GGOS Bureau of Products and Standards

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

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Preface and scope of the document

The GGOS Bureau of Products and Standards (BPS), formerly known as Bureau for Standards and Conventions (BSC), has been established as a component of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) in 2009. 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 parameterisation 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 and to foster homogenisation of adopted geodetic standards and conventions across all components of the 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 acts as contact and coordinating point regarding homogenisation of standards and IAG products. Towards reaching these goals, the BPS has compiled an inventory of standards and conventions currently adopted and used by the IAG and its components for the processing of geometric and gravimetric observations as the basis for the generation of IAG products. The first version of such an inventory has been

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released in January 15, 2016 and published in the Geodesists Handbook 2016 (Angermann et al. 2016; Drewes et al. 2016).

Since 2016, a remarkable progress has been achieved in the field of standards and conventions as well as concerning the data analysis and generation of geodetic products, which will be reported in an updated version of this document. During the last four years, new realisations of the terrestrial and celestial reference systems, the ITRF2014 and ICRF3, as well as an updated series for the Earth Orientation Parameters (EOP 14 C04) were generated by the Product Centers of the International Earth Rotation and Reference Systems Service (IERS). In this time period also the modelling and data analysis of the contributing space techniques Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), Doppler Orbit Determination and Radiopositioning Integrated by Satellite (DORIS) have been significantly enhanced due to the efforts of the technique-specific IAG Services. Furthermore, a significant progress has been achieved in the field of gravity-related products provided by the gravimetric IAG Services as well as regarding the realisation of the International Height Reference Frame (IHRF). Data analysis issues that are common to all the space geodetic techniques are discussed at the Unified Analysis Workshops, which are co-organised by GGOS and the IERS. This updated version of the inventory also reflects the outcome of the two latest Workshops held in Paris in 2017 and 2019.

In this updated version of the inventory the general structure of the original document is largely kept, whereas the contents of the individual sections has been updated to take into account the latest developments. Some (unchanged) parts of the original version are also part of this updated version to ensure the readability as a “stand-alone” document. A summary of the updates is provided in the Document Change Record (see Table 1). This second version of the BPS inventory reflects the status of January 31, 2020.

The scope of this document is summarised as follows: Chapter 1 provides in the first section some general information about GGOS including its mission, goals and the organisational structure. The second part of this introductory chap-

Table 1: Document change record summarizing the major changes of the document.

Version/Date	Comments / Summary of Changes
1.0 2016-01-15	First version of the document Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products. In: Drewes H., Kuglitsch F., Adám J. (Eds.) The Geodesist’s Handbook 2016. Journal of Geodesy, 90(10), 1095–1156, 10.1007/s00190-016-0948-z, 2016
2.0 2020-01-31	Updated Version, prepared for publication in The Geodesist’s Handbook 2020 **Preface** updated. **Chapter 1.1** : IAG/GGOS structure updated, Fig. 1.2 updated. **Chapter 1.2** : Update of Standards and Conventions (e.g., ISO, CODATA, IUGG, IAG and IAU Resolutions), issues on IERS Conventions (e.g., re-writing/revising IERS Conventions) updated. **Chapter 2** : Update of BPS description and organisational structure. **Chapter 3** : Updates on numerical standards, outcome of GGOS/IERS Unified Analysis Workshops 2017 and 2019 incorporated, recommendations on numerical standards updated. **Chapter 4** : Updates of product-based review (see below). **Chapter 4.1** : Summary on ICRF2 (sect. 4.1.2) moved to section 4.1.3.1 “History of ICRS realisations”, new section 4.1.3.2 on ICRF3 included, other sections of 4.1 updated, recommendations updated. **Chapter 4.2** : New section 4.2.2 “History of ITRS realisations” included, former chapter on ITRF2008 shortened and moved to 4.2.2, new section on ITRF2014 (4.2.3) included, other sections of 4.2 updated, outcome of Unified Analysis Workshops incorporated, recommendations updated. **Chapter 4.3** : Section 4.3.2 updated (e.g., IERS EOP 08 C04 replaced by IERS EOP 14 C04), other sections of 4.3 updated, outcome of Unified Analysis Workshops incorporated, recommendations updated. **Chapter 4.4** : Updates on GNSS satellite orbits (e.g., satellite property information, satellite orbit models) and recommendations. **Chapter 4.5** : The chapter on gravity and geoid has been revised to incorporate the developments and the progress with the IGFS during the last four years, in this updated version also new and more specific recommendations are provided. **Chapter 4.6** : This chapter has been revised to incorporate the developments and the progress in the field of height systems and their realisations during the last four years, the recommendations have been revised. **Chapter 5** : A few minor updates have been performed in the summary. **Bibliography** : The references have been updated.

ter deals with standards and conventions from a general view along with some relevant nomenclature, and it presents current standards, standardised units, fundamental physical standards, resolutions and conventions that are relevant for geodesy. In the second chapter the mission and goals of the BPS are summarised, 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 it gives recommendations for future improvements. Chapter 4 is the key element of this document and it contains the product-based review, addressing the following topics: Celestial reference systems and frames, terrestrial reference systems and frames, EOP, GNSS satellite orbits, gravity and geoid, as well as height systems and their realisations. 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 problems and recommendations regarding standards and conventions for the generation of IAG products are provided. Finally, a summary and an outlook towards future developments is provided.

Acknowledgements

The original version of this BPS inventory (published in 2016) has been reviewed in a two step procedure. In the first step an (internal) review initiated by the BPS has been performed, followed by a second review cycle which was conducted under the responsibilty of the IAG Bureau (Chris Rizos, Hermann Drewes and Harald Schuh). The valuable contributions of the reviewers are acknowledged in the 2016 document (Angermann et al. 2016).

It was proposed by the IAG Bureau (Zuheir Altamimi, Markku Poutanen and Richard Gross) that the review of this updated version should be conducted in the same way as for the first version. Thus, it has been suggested that each chapter/product of the inventory should be reviewed by experts in these fields. The list of rewiewers is provided in Table 2. The contributions by all reviewers and the suppport of the IAG Bureau are gratefully acknowledged by the authors.

Table 2: Reviewers designated by IAG to evaluate this document.

Chapter	Reviewers
Chapter 1.1	Markku Poutanen (Finland), Martin Sehnal (Austria)
Chapter 1.2	Michael Craymer (Canada), Markku Poutanen (Finland), Chris Rizos (Australia)
Chapter 2	Markku Poutanen (Finland), Martin Sehnal (Austria)
Chapter 3	Pavel Novák (Czech Republic), Nico Sneeuw (Germany)
Chapter 4.1	John Gipson (USA), Axel Nothnagel (Germany)
Chapter 4.2	Zuheir Altamimi (France), Thomas Herring (USA)
Chapter 4.3	Aleksander Brzezinski (Poland), Richard Gross (USA)
Chapter 4.4	Rolf Dach (Switzerland)
Chapter 4.5	Riccardo Barzaghi (Italy), Adrian Jäggi (Switzerland)
Chapter 4.6	Matt Amos (New Zealand), Dru Smith (USA)

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.

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 organisation 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, and has been slightly revised in 2018.

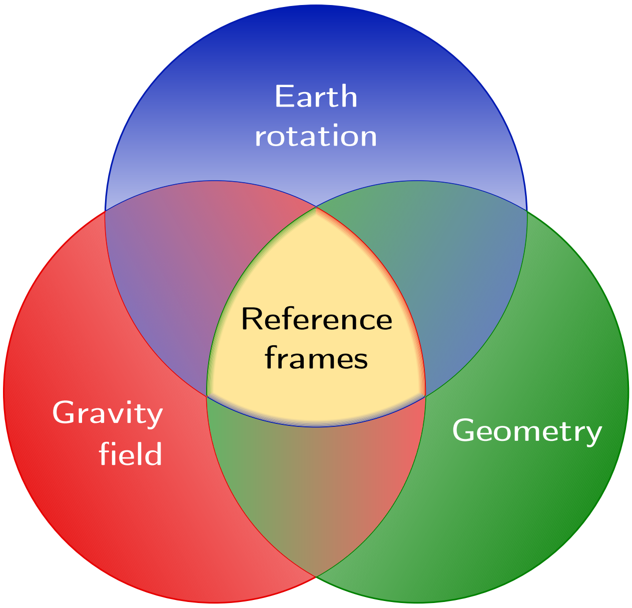


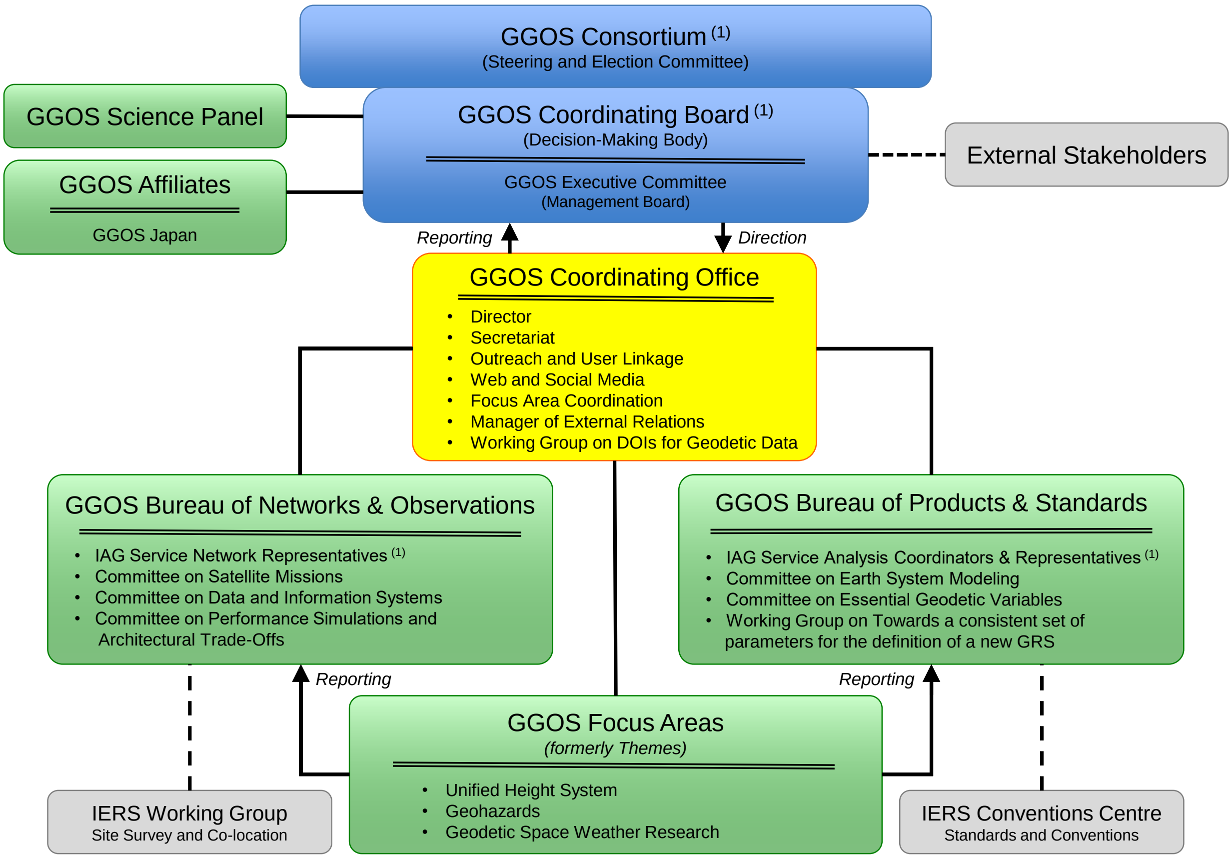
Fig. 1.1: Integration of the “three pillars” geometry, Earth rotation and gravity field (Rummel 2000), modified by (Plag and Pearlman 2009).

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 organisational 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, Standardisation, and Support**: Optimal coordination, support, and utilisation of IAG Services, as well as leveraging existing IAG resources, are critical to the progress of all GGOS goals and objectives.



(1) GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees

Fig. 1.2: Organisation structure of GGOS as adopted in December 2019.

4. **Communication, Education, Outreach**: Marketing, outreach, and engagement are critical elements for sustaining the organisational fabric of GGOS.

The organisational 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-to-day 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; and coordinates GGOS external relations. Newly established components within the Coordinating Office are the position of the Manager of External Relations and the GGOS Working Group on “DOIs for Geodetic Data Sets”.

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 Affiliates – are national or regional organisations that coordinate geodetic activities in that country or region. GGOS Affiliates allow increased participation in GGOS, especially by organisations in under-represented areas of Africa, Asia-Pacific, and South and Central America.

GGOS Committees, Working Groups and Focus Areas (formerly known as 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 organisations. 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) – was a forum that sought to generate a unified voice to communicate with Governments and Intergovernmental organisations (GEO, CEOS, UN bodies) in all matters of global and regional spatial reference frames and geodetic research and applications. GIAC was dissolved when the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) Working Group on the Global Geodetic Reference Frame (GGRF) was elevated to the permanent Subcommittee on Geodesy of the UN-GGIM.

UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) – led by United Nations Member States, UN- GGIM aims to address global challenges regarding the use of geospatial information and to serve as a body for global policymaking in the field of geospatial information management.

Subcommittee on Geodesy (UN-GGIM) (SCoG) – provides an intergovernmental forum for cooperation and exchange of dialogue on issues relating to the maintenance, sustainability and enhancement of the Global Geodetic Reference Frame (GGRF).

1.2 Standards and conventions

Standards and conventions are used in a broad sense and a variety of international organisations and entities are involved. This section gives an overview of the standards and conventions that are currently in use within the geodetic community. According to Drewes (2008) and Angermann (2012) one can distinguish between standards, standardised units, fundamental physical standards, resolutions and conventions. In addition, the background models used for the data analysis 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 organisations 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. Many standards related to geographic information, including geodetic reference systems, have been or are being developed by ISO Technical Committee 211. ISO/TC211 (committee.iso.org/home/tc211) was established to cover the areas of digital geographic information and geomatics. It aims to establish a set of standards information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth. These standards are linked to other appropriate ISO standards for information technology and data where possible, to provide a framework for the development of specific applications using geographic data. Some of the ISO standards related to geodetic reference systems include:

ISO 6709: Standard representation of geographic point location by coordinates (www.iso.org/standard/75147.html).

ISO 19111: Geographic information – Referencing by coordinates (www.iso.org/standard/74039.html).

ISO 19115-1: Geographic information – Metadata – Part 1 Fundamentals (www.iso.org/standard/53798.html).

ISO 19127: Geodetic Register (www.iso.org/standard/41784.html).

ISO 19135-1: Geographic information – Procedures for item registration (www.iso.org/standard/54721.html).

ISO 19161-1: Geographic information – The International Terrestrial Reference System (ITRS): definition, realisations and dissemination.

Also relevant for geodesy is the Open Geospatial Consortium (OGC), an international voluntary standards organisation, established in 1994. In the OGC, more than 400 governmental, commercial, nonprofit and research organisations worldwide collaborate in a consensus process encouraging the 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 chair and vice-chair of the Control Body for the ISO Geodetic Registry (geodetic.isotc211.org) are nominated by the IAG and the director of the BPS acts as the IAG liaison to ISO/TC211.

In February 2015, the UN General Assembly adopted its first geospatial resolution *"A Global Geodetic Reference Frame for Sustainable Development"*. The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) endorsed the GGRF Road Map and established a GGRF Working Group which became the UN-GGIM Subcommittee on Geodesy (SCoG) in 2017 (see www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/69/266 and www.unggrf.org/). Within this SCoG five Working Groups (former Focus Groups) have been established, addressing the areas of Geodetic Infrastructure; Policies, Standards, and Conventions; Education, Training and Capacity Building; Outreach and Communications; and Governance. Implementation Plans have been developed by these Working Groups that were detailed in the GGRF Road Map. Recommendations of the Working Group on Policies, Standards and Conventions are:

- Member States support the efforts already undertaken by IAG and standards organisations, including ISO, towards geodetic standards and to make these standards openly available.
- Member States more openly share their data, standard operating procedures and conventions, expertise, and technology.
- Member States resolve their concerns that currently limit data sharing, as a valuable contribution to the enhancement of the GGRF.

The standards and conventions that are relevant for geodesy are based primarily on decisions made by international organisations 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 the IAU, 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 Standardised 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 (CGPM, 1960), and revised at its 26th meeting in 2018 (effective from 20 May 2019), see www.bipm.org/utils/common/pdf/CGPM-2018/26th-CGPM-Resolutions.pdf.

According to these CGPM Resolutions the SI 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:

- The *second*, symbol [s], is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{CS}}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
- The *metre*, symbol [m], is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 1/299 792 458 when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{\mathrm{CS}}$.
- The *kilogram*, symbol [kg], is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \cdot 10^{-34}$ when expressed in the unit J s, which is equal to kg $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{\mathrm{CS}}$.

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 realisation 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" has been a service of the IAG until the end of 2019. 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 Science Council (ISC). 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, 2010 and 2014 (see, Mohr et al. 2016). The latest version, the 2018 least-squares adjustment of the values of the set of fundamental physical constants was released in 2019. The 2018 set replaces the previously recommended 2014 CODATA set and may also be found at www.physics.nist.gov/Constants. The fundamental physical constants are classified as universal, electromagnetic, atomic and nuclear, or physico-chemical constants as well as adopted values. The set of values provided by CODATA do not aim to cover all scientific fields. Only a few of these fundamental constants are relevant for geodesy, primarily two universal constants and two adopted values:

a) Universal constants
   - Newtonian constant of gravitation (G): $(6.674\,30 \pm 0.000\,15) \cdot 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}$
   - Speed of light in vacuum (c, c_0): $299\,792\,458\ \mathrm{m/s}$ (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).

The astrogeodetic community needs, in addition to these fundamental physical constants, a set of suitable fundamental parameters as a basis for the definition and realisation of reference systems as well as for the generation of geodetic products. The geodetic activities in this field are addressed by the IERS Conventions Center (see Section 1.2.5) in cooperation with international organisations such as CODATA, IUGG and IAU. The present status of numerical standards used within IAG is discussed in Section 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 IAG Geodesist's Handbook (www.iag-aig.org/geodesists-handbook). They are also available at office.iag-aig.org/iag-and-iugg-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 and Luzum 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 represent 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 summarised 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, recognising 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 (1) CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system; (2) the geocentric non-rotating system to be identical to the Geodetic Reference System (GRS) as defined in the IAU resolutions; (3) the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG); (4) the origin of the system to be the geocentre of the Earth's masses including oceans and atmosphere; and (5) the system to have no global residual rotation with respect to horizontal motions at the Earth's surface.

IAU Resolution A4 (1991) has set up a General Relativistic Framework to define reference systems centred at the barycentre of the solar system and at the geocentre.

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 Realisation 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 (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 harmonise 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 and Luzum 2010).

