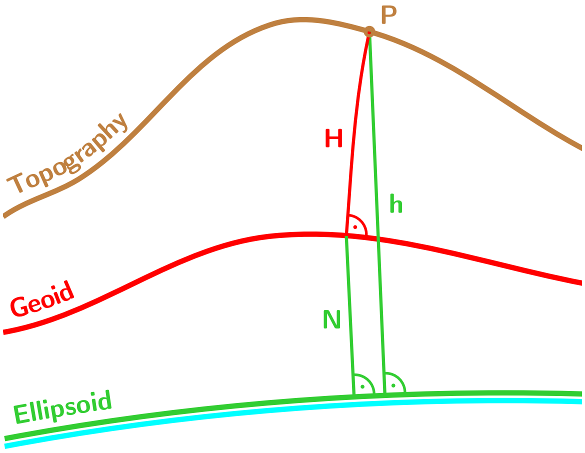
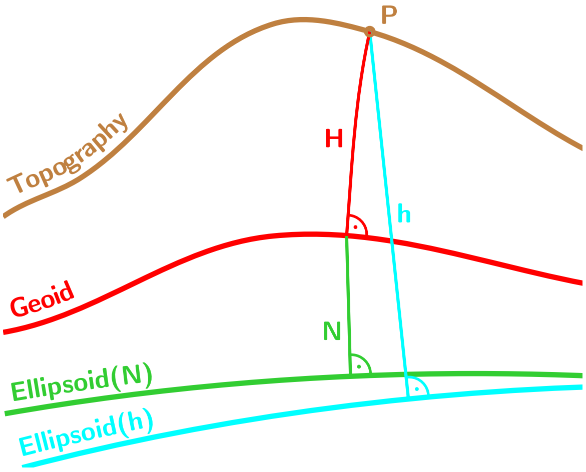
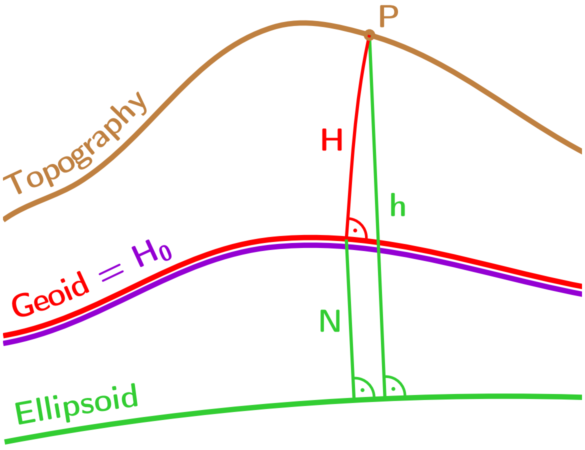
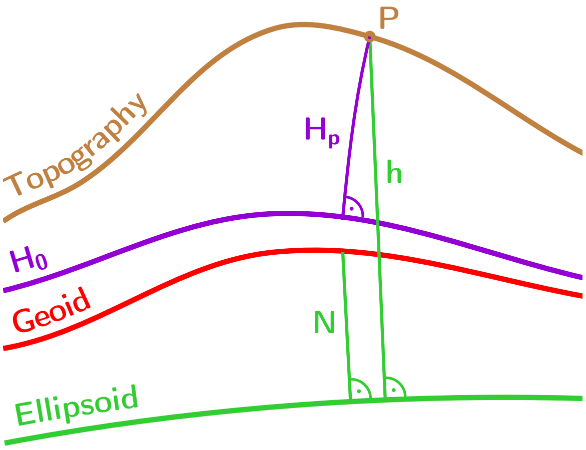
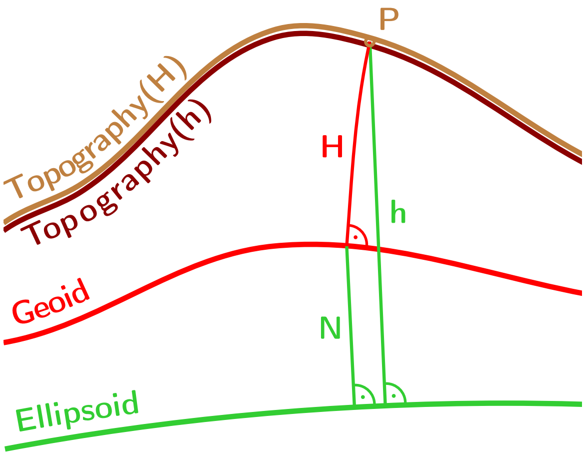
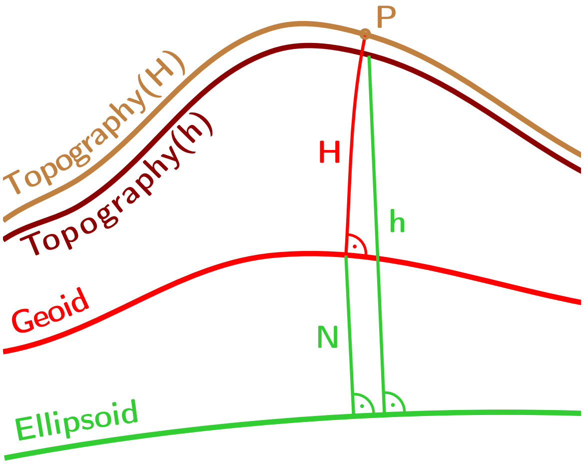
	
Physical heights H and (quasi-)geoid undulations N must reflect the same reference surface; i.e., the height reference surface H_0 obtained by subtracting the physical height H from the ellipsoidal height h shall be consistent with the (quasi-)geoid derived from gravity (solution of the boundary value problem).	– Orthometric heights H and geoid models N obtained from the solution of the boundary value problem are based on different hypotheses. – H and N refer to different tide systems. – Systematic errors over long distances in levelling reduce the reliability of H_0.
	

***Table 4.10** continued*

Requirement	Present status
Physical heights H and ellipsoidal heights h must represent the same Earth's surface	– H and h refer to different epochs and, in the most cases, dH/dt is unknown. – Different reductions (for Earth-, ocean-, atmospheric tides, ocean and atmospheric loading, post-glacial rebound, etc.) are applied.
	

known. According to the GGOS objectives, the target accuracy of these global geopotential numbers is $1 \cdot 10^{-2}$ m^{2}s^{-2}. In practice, the precise realization of the IHRS is limited by different aspects; for instance, there are no unified standards for the determination of the potential values W_P, the gravity field modeling and the estimation of the position vectors $\mathbf{X}$ follow different conventions, the geodetic infrastructure is not homogeneously distributed globally, etc. This may restrict the expected accuracy of $1 \cdot 10^{-2}$ m^{2}s^{-2} to some orders lower ($10 \cdot 10^{-2}$ m^{2}s^{-2} to $100 \cdot 10^{-2}$ m^{2}s^{-2}). Consequently, the next step is to outline the minimum set of fundamentals needed for a reliable and sustainable realization of the IHRS. These activities are being faced by the joint working group *Strategy for the Realization of the International Height Reference System (IHRS)*, which is a common initiative of GGOS Focus Area 1, IAG Commission 2 (Gravity field), IAG Commission 1 (Reference Frames), IAG Inter-commission Committee on Theory (ICCT), and the International Gravity Field Service (IGFS). The expected main result is a document similar to the IERS conventions; i.e. a sequence of chapters describing the different components to be considered for the realization of the IHRS and its practical utilization.

The activities of this working group are based on the results presented by previous work, in particular those of the *IAG Inter-Commission Project 1.2: Vertical Reference Frames* (conventions for the definition of World Height System, 2003–2011), *GGOS Focus Area 1* on the unification of height reference systems (since 2011), the ESA project *GOCE+ Height System Unification with GOCE* (2011–2014), the BPS (inventory of standards and conventions used for the generation of IAG products, since 2009), and the Joint Working Group on *Vertical Datum Standardisation* (2011–2015).

4.6.6 Open problems and recommendations

To improve the standardization of the existing height systems, it is necessary, among other issues, that meta-data describing the characteristics of the existing height systems be implemented. These meta-data should include for instance:

- epoch and time span applied for the mean sea level introduced as a zero-height;
- changes of the mean sea level and vertical position of the reference tide gauges;

- information about the levelling techniques applied to extend the vertical control through the countries;
- gravity reductions applied to the measured level differences;
- precision of levelling and gravity data;
- epoch and tide system to which the vertical coordinates refer, etc.

When this information is available, it would be possible to transform the existing physical heights in such a way that they can be combined with GNSS positioning and (quasi-)geoid models consistently. For that purpose, it is necessary to involve the national agencies responsible for the maintenance of vertical networks.

Since the vertical datum unification is based on the combination of levelling data (+ gravity reductions), GNSS positioning and (quasi-)geoid modeling, it is convenient to outline the minimal requirements to be satisfied by those stations used for this purpose. For instance, it is well-known that the vertical coordinates derived from GNSS positioning are strongly influenced by systematic errors and physical phenomena that reduce their accuracy considerably. The determination of the level discrepancies between different height systems should be determined including the most precise ellipsoidal heights only; i.e., at ITRF stations and regional densification stations like EPN, SIRGAS, NAREF, etc. These stations must also be connected by spirit levelling to the reference tide gauges; and gravity measurements along the levelling lines must be available for the computation of the corresponding geopotential numbers. Complementarily, the geoid models of high resolution should be estimated in a consistent manner. Currently, the geoid computation is not a unified or standardized procedure, and it is possible to find different geoid models over the same region although they are based on the same input data, i.e., there are as many geoids as computations. In addition, it is usual to compute improved geoid models, if new gravity data and new analysis strategies are available; however, it is not clear how frequently the geoid should be updated.