IAU Resolution B3 (2006) is on the re-definition of Barycentric Dynamical Time (TDB) (for more information see the IERS Conventions 2010, Petit and Luzum 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 organisations 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 realisation 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 Earth Orientation Parameters (EOP) as observed and realised by the IAG and its components such as the IERS should be a primary goal in all future realisations 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.

IAG Resolution No. 1 (2015) for the Definition and Realisation 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.

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) recognising 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 organisations such as the Committee of Earth Observation Satellites (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.

IAU Resolution A1 (2018) on the IAU Strategic Plan 2020–2030.

IAU Resolution B1 (2018) on Geocentric and International Terrestrial Reference Systems and Frames. It recommends that the ITRS be adopted as the preferred GTRS for scientific and technical applications; and that the IAU engage, together with other concerned organisations such as the IUGG and IAG, with the United Nations (UN) Global Geospatial Information Management (GGIM) Subcommittee on Geodesy in order to promote the implementation of the UN-GGIM Road Map for the Global Geodetic Reference Frame.

IAU Resolution B2 (2018) on the Third Realisation of the International Celestial Reference Frame. It resolves that, as from 1 January 2019, the fundamental realisation of the International Celestial Reference System (ICRS) shall be the Third Realisation of the International Celestial Reference Frame (ICRF3), as constructed by the IAU Working Group on the Third Realisation of the International Celestial Reference Frame.

IAG Resolution No. 1 (2019) on the International Terrestrial Reference Frame (ITRF). It recommends to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames.

IAG Resolution No. 2 (2019) on the Third Realisation of the International Celestial Reference Frame. It recommends (1) that the ICRF3 should be used as a standard for all future applications in geodesy and astrometry; (2) that the organisations responsible for geodetic VLBI observing programs take appropriate measures to continue existing and develop improved observing and analysis programs to both maintain and improve ICRF3, and (3) that highest consistency between the ICRF, the ITRF, and the EOP should be a primary goal in all future realisations.

IAG Resolution No. 3 (2019) on the Establishment of the International Height Reference Frame (IHRF). It urges all countries to engage with the IAG and concerned components, in particular the International Gravity Field Service (IGFS), in order to promote and support the implementation of the IHRF by (1) installing IHRF reference stations at national level; (2) conducting the necessary gravimetric surveys to guarantee the precise determination of potential values; (3) making data available open access; (4) contributing to the development of analysis strategies to improve the estimation of reference coordinates and modelling of the Earth's gravity field; and (5) describing, archiving and providing geodetic products associated to the IHRF.

IAG Resolution No. 4 (2019) on the Establishment of the Infrastructure for the International Gravity Reference Frame. It urges international and national institutions, agencies and governmental bodies in charge of geodetic infrastructure to (1) establish a set of absolute gravity reference stations on the national level; (2) perform regular absolute gravity observations at these stations; (3) participate in comparisons of absolute gravimeters to ensure their compatibility; and (4) make the results available open access.

IAG Resolution No. 5 (2019) on the Improvement of the Earth's Rotation Theories and Models. It resolves (1) to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOP; (2) that the definition of all the EOP, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components; and (3) that the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

IUUG Resolution No. 2 (2019) on the International Terrestrial Reference Frame (ITRF). It resolves to recommend to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth Science applications, as well as for the definition and alignment of national and regional reference frames.

1.2.5 Conventions

A convention is a set of agreed, stipulated or generally accepted norms, standards or criteria. In the 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 the IAG and its components (Services, Commissions, Inter-Commission Committees, and GGOS). Most established and common are the conventions of the IERS, which are provided by the IERS Conventions Center. 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, etc). Since these reference frames are based on the geometric measurement techniques GNSS, SLR/LLR, VLBI and DORIS, the IERS Conventions provide the basis for the work of the geometric services of the 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 and Behrend 2012), and the International DORIS Service (IDS) (Willis et al. 2010).

The latest printed version are the IERS Conventions 2010 (Petit and Luzum 2010). They consist of eleven chapters that focus on topics, such as general definitions and numerical standards, the definition and realisation 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 official release of the IERS Conventions 2010 was on December 15, 2010. Updates are available at iers-conventions.obspm.fr/conventions_versions.php.

In 2018, the IERS Conventions Center released a Call to Participate in the IERS Conventions seeking volunteer participants as Chapter Editor-in-Chief, Chapter/Assistant Experts, and Software Editor to contribute to the revision of these conventions. The IERS Conventions Center intends to publish a new edition by 2022. Meanwhile, a team of experts for the revision of the IERS Conventions has been established and a work plan (including time schedule) has been defined by the IERS Conventions Center. The director of the BPS has been nominated as Chapter Expert for Chapter 1 "General definitions and numerical standards" and two representatives of the International Gravity Field Service (IGFS) accepted the invitation of the IERS Conventions Center to contribute to the rewriting of this chapter. Hence, for the first time, the gravity field community is directly involved in the development of definitions and numerical standards.

Although the IERS Conventions primarily serve as reference for the geometric observation techniques and products of the IERS, several parts of them also provide the basis for gravity-related data and products. However, for satellite gravity field missions (e.g., CHAMP, GRACE, GOCE), specific standards and conventions have to be used for the data analysis and product generation such as, e.g., EIGEN (Förste et al. 2012), GOCE (European GOCE Gravity Consortium 2014), EGM2008 (Pavlis et al. 2012). These gravity-related standards are not always fully consistent with the IERS Conventions, since also mission constraints (e.g., consistency with respect to former missions) have to be adhered to. Other satellite missions (e.g., altimetry, SAR, remote sensing, . . .) are also often based on standards and conventions issued by the operating agencies such as ESA, CNES or NASA, which may also be different to the IERS Conventions.

In summary, there are currently different conventions in use for the analysis of geometric and gravimetric observations, which need to be carefully considered when different observation types are combined. This situation is not ideal for ensuring a consistent integration of the geometry, rotation and gravity field of the Earth, which is a key goal of GGOS. Thus, the development of a consistent set of conventions is an important requirement that the BPS will address.

1.2.6 Physical and empirical background models

The background models play an important role for the processing of the different space geodetic measurements and for the generation of geodetic products. This is a very broad topic since a large number of background models need to be applied to account for various geophysical phenomena and technique-specific effects. In this section we will address this topic only very shortly to give a brief overview and we refer to the IERS Conventions, which serve as the primary reference for the background models to be used for the analysis of the space geodetic measurements and the product generation. In addition to the IERS Conventions, the technique-specific IAG Services provide specific information for the corresponding space techniques.

Two types of correction models can be distinguished:

- Models to correct for 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, etc).

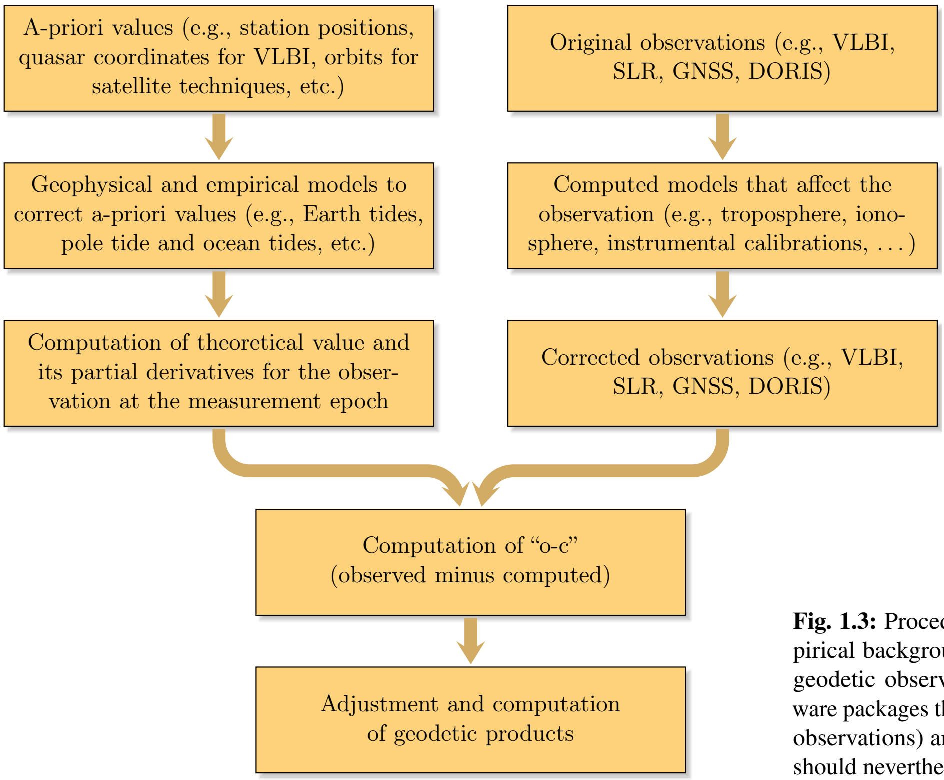


Fig. 1.3: Procedure for applying geophysical and empirical background models in the processing of space geodetic observations. Please note that in some software packages the second type of models (that affect the observations) are applied to the a-priori values, which should nevertheless lead to identical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

- Models to account for effects that directly influence the space geodetic observations such as signal propagation (atmosphere) and technique-specific effects (e.g. GNSS antenna phase centre variations, thermal deformation of VLBI telescopes, SLR range biases, etc).

The first type of models are applied to the a-priori values for station coordinates, satellite orbits and quasar positions (in the case of VLBI), whereas the second type are generally computed in the observation space, but could 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 used as 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 parameterised 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, for example, parameters in the solar radiation pressure model or harmonic coefficients in the description of the Earth's gravitational potential.

Clearly these background models need to be developed with a specific level of accuracy and that these models have to be consistently applied according to well-defined standards and conventions. This is essential for the processing of the different space geodetic observations and a strong requirement for the generation of consistent geodetic products. The IAG Services are responsible for the definiton of the processing standards for their particular space gedetic technique, but this should be done in a coordinated way to ensure consistency of the derived products. Hence it is necessary to address this topic and a perfect forum for this are the Unified Analysis Workshops which take place every two years.

The evolution of the scope and accuracy of the space geodetic observations also requires a continuous improvement of the background models which should be used for the data analysis and which must be implemented in the various software packages. This is a continuous process involving many groups and institutions. A challenge is to ensure that the generation of the geodetic products is based on homogeneously processed observations. This holds in particular for the ITRF generation (see section 4.2), since it requires a unification of the models and processing standards among all the contributing analysis and combination centres of the geometric services as basis for a consistent reprocessing of the VLBI, SLR, GNSS, and DORIS data over the entire observation time spans for these space geodetic techniques. The Unified Analysis Workshops, the workshops of the geometric services and the IERS Directing Board meetings provide forums to discuss the relevant issues in detail.

2 GGOS Bureau of Products and Standards

The GGOS Bureau of Products and Standards (BPS) is a redefinition of the former GGOS Bureau for Standards and Conventions (BSC), which was established as a GGOS component in 2009. The BPS is operated by the Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM) and the Ingenieurinstitut für Astronomische und Physikalische Geodäsie of the Technische Universität München (IAPG) within the Forschungsgruppe Satellitengeodäsie (FGS) (Angermann et al. 2016, 2018; Hugentobler et al. 2012).

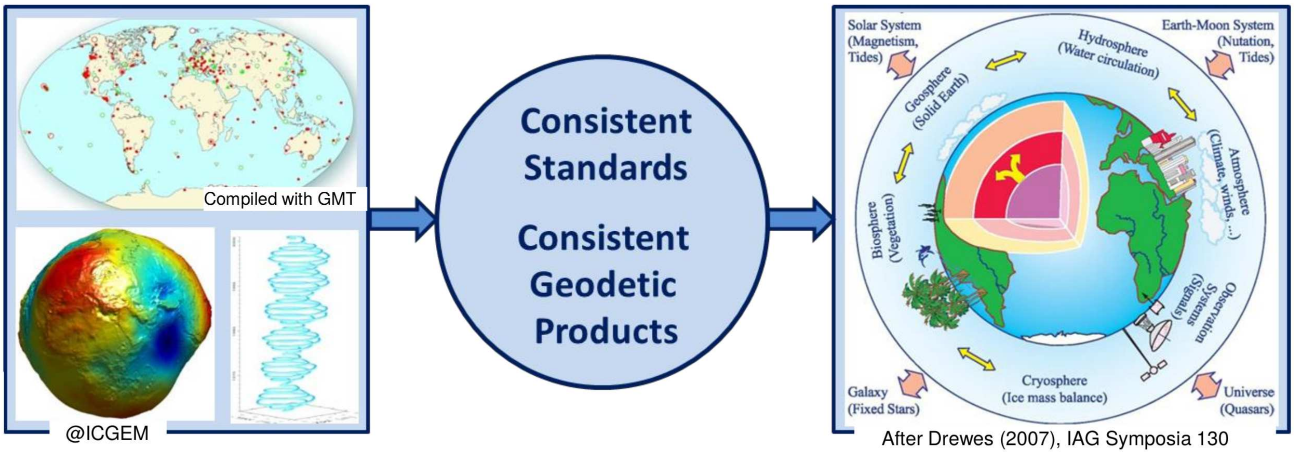
2.1 Mission and objectives

The Bureau of Products and Standards (BPS) supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth. This is an important requirement for reliably monitoring global change phenomena (e.g., global sea level rise) and for providing the metrological basis for Earth system sciences. Figure 2.1 illustrates the integration of the "three pillars" geometry, Earth rotation and gravity field to obtain consistent geodetic products as the basis for studying the Earth system and the interactions between its sub-components and the outer space (e.g., Rummel, 2000; Drewes, 2007; Plag and Pearlman, 2009).

A key objective of the BPS is to keep track of adopted geodetic standards and conventions across all IAG components 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 homogenisation of standards and IAG products. Moreover, the BPS interacts with external stakeholders that are involved in standards and conventions, such as the International Organisation for Standardisation (ISO), the Committee on Data for Science and Technology (CODATA), the International Astronomical Union (IAU) and the UN GGIM Subcommittee on Geodesy (SCoG).

The objectives of the BPS may be divided into two major topics/activities:

- **Standards**: A key objective is the compilation of an inventory regarding standards, constants, resolutions and conventions adopted by IAG and its components. This includes an assessment of the present status, the identification of gaps and shortcomings concerning geodetic standards and the generation of the IAG products, as well as the provision of recommendations. It is obvious that such an inventory needs to be regularly updated since the IAG standards and products are continuously evolving. The BPS shall propagate standards and conventions to the wider scientific community and promote their use. Where necessary, the BPS should propose new standards. In this context, the BPS recommends the development of a new geodetic reference system, GRS20XX, based on the best estimates of the major parameters related to a geocentric level ellipsoid.
- **Products**: The BPS shall take over a coordinating role regarding the homogenisation of standards and geodetic products. The present status regarding IAG Service products shall be evaluated, including analysis and combination procedures, accuracy assessment with respect to



Compiled with GMT

@ICGEM

After Drewes (2007), IAG Symposia 130

Fig. 2.1: The key role of standards and conventions for consistent geodetic products as the basis for Earth system research, for studying interactions between its sub-components and for precisely quantifying global change phenomena.

GGOS requirements, documentation and metadata information for IAG products. The Bureau shall initiate steps to identify user needs and requirements for geodetic products and shall contribute to develop new and integrated products. The BPS shall also contribute to the development of the GGOS Portal (as central access point for geodetic products), to ensure interoperability with IAG Service data products and external portals (e.g., GEO, EOSDIS, EPOS, GFZ Data Services).

2.2 Tasks

The tasks of the Bureau of Products and Standards are to:

- act as contact and coordinating point for homogenisation of IAG standards and products;
- keep track of adopted geodetic standards and conventions across all IAG components, and initiate steps to close gaps and deficiencies;
- interact with external stakeholders in the field of standards and conventions (e.g., IAU, ISO, BIPM, CODATA, UN-GGIM, . . .);
- act as IAG representative to ISO/TC 211 and to the UN-GGIM GGRF Working Group “Data Sharing and Development of Geodetic Standards”;
- contribute to the UN GGIM Subcommittee on Geodesy (SCoG), mainly to the Working Group “Data Sharing and Development of Geodetic Standards”;
- regularly update the inventory on standards and conventions used for the generation of IAG products to incorporate the latest developments in these fields;
- contribute to the re-writing/revising of the IERS Conventions, mainly in the function as Chapter Expert for Chapter 1 “General definitions and numerical standards“;
- focus on the integration of geometric and gravimetric observations, and to support the development of integrated products (e.g., GGRF, IHRF, atmosphere products);
- contribute to the Committee on Essential Geodetic Variables (EGV), such EGVs could then serve as a basis for a gap analysis to identify requirements concerning observational properties and networks, accuracy, spatial and temporal resolution and latency;
- contribute to the newly established Working Group "Towards a consistent set of parameters for the definition of a new GRS";
- contribute to the GGOS Working Group on “DOIs for Geodetic Data Sets”, focusing on Digital Object Identifier (DOI) for geodetic data and products to improve discoverability of data sets and to ensure that data providers receive proper credit for their published data;
- organisational and coordination issues as well as representation and outreach activities, including internal BPS meetings (every two months), external Bureau meetings (twice per year), representing the BPS within IAG and at conferences and workshops, presentation and publication of BPS activities.

2.3 Staff and representation of IAG components and other entities

The present BPS staff members are Detlef Angermann (director), Thomas Gruber (deputy director), Michael Gerstl, Urs Hugentobler and Laura Sánchez (all from Technical University Munich), as well as Robert Heinkelmann (GFZ German Research Centre for Geosciences Potsdam) and Peter Steigenberger (German Aerospace Centre (DLR), Oberpfaffenhofen).

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

- Committee “Contributions to Earth System Modelling”, Chair: M. Thomas (Germany);
- Committee “Definition of Essential Geodetic Variables (EGVs)”, Chair: R. Gross (USA);
- Working Group “Towards a consistent set of parameters for the definition of a new GRS”,
  Chair: U. Marti (Switzerland).

According to its charter, the work of the BPS requires a close interaction with the IAG Analysis and Combination Centers regarding the homogenisation of 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 two committees and the working group as listed above, as well as representatives of the IAG Services and other entities. The status of December 2019 is summarised in Table 2.1. Regarding the development of standards, there is a direct link with the IERS Conventions Center, the IAU, BIPM, CODATA, ISO, and the UN-GGIM Subcommittee on Geodesy.

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 homogenisation 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 2019).