From the organizational point of view, it is necessary that the IAG/GGOS components named in the previous section precisely outline which products are under their responsibility and how they are generated. As a first step, a description similar to the IERS Conventions should be implemented for each product. The standards outlined by each IAG/GGOS component must be classified into a hierarchical structure, showing which of them have to be followed by everyone, which of them are applicable in geometry or gravity only, which of them are technique-specific, etc. Missing products must be identified and the necessary actions taken for their generation. This procedure has to be extended also to the marine and fluvial areas. At present, the discussion concentrates on the height systems on land areas; but the vertical coordinates on water and ice areas should also refer to the same global unified height system.

Summary of recommendations on height systems:

Recommendation 6.1: It is necessary that the IAG/GGOS components involved in the vertical coordinate determination should outline precisely which products are under their responsibility and how they are generated.

Recommendation 6.2 : To achieve the standardization of the existing height systems, it is necessary, among others, that meta-data describing the characteristics of the existing height systems be implemented.

Recommendation 6.3 : Since the vertical datum unification is based on the combination of levelling data (+ gravity reductions), GNSS positioning, and (quasi-)geoid modeling, the minimal requirements to be used for stations should be outlined.

5 Summary

The GGOS Bureau of Products and Standards (BPS), a redefinition of the former GGOS Bureau for Standards and Conventions (BSC) is operated by DGFI and IAPG of the Technische Universität München, within the Forschungsgruppe Satellitengeodäsie (FGS). The work of the BPS is primarily built on the IAG Services and the products they derive on an operational basis from various geodetic observation techniques such as VLBI, SLR/LLR, GNSS, DORIS, altimetry, gravity satellite missions, gravimetry, etc. The purpose and major goal of the BPS is to support GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth, along with its variations in time. In this context, it is essential to provide recommendations and guidelines to ensure that common standards and conventions are adopted and implemented by the IAG components.

According to its Terms of Reference, it is a key activity of the BPS to assess the standards and conventions currently adopted and used by IAG and its components for the processing of geometric and gravimetric observations as basis for the generation of IAG products. The outcome of this assessment is published in this document. This inventory gives a brief introduction into GGOS, including its mission and objectives and an overview about its structure. It presents some general information on standards and conventions and summarizes the current standards, standardized units, fundamental physical constants, resolutions, and conventions that are relevant for geodesy.

Chapter 3 provides the status regarding numerical standards, including time and tide systems and the geopotential value W_0. As shown in the inventory different sources for numerical standards are currently in use and the fundamental parameters are partly given in different time and tide systems, which is a potential source for inconsistencies and even errors in geodetic products. Thus, it is essential that the numerical standards and applied conventions be clearly documented for all geodetic products.

The key element of this document is the product-based inventory (Chapter 4) which addresses the following major topics:

Section 4.1	Celestial reference systems and frames,
Section 4.2	Terrestrial reference systems and frames,
Section 4.3	Earth orientation parameters,
Section 4.4	GNSS satellite orbits,
Section 4.5	Gravity and geoid,
Section 4.6	Height systems and their realizations.

As a major outcome, this inventory presents for each of these products (or topics) the current status regarding standards and conventions, identifies gaps and inconsistencies, and provides recommendations for improvements. At the end of each section the most important recommendations for each product (or topic) are summarized. These recommendations should be discussed with the dedicated experts in the field and future actions and responsibilities should be defined to resolve the remaining issues.

As the list of products addressed in the current version of this inventory is by far not complete, additional products that may be specified as IAG products will be included in an updated version of this document.