T. Herring, N. Stamatakos, USA	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)
S. Bonvalot, France	Bureau Gravimétrique International (BGI)
M. Reguzzoni, Italy	International Service for the Geoid (ISG)
E. S. Ince, Germany	International Centre for Global Earth Models (ICGEM)
K. M. Kelly, USA	International Digital Elevation Model Service (IDEMS)
H. Wziontek, Germany	International Geodynamics and Earth Tide Service (IGETS)
J. L. Hilton, USA	IAU Commission A3 Representative
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	IAG Communication and Outreach Branch
D. Angermann, Germany	IAG representative to ISO/TC211
J. Kusche, Germany	Representative of gravity 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 conventional reference for geodetic work. The GRS80 is defined by four constants GM, a, J_2 and ω, see Table 3.1. The GRS80 is now about 40 years old and thus these conventional constants do not represent anymore good estimates of parameters defining geometric and gravity field models best fitting to the shape and gravity field of the current Earth. In the concept of GRS80, the tidal systems and relativistic theories are not considered (Ihde et al. 2017). However, the IAG recommends the GRS80 parameters as a conventional ellipsoid, i.e., to convert Cartesian coordinates into ellipsoidal coordinates. The GRS80 ellipsoid 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 so we should better speak about *fundamental parameters* instead of *constants* (Groten 2004). Since a substantial progress has been achieved in the estimation of these fundamental parameters and their temporal changes, 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 a new GRS at that time. Nevertheless, some progress was made and a consistent set of fundamental parameters and their current (2004) best estimates have been compiled (Groten 2004). The paper lists several possible values for the parameters. The set of constants defined in Section III of that paper is included in the IERS Conventions 2010 (Petit and Luzum 2010). Table 3.1 summarises the numerical standards given in different sources, namely the conventional GRS80 constants (Moritz 2000), the Earth Gravitational Model 2008 (EGM 2008), (Pavlis et al. 2012), the fundamental parameters of (Groten 2004), the IERS Conventions 2010, and the updated version (2017) of the IERS Conventions 2010 which contains the new conventional geopotential value W_0 issued in the IAG (2015) Resolution No. 1 (Drewes et al. 2016).

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 to define a reference level ellipsoid and its normal gravity field (e.g., the IERS Conventions 2010, Chapter 4, recommend to use the GRS80 ellipsoid to compute geographical coordinates). Except for the angular rotation velocity ω, all other GRS80 parameters 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 adopted standards for EGM 2008 were defined in the same geodetic reference system as adopted for EGM 96 (Lemoine et al. 1998) to ensure consistency between both gravitational 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.

In 2017, in cooperation between the IERS Conventions Center and the BPS, the IAG 2015 conventional value $W_0 = 62\,636\,853.4\,\mathrm{m}^2\mathrm{s}^{-2}$ has been updated in Chapter 1 of the IERS Conventions (Stamatakos 2017, pers. communication). Thus, the former difference beween the IERS Conventions 2010 value and the new IAG 2015 value of about $-2.6\,\mathrm{m}^2\mathrm{s}^{-2}$ (equivalent to a level difference of about 27 cm) has been resolved.

Without going into detail on time systems, it should be mentioned that the IUGG Resolution No. 2 (1991) recommends that the Geocentric Coordinate Time (TCG) shall be used for the geodetic reference system. In practice, however, analysis centres of all IAG geometric services use a time standard consistent with the Terrestrial Time (TT). As described in the IERS Conventions the relation between both time standards is given by the equation

$$L_G = 1 - d(\mathrm{TT})/d(\mathrm{TCG}) = 6.969290134 \cdot 10^{-10} \tag{3.1}$$

Thus, the difference between both time standards 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),

$$GM_{\mathrm{TT}} = GM_{\mathrm{TCG}}\,(1 - L_G)\,. \tag{3.2}$$

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 and Luzum 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

Table 3.1: Comparison of numerical standards used within IAG.

	semi-major axis a [m]	Geocentric Grav. Constant GM $[10^{12}\mathrm{m}^3\mathrm{s}^{-2}]$	Dyn. form factor J_2 $[10^{-6}]$	Earth's rotation ω $[\mathrm{rad\ s}^{-1}]$	Reference potential W_0 $[\mathrm{m}^2\mathrm{s}^{-2}]$
GRS80	6 378 137	398.600 5	1 082.63	7.292 115	(1)
EGM2008	6 378 136.3	398.600 4415(2)	1 082.635 9	7.292 115	62 636 856.0
IERS Conv. 2010	6 378 136.6(3)	398.600 4418(4)	1 082.635 9	7.292 115	62 636 856.0
. . . (update 2017)					62 636 853.4(5)

(1) The reference potential U_0 of the GRS80 is 62 636 860.850 $\mathrm{m}^2\mathrm{s}^{-2}$;

(2) TT-compatible value; (3) value given in zero-tide system; (4) TCG-compatible value;

(5) value updated in the IERS Conv. 2010 in agreement with the conventional W_0 adopted by the IAG Resolution No. 1, 2015.

the Earth shall not be removed (IAG 1984). In the geodetic community the following different tidal systems are in use and have to be distinguished (Denker 2013; Mäkinen and Ihde 2009; Petit and Luzum 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) are 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 of IAG provide their products mostly in the zero-tide system, in agreement with the IAG resolution No. 16 of the 18th IUGG General Assembly 1983, the geometric services supply their products, e.g., ITRF, in the conventional tide-free system. However, the ITRF has adopted, by convention, the same tide system as the analysis centres of IAG services. 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 Open problems and recommendations

There are currently different numerical standards in use within the geodetic community. The parameters of the GRS80 are still used to define a reference level ellipsoid and normal gravity field of the Earth, although it represents the state-of-the-art of the 1970s (methods and data) and it also does not consider tidal effects and relativistic theories. The IERS Conventions 2010 (and its updates) are widely used within geodesy and they form the basis for processing of geometric observations and for generation of the IERS products. In addition to the IERS Conventions, various mission-dependent standards and conventions are used for gravity-related products and in satellite altimetry, which are often not fully consistent with the IERS Conventions. Another shortcoming of the current situation is that the conventional parameters are partly given in different time and tide systems, being a potential source of errors when combining different products.

The foundations of the IAG Resolution No. 16 (1983) are still valid concerning the tide systems. The recommended zero-tide system is the most adequate tide system for the gravity acceleration and 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's 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 should not be changed. The current practice is to use the "conventional" tide-free system for geometry (ITRF), zero-tide system for gravity, mixed (mostly mean-tide system) for physical heights (derived from levelling), and mostly mean-tide system for satellite altimetry. This situation makes the use of geodetic products rather complicated and the inconsistent treatment of the permanent tide should be resolved within IAG.

Another issue concerns the time-tagging: at present, different space techniques and sometimes also different groups working within the same technique use different time standards, for example GPS time vs. UTC. The offset between different time standards does not affect the comparison of most geodetic parameters. However, if a particular parameter varies rapidly, 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 would be used by everyone.

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 its fundamental parameter. In 2017, this value has been updated in the IERS Conventions 2010, so that W_0 is now uniquely defined in the geodetic standards. However, the current set of fundamental parameters do not fulfil the Somigliana-Pizzetti theory of the level ellipsoid. Thus, the definition of a new GRS is also needed from this point (see at the end of this section).

Another issue is the impact of the new W_0 value on the definition of time standards. Since L_G was declared as a defining constant by IAU in 1999, the relationship between TCG and TT does not depend anymore on the geoid realisation. The main implication for the IAU timescales is related to the accuracy in the realisation of the International Atomic Time (TAI). It presently corresponds to a coordinate timescale defined in a geocentric reference frame with the SI second as realised 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 realisation of TT. However, this issue should not be further discussed here, since the TAI definition is under the responsibility of the General Conference of Weights and Measures through the Consultative Committee on Time and Frequency.

The current situation concerning the definition of numerical standards and the use of different time and tide systems within geodesy is a potential source for inconsistencies and even errors of geodetic products. Thus, it is essential for a correct interpretation and use of geodetic products that the underlying numerical standards are clearly documented. Moreover, if geodetic results expressed in different time or tide systems are combined, respective transformations have to be performed to get consistent results. As an ultimate goal all existing inconsistencies should be removed and a consistent set of standards and conventions should be developed.

As outlined in Ihde et al. (2017), IAG is considering the necessity and usefulness for replacing GRS80 by a new geodetic reference system. Towards this aim a new GGOS Working Group “Towards a consistent set of parameters for the definition of a new GRS” has been established as a component of the BPS at the end of 2019. This WG works together with representatives of IAG Commissions 1 and 2, the Inter-Commission-Committee on Theory (ICCT), the International Gravity Field Service (IGFS) and the Committee on Essential Geodetic Variables (EGV). The activities will focus on estimation of a new set of defining parameters for a modern GRS based on current methods and data, and on calculating all derived parameters in a consistent way. First results of such a consistent set of geodetic fundamental parameters have been derived and presented by Oshchepkov (2019). This set of defining parameters for a new GRS was derived in the zero-tide system and TT standard based on the Somiliana-Pizzetti theory of the level ellipsoid, comprising GM, U_0, J_2, and ω. Hence, the semi-major axis a would become a derived parameter. The BPS strongly recommends to work towards a new GRS as the basis for a consistent set of numerical standards to be used within IAG.

Summary of recommendations on the numerical standards, which have also been endorsed as recommendations of the Unified Analysis Workshops 2019 (Gross et al. 2019):

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

Recommendation 0.2 : The inconsistency concerning the treatment of the permanent tide must be resolved within IAG to support the GGRF requirements and user needs.

Recommendation 0.3 : 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., $W_0 = 62\,636\,853.4\ \mathrm{m^2 s^{-2}}$.

Recommendation 0.4 : 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

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 organisation 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 and Pearlman 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 realisations.

The sections for each of these products (or topics) were organised in a similar structure. The first part gives a brief overview, followed by a description and discussion of the present status, and finally open problems 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 due to organisational issues of the IAG Services. Although the celestial reference frame is a product of IAU, it is addressed in this inventory, since IAG is directly involved through the IVS and the consistency between the celestial and terrestrial reference frame is also an important reseach topic of IAG (Section 4.1). Pure IAG products exist for the terrestrial reference frame (Section 4.2) and for the EOP (Section 4.3) which are provided by the responsible Product Centers of the IERS. This updated version of the inventory includes the latest version of these products, the ICRF3, the ITRF2014 and the EOP 14CO4 series. 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. Also for the gravity field and geoid (Section 4.5) as well as for the height systems and their realisations (Section 4.6) a lot of progess has been achieved during the last four years, but on the other hand official IAG products still need to be defined and implemented. Due to this fact the character of these two corresponding sections differs from the four others.

The BPS gives credit to the efforts and contributions of the IAG Services, their contributing Analysis and Combinations Centers, and the Product Centers of the IERS and IGFS, which provide the foundation for the generation of the IAG Products. Without their significant work and valuable support the progress achieved during the past years would not have been possible.

Finally, it should also be noted that the list of topics and IAG products is by far not complete and it should be extended by adding other products in an updated version of this document, to incorporate the ongoing GGOS activities towards the development of integrated geodetic products.

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 organisations 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) (Nothnagel et al. 2017) was the key supplier of observations and analysis capability in the recent past. The IVS was established in 1999 as an international collaboration of organisations 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 organisational structure and technical infrastructure, the IAG, through IVS, has an indirect responsibility for the provision of the celestial reference frame at radio frequencies. The VLBI technique provides the direct link between the celestial and the terrestrial reference frames, 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 and IAG Resolution No. 2, 2019), 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 realisation 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 realised 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 is responsible for monitoring the ICRS, maintaining its realisation, the ICRF, and improving the links with other celestial reference frames. Since 2001, these activities have been run jointly by the ICRS Centre (at the Observatoire de Paris and the US Naval Observatory) of the IERS and the IVS, in conjunction with IAU.

4.1.2 International Celestial Reference System

Following the IAU Resolution B2 (1997), the ICRS replaced the Fifth Catalogue of Fundamental Stars (FK5) as the fundamental celestial reference system for astronomical applications. According to IAU Resolution A4 (1991), the ICRS is a specific Barycentric Celestial Reference System (BCRS), with its axes kinematically non-rotating with respect to the distant objects in the universe (Petit and Luzum 2010). These axes are defined implicitly through a set of coordinates of extragalactic objects, mostly quasars, BL Lac sources and radio galaxies, all of which are Active Galactic Nuclei (AGN), as determined in the most precise realisation of the ICRS, the ICRF (for more information see (Petit and Luzum 2010)). The celestial reference system has its principal plane as close as possible to the mean equator at J2000.0 and the origin of right ascension on this principal plane as close as possible to the dynamic equinox of J2000.0.

4.1.3 International Celestial Reference Frames

History of ICRS realisations

The initial test realisation 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) and Jet Propulsion Laboratory (JPL), both belonging to the National Aeronautics and Space Administration (NASA), 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 axis directions of this first frame. This initial realisation can be considered as the intangible basis of the radio celestial frame, since all subsequent realisations 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 realisation of ICRS by No-Net-Rotation (NNR) constraints.

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

Within the common IAU/IVS Working Group entitled “The Second Realisation of the International Celestial Reference Frame – ICRF2” a new version of ICRF was 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 specified to be 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 computations generally followed the IERS Conventions 2003 (McCarthy and Petit 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 modelled using

- atmosphere pressure loading corrections according to Petrov and Boy (2004),
- troposphere delays based on the Vienna Mapping Functions 1 (VMF1) of Böhm et al. (2006),
- the antenna thermal deformation models of Nothnagel (2009), and

- the a-priori gradient model according to MacMillan and Ma (1997).

The current realisation, the ICRF3

Within the IAU Division A Working Group entitled "Third Realisation of the International Celestial Reference Frame (ICRF3)" a new version of ICRF was computed (Charlot et al. 2020), which was accepted by the IAU at its General Assembly in Vienna, Austria, in August 2018 (see IAU Resolution No. B2, 2018). The developments were supported by the IAG Sub-Commission 1.4 "Interaction of Celestial and Terrestrial Reference Frames". The reliability of the ICRF3 could be improved through comparisons with observations obtained at higher radio frequencies and at optical wavelength provided by European Space Agency (ESA)'s optical astrometry mission Gaia.

The ICRF3 contains the positions of 4536 compact radio sources, including a selected set of 303 defining sources. The stability of the axes betters the one of the previous reference frame, ICRF2. Individual coordinates show a noise floor of about 30 μas. For the first time, the effects of galactic rotation on celestial coordinates is considered in the ICRF3 in terms of a correction on the observation level. Therefore, the reported celestial coordinates refer to the epoch 2015.0. Besides the S-/X-band coordinates, ICRF3 contains several hundreds of objects in K- and/or X-/Ka-bands as well. A comparison of ICRF3 with data release 2 (DR2) of the ESA Gaia mission in optical wavelengths shows no deformations above about 30 μas. Mainly due to the revisiting of ICRF2 survey radio sources, the source coordinate errors have a more uniform sky distribution. Accordingly, the ICRF3 only contains the radio source categories "defining" and "candidates". A comparison with Gaia and ICRF2 revealed that the ICRF2 has small systematic deformations of up to 80 μas.

The a-priori models for geophysical effects and precession/nutation used for the ICRF3 computations generally followed the IERS Conventions 2010 (Petit and Luzum 2010). Specifically, corrections for solid Earth tides, the pole tide, ocean loading, and high frequency EOP variations comply with that conventions. Besides the conventional models mentioned above, other important effects were modelled using tidal and non-tidal atmosphere pressure loading corrections according to Petrov and Boy (2004) instead of the tidal-only atmosphere pressure loading model mentioned in the IERS Conventions 2010.

4.1.4 Discussion of the present status

General issues

The organisational structure regarding the definition and realisation of the celestial reference system is rather complex. Quite a large number of organisations, 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.

ICRS definition and its realisation

The definition and realisation of the ICRS are given in the IERS Conventions (Petit and Luzum 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 realisations were usually not as precise as the subsequent conventional realisations. A series of ICRS realisations has been computed so far, and in each of those the datum has been defined with respect to the previous realisation by applying NNR conditions. But this is depending on the quality, number and distribution of the defining radio sources used in the NNR condition. When applying this procedure, inconsistencies of the predecessor can affect the reference frame definition (mainly the orientation) of new (more precise) frames.

ICRF computations

All ICRS realisations including the latest one, the ICRF3, have been computed by only one IVS Analysis Center using a single software package. Although the final product is controlled through a comparison with individual IVS solutions, the procedure differs from the generation of the ITRF and EOP products, which are generated from a combination of individual contributions (see Section 4.2 and 4.3). Currently, formal errors of the ICRF determined by VLBI are certainly too optimistic since they do not account for uncertainties of a number of technique-specific models and auxiliary observations such as atmospheric pressure and air temperature. Other examples of neglect are antenna axis offsets, thermal expansion modelling, uncertain technique-specific model components and source structure effects. Although, the imbalance of VLBI observatories on the northern and southern hemispheres has been improved for the ICRF3, the impact of such an effect has to be investigated in more detail.

Consistent estimation of the ICRF, ITRF and EOP

The IUGG Resolution No. 3 (2011) urges that the highest consistency between the ICRF, the ITRF and the EOP as observed and realised by IAG and its components such as the IERS should be a primary goal in all future realisations of the ICRS. The newly adopted IAG Resolution No. 2 (2019) recommends that highest consistency between the ICRF, the ITRF, and the EOP should be a primary goal in all future realisations. At present, both frames (the ICRF and ITRF) and the EOP solutions are not fully consistent with each other as they are computed independently by separate IERS Product Centers. Although the recommendations of the IUGG and IAG resolutions have not been fulfilled yet, related studies are being performed by several research groups (e.g., at JPL and Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)), see for example, Seitz et al. (2014), Kwak et al. (2018), and Soja et al. (2019). On the international level, this topic has been addressed by the IAU Working Group "ICRF 3" and it is an ongoing research topic of the IAG Sub-Commission 1.4 "Interaction of celestial and terrestrial reference frames". The topic of the consistency between the ICRF, ITRF, and EOP is addressed at Sections 4.2 and 4.3 as well.

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
- the 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 derived from the mentioned products.

4.1.6 Open problems and recommendations

General issue on ICRS/ICRF

As a consequence of the interactions between IAU and various IAG components, the celestial reference system and frame is part of this inventory, although the latest ICRF3 realisation is labeled as IAU product. It helps to address important scientific questions, like the consistency between the celestial and terrestrial frame. Moreover, the objectives 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, which is also relevant for the implementation of the GGRF.

ICRF computations

It remains to be considered whether the next ICRS realisation shall be estimated from a combination of different analysis centre solutions computed with different software packages, as done by the other Product Centres of the IERS. 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. Recent studies on source structure effects were performed by Anderson et al. (2019).

Consistency of ICRF, ITRF and EOP

This topic was already addressed at the IERS Retreat in Paris 2013 (see www.iers.org/IERS/EN/Organization/Workshops/Retreat2003.html).
In the above mentioned IERS Retreat 2013, it was recommended that the following questions should be addressed: (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? Although the studies mentioned in Section 4.1.4 show already some quality improvements due to the combined adjustment of the celestial and terrestrial reference frame and the EOP, the questions above still need to be addressed in more detail. Thus, research groups that can do the required combinations are encouraged to perform such studies. On the international level the IAG Sub-Commission 1.4 "Interaction of celestial and terrestrial reference frames" and the proposed IAG/IERS/IAU JWG on the Consistency of CRF, TRF, and EOP should also focus on this important topic.

Summary of recommendations on ICRS/ICRF

Recommendation 1.1 : The organisations involved in the definition and realisation of the ICRS are asked to clarify the structure and responsibilities. This is also important in the framework of the implementation of the GGRF, which includes the ICRF.

Recommendation 1.2 : It should be considered by the organisations and their responsible working groups, whether the next ICRS realisation, should be estimated from a combination of different analysis centre solutions.

Recommendation 1.3 : Research groups are encouraged to perform further investigations on source structure effects and to evaluate the impact on the realisation of the celestial reference system.

Recommendation 1.4 : Following IUGG Resolution No. 3 (2011) and IAG Resolution No. 2 (2019), research groups are encouraged to perform the previously mentioned studies regarding the consistency of ICRF, ITRF and EOP. Please note that this recommendation also concerns the Sections 4.2 and 4.3.

4.2 Terrestrial reference systems and frames

4.2.1 Overview

A Terrestrial Reference System (TRS) is a spatial reference system co-rotating with the Earth. Its realisation is called a *reference frame*. The nomenclature and basic concepts of a terrestrial reference system and the frame are well described in Chapter 4 of the IERS Conventions 2010 (Petit and Luzum 2010). The most recent update of Chapter 4 (v1.3.0 of April 2019) is available at iers-conventions.obspm.fr/content/chapter4/icc4.pdf.

Terrestrial reference frames (TRF) are needed to refer the geodetic observations and estimated parameters to a unified global basis. High accuracy, consistency and long-term stability are 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 recognised by the United Nations too. In Feburary 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 International Terrestrial Reference System (ITRS) has been formally adopted and recommended for Earth science applications (IUGG 2007). The IAG Resolution No. 1 (2019) recommends to the user community that the ITRF should be the standard terrestrial reference frame for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames. The IERS is in charge of defining, realising and promoting the ITRS. The IERS Conventions provide the basis for the general definitions and numerical standards as well as for the mathematical representation of the relevant quantities and for the modelling of the contributing geometric space techniques.

The International Terrestrial Reference Frame (ITRF) is a realisation of the ITRS, consisting of 3-dimensional positions and time variations of IERS network stations observed by space geodetic techniques. Currently, the contributing space techniques are VLBI, SLR, GNSS, and DORIS. According to the Terms of Reference of the IERS, the ITRS Center hosted at the Institut National de l'Information Géographique et Forestiere, France (IGN), is responsible for the maintenance of the ITRS/ITRF, including network coordination, for providing the ITRS Combination Centers with specifications, and for evaluating their respective results. The ITRS Combination Centers are responsible to provide ITRF products by combining ITRF inputs from the Technique Centers and others. ITRS Combination Centres are currently maintained by IGN (Paris, France), DGFI-TUM (Munich, Germany) and JPL (Pasadena, USA).

4.2.2 History of ITRS realisations

Until now, thirteen releases of the ITRF were published by the IERS, starting with ITRF 88 and ending with ITRF 2014, each of which superseded its predecessor (see Chapter 4 of the IERS Conventions 2010, (Petit and Luzum 2010)). An updating of ITRS realisations is performed every few years, since the tracking networks of space techniques are evolving, the period of data extends, and also the modelling and data analysis strategies as well as the combination methods improve with time. Furthermore, several large earthquakes might have affected station positions and velocities over large regions. Up to ITRF 2000, long-term global solutions (comprising station positions and velocities) from the four techniques (VLBI, SLR, GNSS, and DORIS) were used as input for the ITRF generation, which have been used by the ITRS Centre at IGN in France to compute the ITRS realisations.

In 2001, when the IERS was restructured, the newly established ITRS Center (former ITRS Terrestrial Reference Frame Section) has been supplemented by ITRS Combination Centers, to enable intercomparisons of the ITRF results. Additionally, the combination strategy for the ITRF computations has been refined. 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 centres. The ITRF 2005 and 2008 solutions were computed at the ITRS Combination Centers operated by IGN and DGFI. A comparison and discussion of the ITRF2008 (Altamimi et al. 2011) and the DTRF2008 (Seitz et al. 2012) is provided in the 2016 version of this inventory (Angermann et al. 2016). The current ITRS realisation, the ITRF2014, is summarised in Section 4.2.3.

In January 2019, the IERS disseminated a call for participation for a new ITRF2020 solution to be released by the ITRS Center at the end of 2021. This new ITRS realisation will contain six years of additional observations until the end of 2020. New sites have been added to the ITRF network and new colocation sites as well as new local ties are now available. Moreover, the geometric IAG Services have further improved their processing strategies, new models have been implemented and the ITRS Combination Centers have refined their combination methodologies.

4.2.3 The current ITRS realisation, the ITRF 2014

The ITRF 2014 is the current realisation of the ITRS (Altamimi et al. 2016). It is based on reprocessed solutions or normal equations of the four space techniques VLBI, SLR, GNSS, and DORIS comprising time series of station positions and EOP. They are generated by individual analysis centres of the technique-specific IAG Services, namely the IGS, ILRS, IVS and IDS. In the ITRF 2014 call for participation it was specified that the input data shall conform to the IERS Conventions 2010 (Petit and Luzum 2010). Moreover, guidelines for the ITRS Combination Centers were provided in this call. The time series cover the entire observation history for each of the four techniques and the individual contributions were combined per-technique by the responsible technique-specific combination centres of the IGS, ILRS, IVS, and IDS. The major characteristics of the input data for the ITRF 2014 are given in Table 4.1.

The ITRF2014 is generated with an enhanced modelling of nonlinear station motions, including seasonal (annual and semi-annual) signals of station positions and post-seismic deformation (PSD) for sites that were subject to major earthquakes. In case of ITRF2014 and for stations subject to PSD, the user should add the sum of all PSD corrections to the linearly propagated position, using equation 4.16 of the most recent update of Chapter 4 of the IERS Conventions (iers-conventions.obspm.fr/content/chapter4/icc4.pdf):

$$\vec{X}(t) = \vec{X}(t_0) + (t - t_0)\dot{\vec{X}} + \delta\vec{X}_{\mathrm{PSD}}(t)$$

The ITRF2014 PSD parametric models, together with all equations allowing users to compute the PSD corrections and Fortran subroutines are available at the ITRF2014 website itrf.ign.fr/ITRF_solutions/ITRF2014.

Compared to the ITRF2008, the input data for the ITRF2014 were significantly improved. Besides six more years of observations, also technical upgrades of satellite and station equipment as well as a higher number of stations and satellites allows for a more robust realisation of the ITRS. Moreover, the entire observation time series for all techniques were reprocessed by using the latest technique-specific and geophysical background models (as specified in the IERS Conventions 2010 and its updates) and, if appropriate, by implementing new parameterisations. Table 4.2 summarises the most important changes in modelling and parameterisation from ITRF2008 to ITRF2014.Detailed information for each of the four techniques is provided in the references given in Table 4.2.

In addition to the local ties used in the ITRF2008 computation, a certain number of new local ties from new colocation sites and/or from new surveys were used for the ITRF2014 (Altamimi et al. 2016).

These input data were used by the three ITRS Combination Centers at IGN (France), DGFI-TUM (Germany) and JPL (USA) to compute the ITRS realisations, i.e., the ITRF 2014 (Altamimi et al. 2016), the DTRF 2014 (Seitz et al. 2020, 2016) and the JTRF 2014 (Abbondanza et al. 2017). While DTRF 2014 and ITRF 2014 are secular frames providing station positions at a reference epoch and constant velocities according to the conventional ITRS definition, the JTRF 2014 is based on a KALMAN filter approach delivering time series of station positions. Thus, the two conventional multi-year solutions computed at IGN and DGFI-TUM are not directly comparable with the JTRF 2014 time series of weekly station position and EOP solutions. The characteristics of these three solutions are summarised in Table 4.3.

The ITRS combination strategies have been substantially improved compared to the ITRF2008 computations. The ITRF2014 involves two main innovations dealing with the modelling of non-linear station motions, namely seasonal signals present in the time series and post-seismic deformation (PSD) for stations subject to major earthquakes. Also the DTRF2014 is characterised by two main innovations: For the first time, it considers non-tidal loading corrections derived from geophysical models. Secondly, it provides as additional DTRF2014 products the time series of the station position residuals, the weekly SLR translation parameters and the non-tidal loading (NT-L) corrections, which were provided by the GGFC (Tonie van Dam). The ITRS Combination Center at JPL provided its first ITRS realisation, the JTRF2014, in the form of time series of weekly solutions comprising station positions and EOP.

The IERS Technical Note on the ITRF2014 (Altamimi et al. 2017) is supplemented by an additional IERS Technical Note

Table 4.1: Input data sets for ITRF 2014 (TC: Techniques' Combination Center, AC: Analysis Center, NEQs: Normal Equations). In addition, also geodetic local tie information is used as input for the ITRF computations.

TC	# ACs per technique	Time period	Sampling	Data	Constraints
IGS	9	1994.0 – 2015.1	Daily	Solutions	Minimum
IVS	9	1980.0 – 2015.0	Daily	NEQs	None
ILRS	7	1983.0 – 1993.0	Fortnightly	Solutions	Loose
ILRS	8	1993.0 – 2015.0	Weekly	Solutions	Loose
IDS	6	1993.0 – 2015.0	Weekly	Solutions	Minimum

Table 4.2: New models and parameterisations applied by the geometric technique services for the generation of the ITRF2014 input data; the table has been taken from (Seitz et al. 2020) and has been slightly modified.

Technique	Service	Model changes and new parameterisation
DORIS	IDS	IDS input data for ITRF2014 (Moreaux et al. 2016) - models improvements of some satellites (Envisat, Cryosat-2, Jason-2) - parameterisation of antenna frequency offsets - most recent time-variable gravity field EIGEN-6S2 (Förste et al. 2012) - improved modelling of radiation pressure accelaration - refined modelling of atmospheric drag - satellite attitude laws in POD software has been re-verified by some ACs - timetagging for Envisat solved - SAA effects on SPOT-5 oscillator solved
GNSS	IGS	IGS input data for ITRF2014 (Rebischung et al. 2016) - switch from weekly to daily resolutions - implementation of IGb08/igs08.atx reference frame - implementation (partly) of new attitude models for ecclipsing satellites - modelling of Earth radiation pressure, and (mostly) of antenna thrust
SLR	ILRS	ILRS input data for ITRF2014 (Luceri and Pavlis 2016) - four satellites: Lageos 1/2 and Etalon 1/2 - daily mean pole values derived from IERS series - centre-of-mass correction for each satellite in specific tables - modelling or estimation of range corrections for a number of sites
VLBI	IVS	IVS input data for ITRF2014 (Bachmann et al. 2016) - provision of celestial pole offsets - fixing of source positions to ICRF2 (Fey et al. 2015) - new axis offsets and eccentricities
general models	IERS	General models according to IERS Conventions 2010 (Petit and Luzum 2010) - mean pole model (all, except ILRS as given above) - Earth's gravity field model - tidal station displacements - tidal variations in Earth rotation - Nutation model - relativistic effects - tropospheric and ionospheric propagation delays

(Altamimi and Dick 2020). It includes the two other ITRS solutions, the DTRF2014 and JTRF2014, a comparision of the three solutions performed at IGN and DGFI-TUM as well as evaluations of the three ITRS solutions done by the IERS Technique Centers, which provide the input data for the ITRF generation. Such Technique Center contributions have been provided by the IDS, ILRS and IVS. These evaluations confirm the high quality of the three ITRS solutions as well as the improvement compared to the ITRF2008.

This IERS Technical Note 40 (Altamimi and Dick 2020) gives credit to the various contributions to the ITRF2014, which yield an excellent basis for the ITRF2014 evaluation. However, concerning the ITRF accuracy, it should be noted that the cross-validations of the three ITRS solutions (which are based on the same input data) are mainly a measure for their consistency, and they do not fully reflect the various impact factors that need be considered to quantify the accuracy of the terrestrial reference frame (see Section 4.2.4).

4.2.4 Discussion of the present status

ITRS definition vs. its realisation

According to the IERS Conventions (Petit and Luzum 2010), the ITRS definition is based on the following principles:

- It is geocentric, the centre 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;
- Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation of the BIH Terrestrial System (BTS) at epoch 1984.0;

Table 4.3: Summary of combination strategies for the ITRF2014, DTRF2014 and JTRF2014 (PSD: Post-seismic deformation, NT-L: Non-tidal loading). More details on the combination strategies are found in the references for the ITRF2014 (Altamimi et al. 2016), the DTRF2014 (Seitz et al. 2020) and JTRF2014 (Abbondanza et al. 2017).

Solution	ITRF2014	DTRF2014	JTRF2014
Institute	IGN (Paris, France)	DGFI-TUM (Munich, Germany)	JPL (Pasadena, USA)
Software	CATREF	DOGS-CS	CATREF + KALMAN
Combination approach	Solution (parameter) level	Normal equation level	Solution (parameter) level
Station position	Position $\mathbf{X}_{\mathrm{ITRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathrm{ITRF}}(t_0)$ + PSD models (selected stations) + periodic signals (on request)	Position $\mathbf{X}_{\mathrm{DTRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathrm{DTRF}}(t_0)$ + NT-L models + SLR origin + residual station motions	Weekly positions $\tilde{\mathbf{X}}_{\mathrm{ITRF}}(t_i)$
Earth orientation parameters	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI *Separate VLBI-only:* – dUT1, – LOD, – Celestial pole	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI, – LOD from GNSS + SLR + VLBI *Separate VLBI-only:* – dUT1, – Celestial pole	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI *Separate VLBI-only:* – dUT1 – Celestial pole

- The time evolution of the orientation is realised 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 realisation:

Origin: The ITRF origin is realised by SLR observations. Through the orbit dynamics, SLR determines the Centre of Mass (CM). According to the IERS Conventions 2010 (Petit and Luzum 2010), the ITRF2014 and DTRF2014 origin follows the mean Earth centre of mass, averaged over the time span of SLR observations used and modelled as a secular (linear) function in time. It can be regarded as a *crust-based* TRF with the origin realised as a mean CM (Blewitt 2003; Dong et al. 2003; Petit and Luzum 2010; X. Wu et al. 2015). However, various geophysical applications and precise orbit determination require station coordinates to be referred to the instanteneous CM. To obtain such an instantaneous geocentric position, it is recommended in the IERS Conventions (Petit and Luzum 2010) to substract the so-called geocentre motion (i.e. the vector from the crust-based ITRF origin to the instanteneous centre of mass) from the ITRF position. However, the expression "geocentre motion" is defined differently in the geodetic literature (e.g., Dong et al. 2003), and moreover, a commonly accepted model to account for this effect is not available yet. The ITRF2014 provides an annual geocentre motion model derived from the same SLR data that define the ITRF2014 long-term origin (Altamimi et al. 2016). The DTRF2014 delivers the time series of the SLR translation parameters as an additional product (Seitz et al. 2016), and the JTRF2014 realises the origin at the quasi-instanteneous CM as sensed by SLR (Abbondanza et al. 2017). Although SLR is the most precise observation technique to realise 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 coordinate time (IAU and IUGG resolutions, 1991), whereas its realisation is consistent with the terrestrial time (TT). The difference between both time scales dTT/dTCG is about $1 - 0.7 \cdot 10^{-9}$ (see Section 3.1), equivalent to a height difference of 4.5 mm at the surface of the Earth. The ITRS scale is realised by SLR and VLBI observations and, similar as for the origin, the results are affected by relatively sparse networks. In the ITRF2014 computations, IGN estimated a scale difference between VLBI and SLR of 1.37 ppb at epoch 2010.0 (Altamimi et al. 2016), whereas the DTRF2014 did not exhibit such a scale discrepancy. Based on the scale tests performed at DGFI-TUM, which did not show a significant scale offset between VLBI and SLR, the DTRF2014 scale was realised as a weighted mean of the SLR and VLBI scale (Seitz et al. 2020). In contrast to DTRF and JTRF, the ITRF2014 includes a scale factor between SLR and VLBI as unknown parameter in the combination model. The scale issue is an ongoing topic mainly of the ILRS, the IVS and the ITRS Combination Centres.

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 realised by external NNR conditions. This is done by successive transformations with respect to the previous ITRF realisation. Thus, its realisation 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 geophysical model NNR-NUVEL-1A (Argus and Gordon 1991; DeMets et al. 1990, 1994). The succeeding realisations, i.e., the ITRF2005, ITRF2008 and ITRF2014, were conventionally realigned to its predecessor. As deformation zones are neglected in the geophysical model and plate motions are averaged over long time periods (up to 1 Myr), there are differences with respect to present-day motions (Altamimi et al. 2012; Argus et al. 2011; DeMets et al. 2010; Drewes 2009; Kreemer et al. 2006). According to Drewes (2012), the resulting station velocity differences are of 1.1 mm/yr around a rotation pole with a latitude of about $-60°$ and a longitude of about $120°$. The first version of this inventory also provides an alternative concept by defining "absolute" plate motions with respect to the Earth's mantle by moving hot spots. Such a "hot-spot" model might be useful for geophysical considerations, but it is not compliant with the ITRS definition.

Input data for ITRF computations

For a particular ITRS realisation, 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 deviations from the recommendations of the IERS Conventions are preferred, it is requested that the effects of those deviations are documented.

Each intra-technique solution is a combination of several Analysis Centre (AC) solutions as shown in Table 4.1 (these are 9 individual solutions for GNSS and VLBI, 8 for SLR, and 6 for DORIS). Moreover, different software packages are in use by the ACs for processing space geodetic observations. Although much care is taken by the ACs to provide data that are fully consistent with these definitions, the current status is that this information is 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 assess the impact of possible deviations, if some of the input data are not fully in accordance with the adopted standards and conventions.

Furthermore, different subsets of the available data are used by the services for generating the ITRF input data, e.g., in case of GNSS, different station networks are selected by the ACs. In addition, some ACs only use GPS and some use GPS and GLONASS, but other GNSS are not considered by the IGS up to ITRF2014. Thus, the IGS input data for the ITRF2014 are different in terms of network geometries and the included GNSS data. In case of SLR, low spherical satellites and tracking data to GNSS satellites are not used in ILRS computations. The ILRS is performing various tests on the inclusion of additional satellites in order to enhance future SLR contributions to the ITRF.

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 and Luzum 2010) as the sum of a regularised 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 regularised station position itself is parameterised 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 $(t_i - t_0)$

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

According to the IERS Conventions 2010 (Petit and Luzum 2010), the displacements of reference markers on the crust are modelled by conventional correction models, considering the effects on stations due to solid Earth tides, ocean loading, rotational deformation caused by polar motion and ocean pole tide loading. Even if these various effects are conventionally modelled, one has to keep in mind that model uncertainties, and possible model errors could affect the corrections of the instantaneous station positions. Such errors and also other effects (that are not considered in the conventional corrections) will become visible as residuals in the position time series.