Glossary

AC	Analysis Center.
ACC	Analysis Center Coordinator.
AGN	Active Galactic Nuclei.
APKIM	Actual Plate KInematic Model.
ASI	Agenzia Spaziale Italiana.
BCRS	Barycentric Celestial Reference System.
BGI	Bureau Gravimetric International.
BIH	Bureau International de l'Heure.
BIPM	Bureau International de Poids et Mesures.
BKG	Bundesamt für Kartographie und Geodäsie.
BPS	GGOS Bureau of Products and Standards.
BSC	GGOS Bureau for Standards and Conventions.
CBE	Current Best Estimates.
CEOS	Committee of Earth Observation Satellities.
CIP	Celestial Intermediate Pole.
CLS	Collecte Localisation par Satellite.
CM	Center of Mass.
CNES	Center National d'Etudes Spatiales.
CODATA	Committee on Data for Science and Technology.
CODE	Center for Orbit Determination in Europe.
CTRS	Conventional Terrestrial Reference System.
DEM	Digital Elevation Model.
DGFI	Deutsches Geodätisches Forschungsinstitut.
DLR	Deutsches Zentrum für Luft- und Raumfahrt.
DORIS	Doppler Orbit Determination and Radiopositioning Integrated by Satellite.
ECMWF	European Center for Medium-Range Weather Forecasts.
EOP	Earth Orientation Parameters.
EPN	EUREF Permanent GNSS Network.
ERF	Epoch Reference Frame.
ERP	Earth Rotation Parameters.
ESA	European Space Agency.
EUREF	IAG Reference Frame Sub-Commission for Europe.
FA	Free-air Anomaly.
FCN	Free Core Nutation.
FESG	Forschungseinrichtung Satellitengeodäsie.
FGS	Forschungsgruppe Satellitengeodäsie.
FICN	Free Inner Core Nutation.
FK5	Fifth Fundamental Star Catalogue.
GCRS	Geocentric Celestial Reference System.
GEO	Group on Earth Observation.
GEOSS	Global Earth Observation System of Systems.
GFZ	Helmholtz Centre Potsdam, German Research Centre for Geosciences.
GGIM	Global Geospatial Information Management.
GGOS	Global Geodetic Observing System.
GGRF	Global Geodetic Reference Frame.
GIA	Glacial Isostatic Adjustment.
GIAC	GGOS Inter Agency Committee.
GIS	Geographic Information System.
GMF	Global Mapping Function.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System.
GPT	Global Pressure and Temperature.
GRS	Geodetic Reference System.
GRS80	Geodetic Reference System 1980.
GSFC	Goddard Space Flight Center.
IAG	International Association of Geodesy.
IAGBN	International Absolute Gravity Basestation Network.
IAPG	Institut für Astronomische und Physikalische Geodäsie.
IAU	International Astronomical Union.
ICET	International Center for Earth Tides.
ICGEM	International Center for Global Gravity Field Models.
ICRF	International Celestial Reference Frame.
ICRF2	Second Realization of the International Celestial Reference Frame.
ICRS	International Celestial Reference System.
ICSU	International Council for Science.
IDEMS	International Digital Elevation Model Service.
IDS	International DORIS Service.
IERS	International Earth Rotation and Reference Systems Service.
IGFS	International Gravity Field Service.
IGG	Institut für Geodäsie und Geoinformation, University Bonn.
IGN	Institut National de l'Information Géographique et Forestiere, France.
IGS	International GNSS Service.
IGSN71	International Gravity Standardization Net 1971.
ILRS	International Laser Ranging Service.

IRNSS	Indian Regional Navigation Satellite System.
ISG	International Service for the Geoid.
ISO	International Organization for Standardization.
ITRF	International Terrestrial Reference Frame.
ITRS	International Terrestrial Reference System.
IUGG	International Union of Geodesy and Geophysics.
IVS	International VLBI Service for Geodesy and Astrometry.
JPL	Jet Propulsion Laboratory.
JWG	Joint Working Group.
LEO	Low Earth Orbiter.
LLR	Lunar Laser Ranging.
NAREF	North American Reference Frame.
NASA	National Aeronautics and Space Administration.
NGA	National Geospatial-Intelligence Center.
NGS	National Geodetic Survey.
NIST	National Institute of Standards and Technology.
NNR	No Net Rotation.
NRCan	National Ressources Canada.
NSFA	IAU Division A Working Group Numerical Standards for Fundamental Astronomy.
OGC	Open Geospatial Consortium.
OMCT	Ocean Model for Circulation and Tides.
PCO	Phase Center Offset.
PCV	Phase Center Variation.
PREM	Preliminary Reference Earth Model.
PSMSL	Permanent Service for Mean Sea Level.
QZSS	Quasi-Zenith Satellite System.
SBAS	Space Based Augmentation System.
SI	International System of Units.
SIRGAS	Geocentric Reference Frame for the Americas.
SLR	Satellite Laser Ranging.
SOFA	Standards of Fundamental Astronomy.
SRP	Solar Radiation Pressure.
TCG	Geocentric Coordinate Time.
TDB	Barycentric Dynamical Time.
TEC	Total Electron Content.
TIGA	Tide Gauge Benchmark Monitoring.
TRF	Terrestrial Reference Frame.
TRS	Terrestrial Reference System.
TT	Terrestrial Time.
UN	United Nations.
USNO	United States Naval Observatory.
UTC	Coordinated Universal Time.
VLBI	Very Long Baseline Interferometry.
VMF1	Vienna Mapping Function 1.
WG	Working Group.
WGM	World Gravity Map.
WGRF	IAU Working Group on Reference Frames.
ZTD	Zenith Total Delay.

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