The updated version of Chapter 4 of the IERS Conventions (iers-conventions.obspm.fr/content/chapter4/icc4.pdf) specifies the regularised coordinates of ITRF stations as parametric functions of time. They are composed of:

- Station positions at a reference epoch and station velocities until ITRF2008. Note that station velocities were taken from geophysical models before ITRF91.

- Station positions at a reference epoch, station velocities and post-seismic deformation (PSD) functions for some stations in ITRF2014.

The time series analysis reveals non-linear motions of several millimeters or even more (up to a few centimeters) for some stations. These motions are caused by various effects that are not properly modelled or for which accurate models are not available (e.g., Bevis and Brown 2014; Blossfeld et al. 2014; X. Wu et al. 2015). 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 a few centimeters are caused by neglected surface loading and other (unmodelled) effects. In the study of Ray et al. (2013), it was found that non-tidal loading deformation does not explain more than half of the vertical annual variations in GNSS station position time series and much less in the horizontal components. Roggenbuck et al. (2015) compared loading models for atmosphere, ocean and hydrology and studied the impact on global SLR, VLBI and GNSS solutions. Männel et al. (2019) studied the surface loading corrections for VLBI and GNSS networks at the observation level. The DTRF2014 applied non-tidal loading corrections for atmosphere and hydrosphere by using models provided by Tonie van Dam (personal communication). The results show that the seasonal variations in the residual time series for station positions and datum parameters (origin and scale) could be significantly reduced (compared to the standard DTRF2014 solution without applying loading corrections).

Furthermore, some stations are located in deformation zones and are affected by post-seismic behaviour after strong earthquakes (e.g., Freymueller 2010; Sánchez et al. 2013). These effects are modelled by exponential post-seismic correction models in ITRF2014 and by a piecewise linear function representation in DTRF2014, whereas the post-seismic behavior is directly captured by the time series-based JTRF2014. A few stations are also affected by anthropogenic effects like, e.g., yearly groundwater withdrawal (Bawden et al. 2001). A dominant source for producing non-linear station motions are systematic errors and technique-specific effects. Examples are modelling discrepancies of the technique-dependent internal reference points, such as GNSS phase centre offsets and variation models for satellites and stations (Schmid et al. 2016) and corrections for radio antenna thermal deformations (Nothnagel 2009) as well as draconitic variations in GNSS positions (Amiri-Simkooei 2013).

Integration of space techniques at colocation sites

A major limiting factor for the integration of the different space geodetic techniques, the inter-technique combination, is the rather inhomogeneous and relatively sparse distribution of colocation sites. In total, 139 local tie SINEX files available for 91 colocation sites (with two or more technique instruments which were or are currently operating) were used in the ITRF2014 (Altamimi et al. 2016). There are not so many colocations between VLBI, SLR and DORIS, and thus, GNSS plays a major role in linking together these three techniques. In total, there are 212 tie vectors between GNSS and the reference points of the three other techniques: 62 to VLBI, 50 to SLR, and 67 to DORIS (Altamimi et al. 2016). On the other hand, the large number of GNSS discontinuities is critical for the combination of GNSS with the other three techniques. The discrepancies between the terrestrial local tie vectors and the space geodetic solutions are a good quality measure for the accuracy of the terrestrial reference frame. According to Altamimi et al. (2016), more than half of the colocations show tie discrepancies larger than 5 mm. The full list of local tie discrepancies is available at the ITRF2014 website. The interpretation of these discrepancies is a challenge, since various impact factors have to be considered such as systematic errors of the space techniques, uncertainties for the definition of the reference points, local site instabilities, outdated local surveys, largely different observation epochs for "old" instruments as well as uncertainties of the terrestrial local tie measurements.

4.2.5 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 for Earth sciences. How well the reference frame can be realised has important implications for Earth system studies and for monitoring global change phenomena such as sea level rise. There is an interaction between the terrestrial reference frame and all other products addressed in this inventory, such as

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

4.2.6 Open problems and recommendations

Reference frame definition

The ITRF origin follows the average CM, realised (linearly with time) by SLR data (Altamimi et al. 2016). However, satellite precise orbit determination and various demanding applications require station coordinates refering to the instantaneous CM. Although the ITRF2014 provides an annual geocentre motion, which allows the computation of such an instantenous CM, the sparseness of the ILRS network along with its temporal variations hinders the highly precise determination of the SLR-derived geocentre motion (X. Wu et al. 2012). Thus, this topic needs to be further studied and it is recommended to include other methods and data for the estimation of the geocentre motion.

The scale of the ITRS is defined in TCG time scale (consistent with IAU and IUGG (1991) resolutions), whereas its realisation 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 realisation of the scale, in the ITRF2014 a significant scale offset between VLBI and SLR was estimated (Altamimi et al. 2016). Although the recent estimation of range biases by the ILRS seems to largely explain the scale offset, this issue needs to be further investigated by the ILRS and IVS together with the ITRS Combination Centres and it should be studied in the framework of the upcoming ITRF2020 computations.

The orientation of the ITRS is realised by external NNR conditions, whereas for each particular realisation successive transformations with respect to the previous ITRF realisation have been performed. Consequently, this procedure depends on the network geometries and the stations used for the transformations. The orientation rate of ITRF2014 as well was successively transformed to that of ITRF2000, which was aligned to that of the geological model NNR-NUVEL-1A, as outlined in Section 4.2.4.

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 present situation it is recommended that the Services (IGS, ILRS, IVS, IDS) together with all contributing ACs compile documentation 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 summarised 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.

Handling of non-linear station motions

Although a significant progress concerning the handling of non-linear station motions has been achieved in the framework of the ITRF2014, this topic is subject of further research. The fact that the three ITRS Combination Centres applied different approaches to account for non-linear station motions is beneficial to do comparisons between them and to perform detailed studies on this issue. Moreover, a comparison of the different observation time series at colocation sites provides valuable information to separate geophysical effects from technique-specific effects. Following the recommendations of the ITRF2020 call for participation and the Unified Analysis Workshop 2019 (Gross et al. 2019), the GGFC should be invited to provide a unified loading model including all contributions (atmosphere, hydrology, and ocean) for all ITRF2020 sites.

Integration of space techniques

The observed discrepancies at colocation sites (which exceed 5 mm for more than half of the colocations) are a major limiting factor for the integration of the different geodetic space techniques. A challenge is the separation of the different impact factors that need to be considered (see Section 4.2.4). A problem in this context is the sparse distribution of high-quality colocation sites. Colocation with GNSS plays a dominant role for the integration of the different techniques, but the large number of GNSS discontinuities is critical. Thus, it is an overall goal to improve the spatial distribution of colocation sites and the availability of precisely measured local ties. However, the required maintenance, sustainability and enhancement of the geodetic infrastructure goes beyond the responsibilities of IAG, and it involves activities on the political level, such as those of the UN-GGIM Subcommittee on Geodesy, which provides an intergovernmental forum for cooperation and exchange of dialogue on these issues. In addition to the *classical* colocation on Earth, a challenge for the future would be the colocation of sensors in space.

Taking into account the current deficiencies and open problems mentioned above, it is obvious that the ITRF accuracy requirements (formulated by IAG/GGOS) at a level of 1 mm and the stability of 0.1 mm/yr are not achieved yet, and probably exceeded by a factor of about 5 to 10.

The following recommendations on the ITRS/ITRF are provided:

Recommendation 2.1 : ITRF defining parameters: The realisation of the ITRF origin, scale, orientation and their time evolution should be consistent with the ITRS definition. Concerning geocentre models, it is recommended to supplement the ITRF2014 geocentre model by other methods and data and to compare the results between different geocentre models. The SLR and VLBI scale issue should be further studied.

Recommendation 2.2 : ITRF input data: In order to get consistent ITRF results, the input data should be based on unified standards and conventions, such as the latest version of the IERS Conventions. The Services (IGS, ILRS, IVS and IDS) and their contributing ACs should provide the relevant information on the status of the standards and conventions currently applied in the data processing.

Recommendation 2.3 : Non-linear station motions: The handling of non-linear station motions should be further studied. The GGFC should be invited to provide a unified loading model including all contributions (atmosphere, hydrogolgy, and ocean) for all ITRF2020 sites (see recommendations of the ITRF2020 CfP and the Unified Analysis Workshop 2019).

Recommendation 2.4 : Integration of space techniques: The station networks and the spatial distribution of high quality colocation sites should be further improved to achieve a more stable integration of the different space techniques. This overall recommendation goes beyond IAG responsibilities, as an improvement of the geodetic infrastructure involves the political level and funding issues. In addition to the colocation on Earth, the benefits of the colocation in space should be studied. This recommendation is fundamental to achieve the IAG/GGOS accuracy requirements for the terrestrial reference frame and to ensure its long-term stability.

Recommendation 2.5 : ITRF evaluation: The availability of three ITRF solutions ensures an evaluation of the quality of the final product. The IERS Technical Note 40, comprising the individual contributions and the product evaluation is gratefully acknowledged and it is recommended that also for upcoming ITRS realisations such a Technical Note is compiled.

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 and Pearlman 2009; Seitz and Schuh 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 rotational 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 realisations 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 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 realisations of the conventional terrestrial and celestial reference systems, the EOP system should be readjusted as soon as a new release of ITRF or ICRF is adopted.

Concerning its numerical realisation, the transformation of Cartesian coordinates from ITRS to GCRS at date t is split into three segments

$$\begin{tikzcd}
\text{ITRS} \arrow[dr, "W(t)", "\text{polar motion}" swap] & & & \text{GCRS} \\
& \text{TIRS} \arrow[r, "R(t)", "\text{Earth rotation}" swap] & \text{CIRS} \arrow[ur, "Q(t)", "\text{precession-nutation}" swap] &
\end{tikzcd}$$

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 Terrestrial Intermediate Reference System (TIRS) and Celestial Intermediate Reference System (CIRS) 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, refering to 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 and Luzum 2010):

- The celestial motion of the Celestial Intermediate Pole (CIP) (precession-nutation) includes all the terms with periods greater than 2 days in the Geocentric Celestial Reference System (GCRS). According to this definition, precession-nutation of the CIP includes the Free Core Free Core Nutation (FCN) signal, but does not include the so-called subdiurnal nutations.
- The terrestrial motion of the CIP (polar motion) includes all the terms outside the retrograde diurnal band in the ITRS (i.e. frequencies lower than -1.5 cycles per sidereal day (cpsd) or greater than -0.5 cpsd).

As outlined in the IERS Conventions 2010 (Petit and Luzum 2010), the motion $Q(t)$ of the CIP in the GCRS is realised by the IAU 2006/2000A precession-nutation model (Wallace and Capitaine 2006) plus additional time-dependent corrections derived by the IERS from space geodetic techniques. 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 and Luzum 2010).

Concerning the realisation 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):

- $\delta X = X - X_{\text{model}},\ \ \delta Y = Y - Y_{\text{model}}:$ corrections to the x- and y-coordinates of the CIP unit vector in the celestial system GCRS using the model IAU 2000/2006,
- $\Delta\text{UT1} = \text{UT1} - \text{UTC}:$ difference of mean solar time (Universal Time UT1) and Coordinated Universal Time (UTC) vice the averaged atomic time,
- x_p, y_p: Cardan angles $W(t) = R_3(-s')R_2(x_p)R_1(y_p)$, called "pole coordinates".

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, 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 IERS 2020). The IERS EOP series result from a combination of different input data provided by different space-geodetic techniques and the corresponding IAG Services, i.e., IDS, IGS, ILRS, and IVS.

In the IERS Conventions 2010, a conventional model for the mean pole is given. It consists of a third order polynomial until 2010.0, and a linear model later on. This model was replaced by a purely linear model (secular pole) in the February 2018 update of the conventions (IERS 2018). This update affects the modelling of displacements of reference points as well as the geopotential due to pole tide and ocean pole tide.

It should also be noted that besides the IERS EOP products, other combined Earth orientation series (e.g., SPACE 2018, COMB 2018, POLE 2018) are generated annually at JPL's Geodynamics and Space Geodesy Group in support of tracking and navigation of interplanetary spacecraft (Gross 2000; Ratcliff and Gross 2019).

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 and Gambis 2009; Bizouard et al. 2019; Gambis 2004; Gambis and Luzum 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/eoppc/bul/bulc/BULLETINC.GUIDE)
Bulletin D contains an announcement of the value $\Delta\text{UT1} = \text{UT1} - \text{UTC}$ (see ftp://hpiers.obspm.fr/eoppc/bul/buld/BULLETIND.GUIDE)
EOP 14C04 contains long term Earth orientation data
(see ftp://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf)

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”, resulting from a combination of EOP series derived from the four space geodetic techniques VLBI, SLR, GNSS, and DORIS. The IERS EOP 14C04 (abbreviated 14C04) solution became the international reference EOP series on February 1, 2017 (Bizouard et al. 2019). It replaced the former IERS EOP 08C04 series (Bizouard and Gambis 2009). The 14C04 series is available from 1962 on and it provides updates until about 30 days in the past. 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 it is aligned on the ITRF2014 and ICRF2. The 14C04 series is updated on a daily basis with a latency of 30 days and the data are accessible as yearly files since 1962 and as one file 1962–now. A documentation for this EOP series is given by Bizouard et al. (2019).

The generation of the 14C04 solutions is based on the combination of operational series as provided by the technique centres of IVS, ILRS, IGS, and IDS, as well as operational solutions maintained by several IVS analysis centres (including VLBI intensives) and one IGS analysis centre (Bizouard et al. 2019). Thus, in case of VLBI and GNSS, in addition to the intra-technique combined series also solutions of individual analysis centres are used for the 14C04 combination. While the three satellite techniques deliver continuous input data for estimating pole coordinates and LOD, VLBI provides the full set of all five EOP, but with non-continuous observations organised in VLBI sessions. In addition, also the EOP solution associated with the ITRF2014 is used as reference series to align the 14C04 solution with the latest realisation of the terrestrial reference frame.

The computation of the C04 series is split into two parts (Bizouard et al. 2019):

- In the initial part, the data preparation is performed once per year. This data preparation comprises the selection of input series, the rescaling of the formal uncertainties provided with the EOP values, and the characterisation of their eventual inconsistency with respect to the ICRF and ITRF.
- The second part is the combination procedure itself which is done on a daily basis. This procedure comprises several steps which are described in Bizouard et al. (2019).

The IERS Earth Orientation Center has upgraded the processing to align the 14C04 results with the ITRF2014 (Bizouard et al. 2017). By estimating and removing continuous piece wise linear functions from the intra-technique solutions over a period of 31 years (1984–2015) with respect to the guide series, namely the EOP solution associated with the ITRF2014 and the IVS combined series, the 14C04 results get rid of the so-called “network effect”. This leads to an improved consistency and stronger long-term stability of the solution, which has been confirmed by Allan deviation analysis (Bizouard et al. 2017).

To assess the accuracy of the 14C04 solution various comparisons have been performed (Bizouard et al. 2019). A comparison with the former 08C04 series indicates a significant improvement of the EOP results. The y-pole component of the 08C04 series shows a jump of about 30 μas in 2011, which is not visible in the new 14C04 series. Also the noise level of the x- and y-pole components obtained from 14C04 could be reduced significantly compared to the previous 08C04 series. This is evidenced by the standard deviations of the differences between the C04 (both 08C04 and 14C04) and the intra-technique and guide series (see Table 6 in Bizouard et al. (2019)). The 14C04 differences to the IVS combination exhibit standard deviations of less than 30 μas for nutation and 3.4 μs for UT1 over the period 2010–2015. The differences to the pole coordinates of the IGS solution reveal a standard deviation of 30 μas for polar motion.

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 and Luzum 1991; Stamatakos et al. 2020, 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://cddis.gsfc.nasa.gov/pub/products/iers/readme.bulla).

Standard Rapid EOP Data contain quick-look weekly estimates of the EOP since 1973-01-02 (`finals.all`) or since 1992-01-01 (`finals.data`) and predictions for the next 365 days (see ftp://cddis.gsfc.nasa.gov/pub/products/iers/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://cddis.gsfc.nasa.gov/pub/products/iers/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://cddis.gsfc.nasa.gov/pub/products/iers/readme.gpsrapid).

Realisation of real-time EOP and predictions

The input data series for the IERS Rapid Service and Prediction Center along with estimated accuracies for each of these contributions to the EOP combination solutions are given in Table 1 of Stamatakos et al. (2020). These series include combined intra-technique solutions of the IVS, IGS and ILRS as well as VLBI, SLR and GNSS solutions of individual analysis centres. All the VLBI contributions provide direct measurements of UT1. The IGS ultra-rapid solutions (IGS Ultra) provide LOD as input parameter, and the solutions labelled as USNO GPS UT contain UT1-like estimates based on GPS orbit modelling. The IGS Final and IGS Rapid as well as the solutions of the ILRS only provide pole coordinates as input parameters. Due to orbit modelling issues of the satellite techniques and correlations between orbit parameters and the EOP, the VLBI solutions have been used to correct for an LOD bias and to minimise drifts in UT estimates in the IGS Ultra and the USNO GPS UT solutions.

The algorithm used for the determination of the quick-look EOP results is based on a smoothing cubic spline interpolation. Each of the input data is weighted according to their reported errors. The procedure is referred to as a "weighted smoothing cubic spline" (Luzum et al. 2014; McCarthy and Luzum 1991). The input series are corrected for possible systematic differences in the form of offsets and rates with respect to the long-term 14C04 series of the IERS Earth Orientation Centre by using a robust linear estimator. The statistical weights used in the spline are proportional to the inverse square of the estimated accuracy of the individual techniques computed over the past several years. Minimal smoothing is applied, consistent with the estimated accuracy of the input data. More information on the combination approach is provided in the literature (Luzum et al. 2014; Stamatakos et al. 2020).

The accuracy of the combined EOP solutions of Bulletin A is shown in Table 2 of Stamatakos et al. (2020). The mean and standard deviations are derived from a comparison of the running, weekly, and daily products compared to the long-term 14C04 series of the IERS Earth Orientation Center. The obtained standard deviations are in the range of about 40 to 80 μas for the pole coordinates and between 50 and 75 μs for UT1–UTC.

Concerning the prediction techniques, the algorithm for polar motion predictions was changed in 2017 to incorporate a least-squares, autoregressive (LS+AR) method as described in (Stamatakos et al. 2020). The UT1–UTC prediction makes use of UT1-like data product derived from a combination of the operational National Centers for Environment Prediction (NCEP) and US Navy's Global Environmental Model (NAVGEM) Atmospheric Angular Momentum (AAM) analysis and forecast. AAM-based predictions are used to determine the UT1 predictions for a prediction length up to 7.5 days (Johnson et al. 2005). For longer predictions, the LOD excitations are combined smoothly with the longer-term UT1 predictions as described by McCarthy and Luzum (1991).

Table 4.4 summarises the quality of the predictions of the pole coordinates and UT1–UTC until 90 days in the future (Stamatakos et al. 2020). The RMS values of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14C04 solution demonstrate that the accuracy of the predictions could be significantly improved due to the implementation of refined procedures.

Table 4.4: Root mean square of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14C04 combination solutions for 2017 (the values are extracted from Table 3a of Stamatakos et al. (2020)).

Days in future	x_p mas	x_p mas	UT1–UTC ms
0	0.07	0.04	0.074
1	0.31	0.23	0.087
5	1.75	1.32	0.198
10	3.29	2.29	0.537
20	5.89	3.80	2.347
40	10.24	5.78	5.118
90	17.25	9.28	9.748

4.3.4 Discussion of the present status

Theoretical aspects of precession-nutation models

In 2015, IAU and IAG established a Joint Working Group (JWG) "Theory of Earth rotation and validation" that continued the former IAU/IAG JWG "Theory of Earth Rotation" (Ferrándiz and Gross 2015). During the current term, the JWG is continuing under the name "Improving Theories and Models of the Earth's Rotation". The purpose of this JWG is to promote the development of theories of Earth rotation that are fully consistent and that agree with observations, useful for providing predictions of the EOP with the accuracy required to meet future needs as recommended by GGOS. From the findings of this JWG, it can be concluded that various issues are affecting the accuracy and consistency of the presently available precession-nutation models. The work provided the basis for the formulation of

IAG resolution No. 5 (2019) “Improvement of the Earth’s Rotation Theories and Models” (see Section 1.2.4). The issues of precession-nutation models have been discussed during the Unified Analysis Workshop 2019 in Paris, and several recommendations have been provided (Ferrandiz and Escapa 2019; Gross et al. 2019). A summary of these recommendations is given at the end of this section. More information on this JWG is available at the website hosted by the University Alicante at web.ua.es/en/wgterv/.

Input data for EOP generation

The EOP products provided by the Earth Orientation Center and the Rapid Service/Prediction Center of the IERS are generated from VLBI, SLR, GNSS data. For the latest 14C04 series also DORIS data have been included for the first time. The input data comprise intra-technique combined solutions provided by the technique centres of the IVS, ILRS, IGS, and IDS, as well as individual analysis centre solutions and the EOP solution associated with the ITRF2014 for the alignment with the ITRS. As a consequence, several measurements of the same space geodetic technique are included more than once in the EOP combination. At the same time, the corresponding stochastic model does not account for the multiple usage of identical input data leading to over-optimistic formal errors.

Although the standards and conventions used by all the contributing AC should follow the IERS Conventions as closely as possible, the current status is that they are not always fully (or clearly) documented, and that in some cases the corresponding AC log files are not up to date. Thus, it is difficult to assess the impact of inconsistencies on the EOP products.

Combination methods and consistency of EOP products

The combination procedure for the generation of the 14C04 series comprises several processing steps, which are performed on the solution (parameter) level. Regarding the contributing input solutions, only VLBI contains the full set of EOP, whereas the satellite techniques provide the pole coordinates and LOD. By using these data sets, not all correlations among the EOP can be considered in the combination, and in addition the parametrisations of the EOP are not fully consistent across the different techniques. Thus, the procedure of the IERS Earth Orientation Centre cannot be considered as a rigorous combination approach. Moreover, the literature gives a rather general description of the various data preparation and processing steps for the generation of the 14C04 series, whereas the analytical/mathematical combination model (including the alignment and extrapolation of the series) is not fully described. Thus, it is difficult to judge the present combination procedure comprehensively and for assessing their impact on the combination results.

The procedure applied at the IERS Rapid Service/Prediction Center for the generation of the real-time EOP and predictions cannot be considered as a rigorous combination, since it is also based on various processing steps on the solution (parameter) level. Although the general procedure is described in the literature, a detailed documentation of the analytical and mathematical foundations is partly missing. It was reported by Stamatakos et al. (2017), that beginning in 2016, a UT1–UTC convergence solution problem was occurring more often than in previous years. It was found that a probable cause could be the UT GPS inputs or the pre-processing of these input data before using it in the combination.

As described in Bizouard et al. (2019), the 14C04 solution has been tied to the two guide series, the IVS combination and the EOP solution associated with the ITRF2014, to ensure the consistency with the conventional reference frames, the ICRF2 and ITRF2014. However, this procedure does not include all relevant parameters of the contributing space techniques, and thus, it does not ensure full consistency between the EOP and the terrestrial and celestial reference frame.

4.3.5 Interaction with other products

The Earth Orientation Parameter are directly linked with

- Celestial reference frames
- Terrestrial reference frames
- Second degree gravity field coefficients (C_{20}, C_{21}, S_{21})
- Satellite orbits
- Parameters of geophysical fluids, particularly atmospheric, oceanic and hydrologic angular momentum (AAM, OAM, HAM).

4.3.6 Open problems and recommendations

Theoretical aspects of precession-nutation models

Issues affecting the accuracy and consistency of the presently available precession-nutation models were addressed by the joint IAU/IAG Working Group (JWG) “Theory of Earth rotation and validation” that continued the former JWG “Theory of Earth Rotation” (Ferrándiz and Gross 2015). Some of the major findings of this JWG was presented at the Unified Analysis Workshop (Ferrandiz and Escapa 2019). The following recommendations were provided at this Workshop (Gross et al. 2019): (1) the amplitudes of the leading nutations of the IAU2000 theory be updated and a shortened series for certain operational purposes be tested; (2) the inconsistencies found in the precession-nutation models be corrected; (3) the available FCN models be tested (for fitting Celestial Pole Offset (CPO)) and consideration be given to the question of whether or not the IERS should recommend the FCN models to use; and (4) the tasks of the joint IAU/IAG Working Group on Improving Earth Rotation Theories and Models be prioritised to get outcomes in two years.

Input data for EOP generation

In order to get consistent EOP products, it is a fundamental requirement that the input data must be based on unified standards, conventions and models. This objective is the basis for the following recommendations:

(1) Although the contributions used for the generation of the EOP products should be based on the latest version of the IERS Conventions, it is not clear if there are any deviations. Thus, all the geometric services (IGS, ILRS, IVS, and IDS) together with their contributing analysis centres should provide the relevant information on the present status of the standards and conventions currently applied in the data processing.

(2) The subsequent change of the mathematical representation of EOP functions in solutions or normal equations can involve a considerable loss of approximation accuracy. Thus, the parameterisation of the EOP functions should be identical for the contributions of all individual space geodetic techniques.

(3) Though VLBI only allows to solve for the full set of EOP, the satellite techniques should provide solutions or equations containing all five EOP regardless of whether some of them were fixed or constrained. That makes the full information contained in the different space techniques available for the combination, which is necessary to derive realistic correlations between the parameters.

(4) Moreover, the measurements of a single space geodetic technique should only be included once in the EOP combination in agreement with the associated stochastic model.

(5) It is also recommended to investigate all the contributing input data in detail to avoid any data problems or inconsistencies in the EOP combinations.

(6) At the Unified Analysis Workshop 2019 (Gross et al. 2019), it was recommended that also LLR data should be considered for the EOP combinations.

Combination methods and consistency of EOP products

A reference paper for the generation of the 14C04 has been provided by Bizouard et al. (2019). The procedures for the determination of the near-real time and predicted EOP are mainly described in the IERS Annual Reports (Stamatakos et al. 2020). It is recommended that the analytical and mathematical foundations of the EOP combination procedures are described in full detail. This holds also for the alignment of the long-term series with the terrestrial and celestial reference frame as well as for the extrapolation of the EOP beyond the ITRF2014 data period. The IERS Earth Orientation Center and the IERS Rapid Service/Prediction Center should consider a detailed description of the procedures including the full mathematical and analytical background in IERS Technical Notes (in the same way as for the ITRF). Although the accuracy of both, the 14C04 series and the near real-time and predicted EOP has been improved due to advanced procedures, it is recommended that the EOP Product Centers should consider the implementation of rigorous combination methods. Concerning EOP predictions, it should be investigated how the results could be further improved by reducing the latency of the last data point and by more frequently updating the AAM and Oceanic Angular Momentum (OAM) data.

Concerning the accuracy of the 14C04 series, the estimates published in the literature (Bizouard et al. 2019) are derived from an internal comparison, and are certainly too optimistic. Thus, it is recommended to use also external data and geophysical models for an accuracy assessment of the EOP products. Another topic is the consistency of the ICRF, the ITRF and the EOP (see IUGG resolution No. 3 (2011) and IAG resolution No. 2 (2019)) which has been addressed in Section 4.1 (see Recommendation 1.4).

Summary of recommendations on EOP

Recommendation 3.1 : Review of precession-nutation models: As outcome of the Unified Analysis Workshop 2019, the following recommendations were provided (Ferrandiz and Escapa 2019): (1) update the amplitudes of the leading nutations of the IAU2000 theory and test shortened series for certain operational purposes; (2) correct the inconsistencies found in the precession-nutation models; (3) test the available FCN models and consider whether the IERS should recommend FCN models or not. (4) The IAU/IAG JWG on Improving Earth rotation theories and models should prioritise these tasks to get outcomes in two years.

Recommendation 3.2 : Input data for EOP products: complete and up-to-date documentations of the standards and conventions for the contributing input solutions are necessary. Remaining inconsistencies need to be resolved to ensure consistent EOP products. The weighting should be properly performed if measurements of the same space geodetic technique are included more than once in the EOP combination.

Recommendation 3.3 : EOP combination procedure: The general procedures for the EOP combinations are described in the literature. It is recommended that also the analytical and mathematical foundations are described in full detail, which probably could be done in an IERS Technical Note. Furthermore, the development of rigorous combination methods should be considered by the EOP Product Centers.

Recommendation 3.4 : EOP Prediction: Although the accuracy has been improved significantly by implementing refined procedures it should be investigated how the results can be further improved by reducing the latency of the last data point and by more frequently updating the AAM and OAM data.

4.4 GNSS satellite orbits

Global Navigation Satellite Systems (GNSS) like the US American GPS, the Russian GLONASS, the European Galileo, and the Chinese BeiDou 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 realising global and regional reference systems, geophysical studies, surveying, deformation monitoring, and cadastre.

The Analysis Centres (ACs) 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. GPS and GLONASS final orbits are generated by the IGS Analysis Centre Coordinator (ACC) as a weighted mean of the individual AC orbits (Beutler et al. 1995; Griffiths and Ray 2009). They are provided with a latency of 12 – 18 days.

For the two new global navigation systems, Galileo and BeiDou, and the regional Quasi-Zenith Satellite System (QZSS), satellite orbits are computed by the ACs of the Multi-GNSS Pilot Project (Montenbruck et al. 2017b) of the IGS. The Indian Regional Navigation Satellite System (IRNSS) is currently not covered by the MGEX ACs due to lack of dual-frequency tracking data. An experimental multi-GNSS orbit product is generated by the IGS ACC since April 2019 covering GPS, GLONASS, Galileo, BeiDou, and QZSS (acc.igs.org/mgex_experimental.html).

Due to advances in observation modelling 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 two reprocessing campaigns up to now. The second reprocessing covers 1994 – 2014 (Griffiths 2018) and provided the input for ITRF2014 (Altamimi et al. 2016). The third reprocessing campaign is currently in progress and will provide input for ITRF2020. 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 centres contributing to the IGS 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

4.4.1 Summary of standards

The standards listed in Table 4.5 are based on the recommendations for the second and third IGS reprocessing campaign (acc.igs.org/reprocess2.html and acc.igs.org/repro3/

Table 4.5: Selected standards of the third IGS reprocessing campaign.

General Standards	IERS 2010 Conventions (Petit and Luzum 2010)
Reference Frame	ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.snx
Antenna Model	http://ftp.aiub.unibe.ch/users/villiger/igsR3_2077.atx
P1C1 Code Biases	ftp://ftp.unibe.ch/aiub/bcwg/cc2noncc
Phase Wind-Up	according to J. Wu et al. (1993)
Gravity Field	e.g., GGM05C (Ries et al. 2016)
Ocean tide model	FES2014b (Carrere et al. 2015)
Pole tide	linear mean pole (IERS 2018)
Subdaily ERP Model	Desai and Sibois (2016)
Earth radiation pressure	applied, http://acc.igs.org/orbits/ERPFBOXW.F
Antenna thrust	applied (Steigenberger et al. 2018, 2019)
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	GPT2 model (Lagler et al. 2013) to compute hydrostatic delays according to Davis et al. (1985)
Troposphere Mapping	GPT2 (Lagler et al. 2013) or more modern

repro3.html) as well as the recommendations of the IGS Analysis Center Workshop 2019 and the Unified Analysis Workshop 2019 (acc.igs.org/workshop2019.html and www.ggos.org/en/unified-analysis-workshop-2019/general-uaw/). For the third IGS reprocessing, the IGS Reference Frame Working Group and the Antenna Working Group prepared dedicated reference frame and antenna calibration files, see Table 4.5. 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

Solar radiation pressure modelling

Modeling of the Solar Radiation Pressure (SRP) is probably the largest error source of today's GNSS orbits. Deficiencies in the SRP modelling are visible as harmonics of the draconitic year in orbital (Griffiths and Ray 2013) and other parameters: station positions (Amiri-Simkooei 2013; Ray et al. 2008), geocentre (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).

A partly reduction of these systematic errors was achieved by recent developments including 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. 2015b), a box-plate model for GIOVE-B (Steigenberger et al. 2015), and box-wing models for Galileo (Bury et al. 2019), BeiDou (X. Yan et al. 2019), and QZS-1 (Montenbruck et al. 2017a; Zhao et al. 2018a). The ray-tracing approach is the most sophisticated SRP modelling technique (Bhattarai et al. 2019; Darugna et al. 2018; Z. Li et al. 2018) but requires detailed knowledge about geometry and optical properties. Optical properties and surface areas are currently available for GPS Block II (Fliegel et al. 1992), Block IIR (Fliegel and Gallini 1996), Galileo IOV and FOC satellites (GSA 2019), and the QZS-1 – 4 satellites (Cabinet Office 2019a,b,c,d). Incomplete optical properties (only absorption coefficients) and surface areas are available for BeiDou-2 (CSNO 2019b) and BeiDou-3 (CSNO 2019a). However, no public information on the detailed geometry of any GNSS satellites is currently available.

Table 4.6 lists orbit models recommended for different satellite types included in the third IGS reprocessing. Depending on the satellite type, different versions of the Empirical CODE Orbit Model (ECOM, Arnold et al. 2015; Beutler et al. 1994) or the GPS Solar Pressure Model (GSPM, Bar-Sever and Kuang 2005) are recommended as a minimum modelling standard. However, applying a bow-wing model together with additional empirical parameters is preferred.

Earth radiation pressure

Earth radiation pressure due to visible and infrared emissions of the Earth in particular affects the scale of the orbits (Bury et al. 2020; Rodriguez-Solano et al. 2011; Ziebart et al. 2007). Starting with the switch to IGS14/igs14.atx, Earth radiation pressure is considered by most ACs. Whereas optical properties of satellite surfaces for visible light are available for several satellites as mentioned in the previous section, coefficients for infrared radiation are not yet available.

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.

Steigenberger et al. (2018) measured the transmit power of selected GPS, GLONASS, Galileo, and BeiDou-2 satellites with a high-gain antenna. They report transmit power values between 20 and 265 W resulting in radial orbit shifts between 1 and 27 mm. Manufacturer values for the transmit power of the QZSS satellites are published in (Cabinet Office 2019a,b,c,d). Recent transmit power measurements of newly launched GLONASS satellites are given in Steigenberger et al. (2019). Due to the lack of transmit antenna gain pattern, the BeiDou-2 gain pattern were

Table 4.6: Orbit modelling recommendations for the third IGS reprocessing campaign according to Moore (2019).

Satellite type	Minimum modelling	Preferred modelling
GPS Block IIA	ECOM-2, GSPM	Box-wing + empirical
GPS Block IIR	ECOM-2, GSPM	Box-wing + empirical
GPS Block IIF	ECOM-1, GSPM	Box-wing + empirical
GPS Block III	ECOM-2, GSPM	Box-wing + empirical
GLONASS	ECOM-1, GSPM(GLONASS)	Box-wing + empirical
Galileo	ECOM-2	Box-wing + empirical

used for estimation of the BeiDou-3 MEO satellite transmit power included in the IGS satellite metadata file available at mgex.igs.org/IGS_MGEX_Metadata.php. The transmit power of the BeiDou-3 IGSO and GEO as well as all IRNSS satellites is currently unknown.

Attitude

The basic attitude condition of a GNSS satellite is that the navigation antenna points to the centre of the Earth and the solar panels are oriented perpendicular to the Sun (Montenbruck et al. 2015a). To fulfill 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 dedicated GNSS satellites are available but these models are not used by all ACs at the moment.

- GPS Block II, IIA, IIR: Kouba (2009a)
- GPS Block IIA: Rodriguez-Solano et al. (2013)
- GPS Block IIF: Dilssner (2010)
- GLONASS-M: Dilssner et al. (2010)
- BeiDou-2 IGSO-1, IGSO-6, MEO-6: Dilssner (2017)
- BeiDou-3S: X. Li et al. (2018)
- BeiDou-3: CSNO (2019c) and Shanghai Engineering Center for Microsatellites (2018)
- Galileo IOV and FOC satellites: GSA (2019)
- QZSS: Cabinet Office (2019a,b,c,d).

Satellite antenna model

GNSS measurements refer to the electrical phase centre of the transmission and receiving antennas. The mean differences between the mechanically well-defined antenna reference point of the receiver antennas and the centre of mass for the satellite antennas are called Phase Centre Offsets (PCOs). Variations of the actual phase centre depending on azimuth and elevation of the transmitted/received signal are called Phase Centre Variations (PCVs). As no ground calibrations are available for the transmitting antennas of GPS and GLONASS except for the first GPS III satellite (G074), satellite antenna phase centre offsets and variations were estimated from global GNSS data to derive antenna models for these systems.

For GPS and GLONASS, the current model `igs14.atx` (Rebischung et al. 2016) contains only block-specific PCVs and satellite-specific PCOs for the ionosphere-free linear combination of L1 and L2. Azimuthal variations of the satellite antennas (Schmid et al. 2005) are not yet considered for these GNSS. Furthermore, satellite-specific antenna PCVs could account for deviations of the individual transmitting antennas from the block-specific mean values. Such satellite-specific PCVs are published for each transmit frequency of Galileo IOV and FOC (GSA 2019) as well as QZS-2 – 4 (Cabinet Office 2019b,c,d).

Lockheed Martin published L1, L2, and L5 PCO values for the first GPS III satellite (Lockheed Martin 2019). L5 satellite antenna calibrations for the other GPS satellites as well as GLONASS L3 calibrations are currently not available. Manufacturer PCO values for the BeiDou-3S satellites are given in (Zhao et al. 2018b). Frequency-specific satellite antenna phase centre offsets of the active BeiDou-2 and BeiDou-3 satellites for B1, B2, and B3 were published by the China Satellite Navigation Office (CSNO) in December 2019.

The availability of pre-flight calibrations for the Galileo satellite antennas makes it possible to derive the terrestrial scale from GNSS observations. The inclusion of Galileo in the third IGS reprocessing might even enable a contribution of GNSS to the scale definition of ITRF2020 (Villiger et al. 2019).

Receiver antenna model

The IGS receiver antenna model is mainly composed of absolute robot calibrations for L1 and L2. Only for a few antennas, converted relative calibrations are included. For the third IGS reprocessing campaign, a dedicated file IGSR3_2077.atx was compiled by the Antenna Working Group including 36 robot calibrations by Geo++ and one chamber calibration by University of Bonn for the following additional frequencies:

1176.45 MHz:	GPS L5, Galileo E5a, BeiDou B2a
1191.795 MHz:	Galileo AltBOC and BeiDou ACE-BOC
1207.14 MHz:	Galileo E5b, BeiDou B2b
1268.52 MHz:	BeiDou B3
1278.75 MHz:	Galileo E6, QZSS L62

However, not all frequencies are available for all calibrations. In addition, calibrations for GLONASS L3 (1202.025 MHz) and the IRNSS S-band frequency of 2492.028 MHz are still missing. The latter fact is insignificant at the moment as none of the antennas currently used within the IGS has a dedicated S-band capability and only one receiver type supports tracking of this signal.

Non-tidal loading

It is currently not recommended to apply non-tidal loading corrections at the observation 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).

Subdaily ERP model

Griffiths and Ray (2013) found subdaily alias errors in IGS orbit, coordinate, geocentre, and ERP products. They attributed these errors to deficiencies of the IERS subdaily ERP model and concluded that an improved model is needed to mitigate these errors. As a consequence, an IERS Working Group on Diurnal and Semi-diurnal EOP Variations was established. In July 2019, this working group recommended the model of Desai and Sibois (2016) based on hydrodynamic ocean models obtained from altimetry.

Thermal modelling of monuments

Temperature changes induce thermal expansions of the bedrock and the monuments, where the GNSS antennas are mounted on, as well as tilts of the monuments. Romagnoli et al. (2003), H. Yan et al. (2009), Hiroshi (2013), Wang et al. (2018) report vertical displacements in the order of a few millimeters. However, as additional information about the thermal properties of the bedrock and the monument as well as temperature data are required, these corrections are currently not applied by the IGS ACs.

Operational information

The knowledge about selected operational information, in particular orbit maneuvers and attitude mode switches, is essential for precise orbit determination. Most GNSS providers issue so-called notice advisories announcing, e.g., planned outage periods of individual satellites:

GPS	Notice Advisory to NAVSTAR Users (NANU)
GLONASS	Notice Advisory to GLONASS Users (NAGU)
Galileo	Notice Advisory to Galileo Users (NAGU)
QZSS	Notice Advisory to QZSS Users (NAQU)

However, these advisories do not contain information about the exact maneuver epoch(s). Such information is currently only provided for QZSS by Cabinet Office, Government of Japan (CAO) in the form of detailed Operational History Information (OHI), i.e., time, duration, and magnitude of orbit maintenance maneuvers, changes of attitude modes, and time of reaction wheel unloading (Cabinet Office 2019e, 2020a,b,c).

Satellite metadata

Many of the effects and models described in the paragraphs above require knowledge about the corresponding GNSS satellites, e.g., satellite mass, sensor offsets, transmit power, etc. The IGS Multi-GNSS Working Group (MGWG) prepared an extension of the SINEX format in order to store and exchange these GNSS metadata (mgex.igs.org/IGS_MGEX_Metadata.php). The MGWG also maintains a draft release of the IGS satellite metadata file available at mgex.igs.org/igs_metadata.snx. More details on the importance and availability of satellite metadata are given in a white paper of the MGWG (Montenbruck and Steigenberger 2020).

4.4.3 Links to other products

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

- Terrestrial Reference Frame (TRF)
- TRF densification, e.g., regional reference frame of the IAG Reference Frame Sub-Commission for Europe (EUREF), or Sistema de Referencia Geocéntrico para las Américas (Geocentric Reference Frame for the Americas) (SIRGAS)
- 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 modelling affect the following products utilizing GNSS satellite orbits:

- Low Earth Orbiter (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 modelling and recommendations for further studies. These include:

- The consistency of the orbit solutions submitted by the IGS Analysis Centers has to be assured.
- Radiation pressure modelling and aliasing of orbital errors into geodetic parameters needs to be further studied.
- The impact of different arc lengths (1-day vs. 30 hours vs. 3-day) on geodetic parameters needs to be assessed. Selected aspects are already published in (Lutz et al. 2016)
- Receiver antenna calibrations beyond L1/L2 are required for *all* antennas and *all* frequencies used in the IGS.
- Satellite antenna offsets are required for IRNSS and SBAS satellites.
- Satellite antenna phase centre variations are required for BeiDou, IRNSS, QZS-1, and SBAS.
- Attitude models are required for GPS III, IRNSS, and SBAS satellites.
- Transmit power levels are required for GPS III, IRNSS, and SBAS satellites.
- No combined clock product is available for GLONASS, BeiDou, Galileo, and QZSS.
- No orbit products are available for IRNSS and SBAS.

Summary of recommendations on GNSS orbits

Recommendation 4.1: Up-to-date analysis strategy summary files should be provided by all ACs for their operational, MGEX, and reprocessed products.

Recommendation 4.2: The impact of analysis strategies such as radiation pressure modelling and orbit arc length on derived geodetic parameters should be investigated in detail.

Recommendation 4.3: The contribution of Galileo antenna calibrations to a GNSS-derived realisation of the terrestrial scale should be studied.

Recommendation 4.4: Satellite operators should be urged to provide missing detailed information about satellite dimensions, optical and infrared surface properties, attitude models, antenna offsets, antenna phase patterns, radio emission power, transmit antenna gain pattern, and operational information such as maneuvers.

Recommendation 4.5: A multi-GNSS-capable orbit and clock combination software shall be developed.

4.5 Gravity and geoid

Gravity and geoid related data and products are collected and prepared by several IAG services, which all together are organized under the umbrella of the International Gravity Field Service (IGFS). The overall goal of IGFS is to coordinate the collection, validation, archiving and dissemination of gravity field related data and to coordinate courses, information materials and general public outreach relating to the Earth's gravity field. One of the overarching goals of the IGFS is to unify gravity field related products for the needs of the Global Geodetic Observing System (GGOS). IGFS coordinates the servicing of the geodetic and geophysical communities with gravity field-related data, software and information. The combined data of the IGFS entities include global models of the static (mean) Earth gravity field and its time-variable component, terrestrial, airborne, satellite and marine gravity observations, Earth tide data, Global Positioning System (GPS) levelling data, digital models of terrain and bathymetry as well as the oceanic gravity field and geoid from satellite altimetry.

Under the umbrella of the IGFS the following services and centres are available. They represent the "operating arms" of the IGFS and are independently organized. Nevertheless the IGFS coordinates their activities specifically regarding joint standards and conventions in order to ensure inter-operability of their products. In addition the IGFS Central Bureau (IGFS CB) develops and provides online applications for the creation of metadata for gravity and geoid data. This shall ensure that all metadata required to fully describe a numerical dataset are available.

BGI Bureau Gravimétrique International, Toulouse, France: The overall task of BGI is to collect, on a worldwide 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.

ISG International Service for the Geoid, Milano, Italy: The main tasks of ISG are to collect geoid data on a worldwide scale, to collect and distribute software for geoid determination, to conduct research on procedure for geoid determination, to organize geoid schools, and to edit and distribute the Newton's Bulletin.

ICGEM International Center for Global Earth Models, Potsdam, Germany: The main tasks of ICGEM are to collect and archive all existing global gravity field models, web interface for getting access to global gravity field models, web based visualization of the gravity field models, their differences and their time variation, web based service for calculating different functionals of the gravity field models, web site for tutorials on spherical harmonics and the theory of the calculation service.

COST-G International Combination Service for Time-variable Gravity Fields, Bern, Switzerland:
COST-G is the Product Center of the IGFS for time-variable gravity fields. COST-G provides consolidated monthly global gravity models in terms of spherical harmonic coefficients and thereof derived grids by combining solutions from individual analysis centres (ACs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from
GRACE/GRACE-FO,
low-low satellite-to-satellite tracking (ll-SST),
high-low satellite-to-satellite tracking (hl-SST),
Satellite Laser Ranging (SLR).

IDEMS International Digital Elevation Model Service, ESRI, Los Angeles, USA:
The main tasks of IDEMS are the distribution of data and information about Digital Elevation Models, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain.

IGETS International Geodynamics and Earth Tide Service, Strasbourg, France: The primary objective of IGETS is to provide a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS continues the activities of the GGP to provide support to geodetic and geophysical research activities those of ICET in collecting, archiving and distributing Earth tide records.

The general character of the products offered by the IGFS services is slightly different to 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 mostly 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 shall 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, following specific standards and conventions implemented at some point form the basis for generating the products. These standards and conventions often are unknown or not specified together with the products.

In the following sections the products offered by the IGFS centres are shortly described and references for these products are provided. In the subsequent table for each identified product an inventory of the standards needed to describe 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 IGFS – Central Bureau

The IGFS Central Bureau (IGFS CB) acts as the central coordination and communication centre of the IGFS. The IGFS CB high level tasks include

- The provision of the link between the IGFS entities, IAG, and external projects, networks or organisations (oceanic, atmospheric, hydrology and others).
- The provision of the link to the GGOS bureau and communicate their requirements and recommendations to the IGFS.
- The implementation of standards and recommendations related to gravity field observations, securing consistency with geometric standards, and promotion of their use within the geoscientific community.

Within these activities the IGFS CB is developing online applications for the creation of metadata for gravity and geoid data, which shall be established as a service for searching the metadata database in order to locate dataset sources. In addition the metadata description secures that for a numerical dataset all needed information is available in order to correctly interpret it. So far draft versions for a geoid metadata editor and for a gravity data editor have been developed as Web applications. These metadata editors ask for the following information classes :

Geoid Metadata Editor (v0.1.3) and **Gravity Metadata Editor** (v0.2.6).

Section 1: Metadata Reference Information

- Responsible Organisation and Contact
- Metadata Creation and Review Dates
- Metadata Prototype Information:

Section 2: Identification Information

- Resource Coordinate Reference System
- Resource Citation
- Resource Description
- Resource Status
- Resource Point of Contact
- Spatial Extent Geographic Bounding Box Coordinates
- Resource Maintenance and Updates
- Keywords
- Resource Constraints and Security Information

Section 3: Distribution Information

- Distributor
- Standard Order Process
- Metadata Constraints

Section 4 – Alternative Geoid Data: Standard and Conventions

- General Standards and Conventions (GM, a, f)
- Tide System
- Reference Ellipsoid
- Standard Density of the Earth

Page 4 – Alternative Gravity Data: Standard and Conventions

- General Standards and Conventions (GM, a, f, normal gravity reference ellipsoid)
- Earth's Gravity Field Permanent Tide System
- Earth Orientation Parameters Specifications
- Tidal Conventions
- Station Coordinates and Corrections

Section 5 – Alternative Geoid Data: Data and Data Quality Information

- Attribute Accuracy
- Logical Consistency Report
- Completeness Report
- Data Distribution
- Geoid Data / Gravity Data
- Position Accuracy / Position and Height Accuracy

Section 5 – Alternative Gravity Data: Data and Data Quality Information

- Attribute Accuracy
- Logical Consistency Report

- Completeness Report
- Data Distribution
- Gravity Data
- Position and Height Accuracy
- Time Period of Content

4.5.2 BGI – Bureau Gravimétric International

The overall task of the Bureau Gravimétrique International (BGI) is to collect, on a worldwide 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. BGI central office is located in Toulouse, France, in the premises of the Observatoire Midi-Pyrénées (OMP).

The products of the BGI are

Gravity Databases:

- Collection of land and marine gravity data.
- Gravity data at reference stations.
- Data from absolute gravity stations (see mirror site: agrav.bkg.bund.de).

Grids and Models:

- 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 computed from the Earth Gravitation Model 2008 (EGM 2008).
- Gridded estimates of (i) gravity accelerations, (ii) gravity disturbances, (iii) quasigeoid undulations, and (iv) deflection of the vertical components from the ultra high resolution GGMplus global gravity field model (Hirt et al. 2013).

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

- 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/723/9056/file/BGI_Normal_gravity_determination.pdf
- Définition des anomalies gravimétriques (in French):
  bgi.omp.obs-mip.fr/content/download/724/4972/file/FORMUL00.pdf
- Gravity definitions & anomaly computations (NGA document):
  bgi.omp.obs-mip.fr/content/download/725/4975/file/computations.pdf
- Description of the International Database for Absolute Gravity Measurements:
  bgi.omp.obs-mip.fr/content/download/727/4992/file/AGrav_Wziontek_etal2.pdf
  See also: (Wilmes et al. 2009).

Apart from the product descriptions a number of tutorials are offered in English and French language providing the fundamentals of gravity theory and satellite geodesy.
See: bgi.omp.obs-mip.fr/data-products/Documentation/tutorials.

4.5.3 ISG – International Service for the Geoid

ISG activities are on educational, research, and data distribution sides : principal purposes of ISG are the collection and distribution of geoid models, the collection and distribution of software for geoid computation, and the organisation of technical schools on geoid determinations. The 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 researches on procedure for geoid determination (projects)
- to organize Geoid schools
- to edit and distribute the Newton's Bulletin

The products of the International Service for the Geoid (ISG) are

- Grids of local and regional geoid estimates, collected worldwide (geoid repository).
- Geoid Software (local geoid estimation; spherical harmonics manipulation; global models handling, evaluation of different functionals of the gravity field). As this is specific software and not a data product no standards and conventions are identified.
- International schools on geoid determination and thematic schools. As this is not a data product no standards and conventions are identified.

More details about tasks and products can be found at the service web site www.isgeoid.polimi.it/index.html and in the following documents offered by the web site:

- Geoid model specifications: www.isgeoid.polimi.it/Geoid/ISG_format_20160121.pdf
- Software is provided via this web link: www.isgeoid.polimi.it/Software/software.html

4.5.4 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 this includes: 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 International Centre for Global Earth Models (ICGEM) are

- Static gravity field models as spherical harmonic series.
- Gravity field solutions for dedicated time periods (time variable model series) as spherical harmonic series. Monthly, weekly and daily solutions with or without applying non-isotropic filtering.
- Topographic gravity field models model . . . spherical harmonic series in ICGEM format (topography heights and gravitational potential).
- Calculation of gravity functionals on freely selectable grids or on user defined points. The following functionals are implemented so far: height anomaly, geoid height, gravity disturbance, gravity anomaly, Bouguer anomaly, gravity, gravitation, radial gravity gradient, equivalent water height.
- Visualization service for static and temporal gravity field model functionals, trends and amplitudes for temporal fields and spherical harmonics.
- Evaluation of gravity field models by degree variances and by GNSS-levelling comparisons.
- Additionally ICGEM offers also gravity field models of other celestial bodies (Moon and Mars) including the calculation and visualization service.

More details about tasks and products can be found at the service web site icgem.gfz-potsdam.de/home and in the following documents offered via the web site:

- The theory and formulas used by the calculation service of the ICGEM are described in the Scientific Technical Report STR09/02: icgem.gfz-potsdam.de/str-0902-revised.pdf
- Article about global models: icgem.gfz-potsdam.de/GlobalModelsEncyclopedia.pdf
- Description of the ICGEM format: icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf
- Information on the topographic gravity field models: icgem.gfz-potsdam.de/Topomodels_description_ICGEM.pdf

4.5.5 COST-G – International Combination Service for Time-variable Gravity Fields

COST-G is the product centre of IGFS for standardization of gravity derived mass transport products in order to improve the quality, robustness and reliability of individual solutions and in order to enable hydrologists, glaciologists, oceanographers, geodesists and geophysicists to take full advantage of one well-defined, consolidated time variable gravity product. COST-G tasks are: (1) Developing the synergy between international teams working on gravity field modelling; (2) Improving and homogenizing the modelling adopted by the Analysis Centers (AC); (3) Providing combined reference solutions by the Combination Center (CC); (4) Assessing the reference solutions by a Validation Center (VC); (5) Organizing dissemination by a dedicated webmaster (WM). The combination service infrastructure will improve the actual standards and turn it into an operational mode that will enable the use of Gravity Recovery And Climate Experiment (GRACE) and Gravity Recovery And Climate Experiment – Follow On (GRACE-FO) mass redistribution data for monitoring hydrological events such as floods or droughts for instance. COST-G will provide consolidated time-variable global gravity models in terms of spherical harmonic coefficients and thereof derived grids by combining solutions from individual analysis centres as well as validation criteria which will be made available through dedicated web-interfaces.

The main products of COST-G are monthly global gravity field models derived from the combination of solutions from the COST-G analysis centres and partner analysis centres. In particular products at different processing levels are provided: Monthly global gravity field models in terms of spherical harmonic coefficients (Level-2 products). Post-processed Level-2 products in terms of spherical harmonic coefficients with various corrections applied (Level-2B products). User-friendly grids based on Level-2B products (Level-3 products) for various scientific applications as described at GFZ's Gravity Information Service (GravIS, gravis.gfz-potsdam.de/home).

Apart from these main products COST-G is also offering additional products helping to process the main products: Monthly means of background models that are generated by a weighted combination of the corresponding products of the individual analysis centres (applying the same weights as used for the generation of the combined gravity field models) Monthly means of combined atmosphere and ocean dealiasing products.

The COST-G products are disseminated via ICGEM and GFZ's ISDC at icgem.gfz-potsdam.de/series/02_COST-G/ and ftp://isdcftp.gfz-potsdam.de/grace/GravIS/COST-G respectively. The COST-G Processing Standards and Release Notes are available at cost-g.org/download/COST_G_STANDARDS.pdf and cost-g.org/download/COST_G_RL01.pdf, respectively. Visualizations of the COST-G products are provided by GFZ's Gravity Information Service (GravIS, gravis.gfz-potsdam.de) and the COST-G Plotter (cost-g.org/).

4.5.6 IDEMS – International Digital Elevation Model Service

The website of the IAG International Digital Elevation Model Service (IDEMS) provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth's global topography, lunar and planetary Digital Elevation Model (DEM), relevant software and related datasets. All information is provided via the service web site www.cse.dmu.ac.uk/EAPRS/iag/.

Currently, this site hosts different categories about products and information about DEMs, namely:

- Bathymetry and Ice Data,
- Earth Models,
- Geodesy relevant DEM and Bathymetric Terrain Model (BTM) Studies
- Global DEMs
- Planetary Terrain Data
- Regional DEMs
- Software and Apps
- Using DEMs and Esri Products.

The products of IDEMS are:

- Compilation, tutorial-style provision and maintenance of information on global gridded DEMs;
- Compilation of available national elevation data sets with information on data resolution, methods used for DEM generation and links to providers;
- Generation and dissemination of spherical-harmonic models of Earth's global topography and bathymetry;
- Compilation of geodesy-relevant DEM-studies;
- Extension of the focus from Earth to Moon and terrestrial planets through compilation of information on available planetary topography models.

The service does hardly provide data products via its web site, but mostly links to other institutional, project related or satellite mission web sites, where digital elevation models are made available. Standards and conventions for IDEMS products are not specified and no documentation about the most important digital elevation products is provided. Only a short tutorial "Getting started with IDEMS" an introduction to DEMs, and a bibliography is provided via the web site. The tutorial about the IDEMS in the present form is a mix of a general user manual and some kind of ArcGIS advertisement. From the information available at the web site it is not immediately obvious which models are freely accessible to the public.

4.5.7 IGETS – International Geodynamics and Earth Tide Service

The International Geodynamics and Earth Tide Service (IGETS) provides a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS is composed by two analysis centres hosted by University of French Polynesia in Tahiti and by University of Strasbourg and by a main data centre hosted GFZ Potsdam. Additionally, University of Strasbourg is hosting the central bureau and a secondary data centre. More details about IGETS can be found on the following web site: igets.u-strasbg.fr/index.php.

The main products of IGETS are the raw and processed data from worldwide superconducting gravimeters. In particular data at different processing levels are provided. These are :

- Raw gravity and local pressure records sampled at 1 or 2 seconds, in addition to the same records decimated at 1-minute samples (Level 1 products).
- Gravity and pressure data corrected for instrumental perturbations, ready for tidal analysis (Level 2 products).
- Gravity residuals after particular geophysical corrections (including solid Earth tides, polar motion, tidal and non-tidal loading effects) (Level 3 products).

Apart from these main products IGETS is also offering additional products helping to process the main products (via links to other web sites). These are :

- Superconducting gravimeter data for major Earthquakes (minute and second sampling);
- Atmospheric attraction computation service;
- mGlobe Matlab/Octave toolbox for computation of global hydrological, atmospheric and non-tidal ocean loading effects;
- Loading service (displacements, gravity, tilts).

Details about the main IGETS products can be found at the ISDC Web site of GFZ at isdc.gfz-potsdam.de/igets-data-base/documentation/. In particular there is available a report providing documentation and conventions for the IGETS products. See gfzpublic.gfz-potsdam.de/pubman/item/escidoc:1870888:7/component/escidoc:1948897/STR-1608_voigt.pdf.

4.5.8 IGFS Products Inventory of Standards

From the descriptions provided in the previous chapters the following product categories of the IGFS can be summarized. For these product categories certain standards and conventions need to be identified such that they are compatible (product identifier: product description):

BGI1	Land and marine gravity data and gravity data at reference stations
BGI2	Absolute gravity station data
BGI3	Grids of gravity anomalies
ISG1	Grids of regional geoid solutions
ICGEM1	Global gravity field model as spherical harmonic series (static, time variable)
ICGEM2	Gravity field functionals on a grid
IDEM1	Grids of digital elevation models
IGETS1	Superconducting gravimeter data

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 at all. So far metadata definitions have only been generated for geoid and gravity data either on grids or point-wise. Metadata for spherical harmonic series still need to be defined, but are overlapping to a large extent with metadata elements as defined for gravity and geoid products. The following list summarizes metadata, which are related to standards and conventions (metadata code and metadata description). The numbers are indicating the metadata field number, while letters indicate if a metadata entry is either specified for the geoid (**N**), for gravity observations (**G**) or both (**A**).

Metadata related to product standards and conventions:

A4.1.1	Gravitation constant of the Earth (GM)
A4.1.2	Equatorial radius of the Earth
A4.1.3	Flattening of the Earth
G4.1.4	Reference ellipsoid for normal gravity computation
A4.2.1	Permanent tide system
G4.2.2	Permanent tide system Earth orientation parameters
N4.3	Reference ellipsoid for geoid heights
G4.3	Earth orientation parameters specifications
N4.4	Standard density of the Earth value
G4.4.1	Solid Earth tides
G4.4.2	Solid Earth pole tide model
G4.4.3	Oceanic pole tide model
G4.4.4	Tidal ocean loading
G4.4.5	Non-tidal ocean loading model
G4.4.6	Non-tidal atmospheric loading model
G4.5.1	Horizontal and vertical coordinates
G4.5.2	Standard density of the Earth value
G4.5.3	Vertical gravity gradient
G4.5.4	Air pressure correction
A5.4	Data distribution: points or grid and grid specifications
N5.5.1	Geoid model type (gravimetric, hybrid, etc.)
N5.5.2	Fitting or integration methodology
G5.5	Gravity data type (absolute, type of anomaly, etc.)
N5.6	Geoid height data type (undulation or height anomaly)
G5.8	Time period and time reference

The following Table 4.7 provides a summary of the identified standards and conventions for the above mentioned IGFS products and specifically if they are addressed by the metadata descriptions (✓= metadata description available; N/A = not applicable for this product). Each line in the table represents one of the above mentioned metadata. In case additional metadata are needed for specific products they are indicated by additional lines in the table. So far the following additional metadata were identified: Degree = Maximum degree of spherical harmonic series applied to determine the product; Filter = Indication if a filter has been applied and what filter parameters were used.

4.5.9 Recommendations

The updated IGFS web-site acts as an umbrella for all its services and provides basic information about their tasks and products. 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 shall 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 could provide information about their products in a more concise way. Further remark on BGI and IDEMS: Many of the products collected by these services are not publicly available. Although they appear as IAG Services, this data is not available for research within the IAG. From the analysis of the services and their products some recommendations can be drawn.

Recommendation 5.1 : For all IGFS products (i.e. from the affiliated services and centres) metadata as specified by the IGFS-CB shall be provided. If needed, further metadata categories in addition to geoid and gravity shall be developed by the IGFS-CB.

Table 4.7: Summary of the identified standards and conventions for IGFS products.

	BGI1	BGI2	BGI3	ISG1	ICGEM1	ICGEM2	IGETS1
A4.1.1	✓	N/A	✓	✓	✓	✓	✓
A4.1.2	✓	N/A	✓	✓	✓	✓	✓
A4.1.3	✓	N/A	✓	✓	✓	✓	✓
G4.1.4	✓	N/A	✓	N/A	N/A	✓	✓
A4.2.1	✓	✓	✓	✓	✓	✓	✓
G4.2.2	✓	✓	✓	N/A	N/A	N/A	✓
N4.3	N/A	N/A	N/A	✓	N/A	✓	N/A
G4.3	✓	✓	✓	N/A	N/A	N/A	✓
N4.4	N/A	N/A	N/A	✓	N/A	N/A	N/A
G4.4.1	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.2	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.3	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.4	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.5	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.6	✓	✓	✓	N/A	N/A	N/A	✓
G4.5.1	✓	✓	✓	N/A	N/A	✓	✓
G4.5.2	✓	N/A	✓	N/A	N/A	N/A	✓
G4.5.3	✓	N/A	✓	N/A	N/A	N/A	✓
G4.5.4	✓	✓	✓	N/A	N/A	N/A	✓
A5.4	✓	✓	✓	✓	N/A	✓	✓
N5.5.1	N/A	N/A	N/A	✓	N/A	✓	N/A
N5.5.2	N/A	N/A	N/A	✓	N/A	✓	N/A
G5.5	✓	✓	✓	N/A	N/A	✓	✓
N5.6	N/A	N/A	N/A	✓	N/A	✓	N/A
G5.8	✓	✓	✓	N/A	✓	✓	✓
Degree	N/A	N/A	N/A	N/A	N/A	✓	N/A
Filter	N/A	N/A	N/A	N/A	N/A	✓	N/A

Recommendation 5.2 : BGI shall collect and distribute grids of altimetric gravity anomalies. So far these data are not yet offered by the IGFS.

Recommendation 5.3: BGI and IGETS partially are providing similar products, i.e. observations from ground gravimeters. It is recommended that both services implement joint standards for these products in order to ensure compatibility.

Recommendation 5.4 : The ISG Software has some overlap with the on-line tools available at the ICGEM. It is strongly recommended to make sure that both Software systems are compatible, i.e., that the same standards and conventions are used.

Recommendation 5.5 : COST-G products shall be disseminated via the ICGEM. It is recommended not to establish a separate service for provision of combined time variable gravity field series. Same standards as used by ICGEM (e.g. format) shall be applied. What concerns mass transport grids, it shall be made sure that these are as well compatible to the ICGEM calculation service. In addition the relationship to the GFZ driven GravIS system shall be defined and ideally both shall be combined.

Recommendation 5.6 : The IDEMS in the present form cannot be regarded as a product repository as it hardly provides access to real digital elevation data grids. At various places on the IDEMS web pages links to ArcGIS are set. In order to make full use of the web site an ArcGIS software license seems to be needed. So IDEMS shall not be regarded as an open access scientific service, but a mix of service and public relation for ESRI who is maintaining the IDEMS web site. It is strongly recommended to separate the web site content to a product service part, which should point towards accessible DEM's (the real IDEMS) and another section which might be more related to ArcGIS applications.

Recommendation 5.7 : All products to be delivered under the umbrella of IGFS shall be publicly available for research applications. Otherwise these products shall not be advertised anymore as IGFS supported products.

4.6 Height systems and their realisations

In the first version of this inventory, published in 2016 (Angermann et al. 2016), the section "Height Systems and their realisations" concentrated on the discrepancies of the local height systems and their combination with geometric (ellipsoidal) heights and (quasi-)geoid models. Special care was given to the inventory of corrections or reductions applied to the different vertical coordinates to remove or retain geophysical effects influencing the vertical positioning. In this updated version of the inventory, we add a description of the standards that are being discussed (as of December 2019) for the implementation of the International Height Reference System (IHRS) and its realisation, the International Height Reference Frame (IHRF), as stated by the IAG Resolution No. 1, 2015 released in the IUGG2015 General Assembly (Drewes et al. 2016).

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 according to 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 orthometric or normal 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 specific guidelines (Dahle et al. 2013; Gruber et al. 2010; Lühr et al. 2002). However, the computation of the long-wavelength constituents of the (quasi-)geoid (degree $n \leq 200\ldots250$ 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 ($n > 250$) of the (quasi-)geoid are usually estimated by combining surface (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 surface 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.

Historically, the determination of the physical heights initially followed two basic conventions: (1) the geoid coincides with the mean sea level and (2) the corresponding vertical coordinate must be the orthometric height. The realisation 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 realisation of the orthometric height system, but also of the geoid as a level surface running in the Earth's interior over the continents. Alternatively, and since about the middle of the 20th century, some height systems are based on normal heights and the quasi-geoid as the reference surface. The geoid and the quasi-geoid are practically identical in marine areas, and the realisation of the quasi-geoid can also be set equivalent to the local mean sea level at the reference tide gauges. In general, the existing physical heights not only refer to local (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-modelled 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 modelling 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 standardisation (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 *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.

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. – **Realisation**: 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 modelling both the mean sea surface and the geoid, e.g., (Ekman 1995; Heck 2004; Heck and Rummel 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 realise 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). – **Realisation**: levelling with gravity reductions (in same cases 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 realise different orthometric height types depending on the applied orthometric hypothesis. – There is no unique relation between reference surface and vertical coordinates if the geoid is not computed using the same orthometric hypothesis as applied for the orthometric heights. – The determination of normal heights does not depend on any orthometric 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 realisation to m-level.

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 *regularised* 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 or near 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 summarises 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 realisation 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 and Luzum 2010, Chapters 6 and 7)). This approximation is called the *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 and MacDonald 1960)). This approximation is called the *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 the 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 the conventional tide-free or zero-tide system. The mean-tide system is also used especially for oceanographic applications.

The tide-generating potential is modelled according to:

- for the geometric coordinates (following IERS Conventions): Cartwright and Edden (1973) and Cartwright and Tayler (1971). Transformation parameters to the models of Doodson (1921) and Hartmann and Wenzel (1995) are also provided;
- for the CHAMP, GRACE, and GOCE data: the same as the IERS Conventions;
- for the terrestrial gravity: beside the Cartwright model (Cartwright and Edden 1973; Cartwright and Tayler 1971), the Longman (1959) formulation was also widely applied before IGSN71. In recent years, the model of Hartmann and Wenzel (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 and Anderson 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 and MacDonald 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 modelled 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 and Lyard 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 modelled according to (Ray and Ponte 2003), while in the GRACE data processing the model of Biancale and Bode (2006) is used. GOCE data processing does not reduce this effect directly; it is modelled together with non-tidal effects.

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 (modelled 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 (modelled 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 (modelled as hydrostatic equilibrium)	±0.0018 m (vert), ±0.0005 m (hz)	unknown	negligible	±0.0018 m
LOD variations (modelled 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

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 Centre 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 modelled 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);
- systematic effects and distortions, e.g., long-wavelength (quasi-)geoid errors, poorly modelled 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 (standardise) the existing height systems; i.e., to refer all physical heights to one and the same reference level (defined and realised 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 regularised 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 The IAG resolution for the definition and realisation of an *International Height Reference System (IHRS)*

A first concrete step oriented to the establishment of a worldwide unified (standardised) vertical reference system is the release of an IAG resolution for the *definition and realisation of an International Height Reference System (IHRS)*. This resolution 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 ($-\Delta W_\mathrm{P} = C_\mathrm{P} = W_0 - W_\mathrm{P}$) referring to an equipotential surface of the Earth's gravity field realised by the IAG conventional value W_0 = 62 636 853.4 $\mathrm{m^2s^{-2}}$. The spatial reference of the position P for the potential $W_\mathrm{P} = W(\vec{X})$ is given by coordinates $\vec{X}$ of the ITRF. The units of length and time are the meter (m) and the second (s) as expressed by the International System of Units (SI). 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. More details about the foundations of this IAG resolution can be found in (Ihde et al. 2017) and (Sánchez et al. 2016).

4.6.5 Towards an standardisation for the IHRS realisation

The convention $W_\mathrm{P} = W(\vec{X})$, with $\vec{X} = [X, Y, Z]_\mathrm{ITRF}$ makes evident that the IHRS is based on the combination of a geometric component given by $\vec{X}$ and a physical component given by the determination of W at $\vec{X}$. $\vec{X}$ is to be determined in the ITRS/ITRF and consequently, it follows the IERS standards and conventions (see details in Section 4.2). The potential values W may be in general determined from geopotential numbers C_P or by solving the geodetic boundary value problem (GBVP). Geopotential numbers C_P are known from levelling with gravity reductions and the potential values W would be given by $W_\mathrm{P} = W_0 - C_\mathrm{P}$. However, as they refer to local vertical datums (different reference levels), this approach requires the vertical datum unification of the levelling-based height systems into the IHRS and its reliability is limited by the drawbacks of the existing height systems (see Table 4.8). Therefore, this approach is useful for the transformation of the existing height systems to the IHRS, but it is unsuitable for the precise realisation of the IHRS (Sánchez and Sideris 2017).

The determination of absolute potential values W_P from observational data is only possible after introducing adequate

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

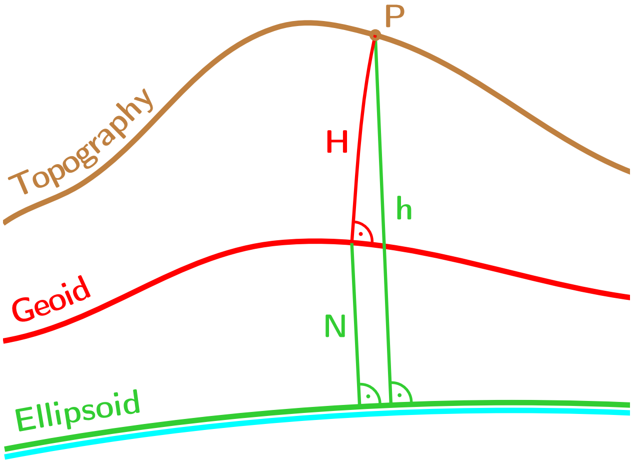
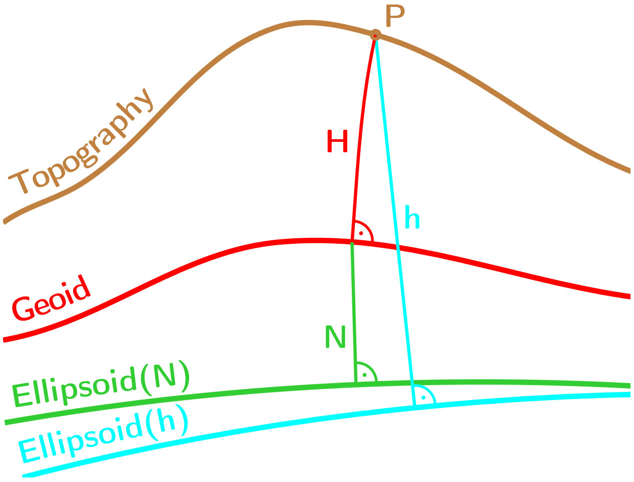
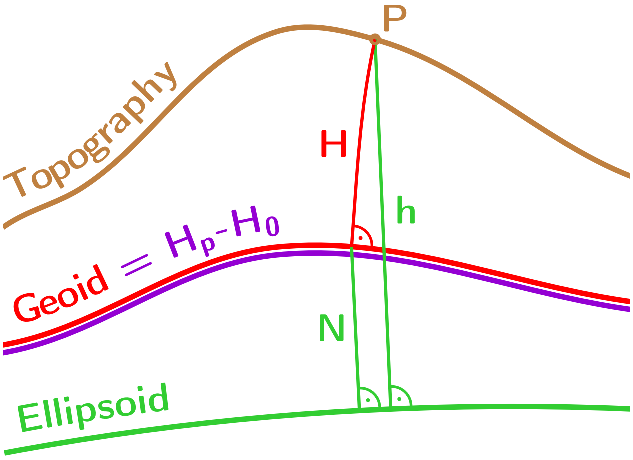
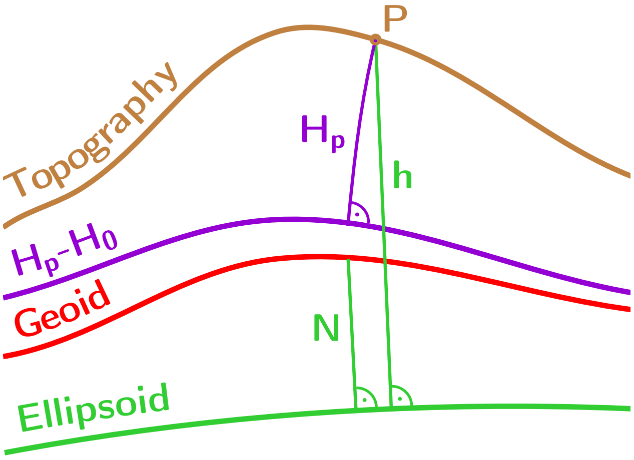
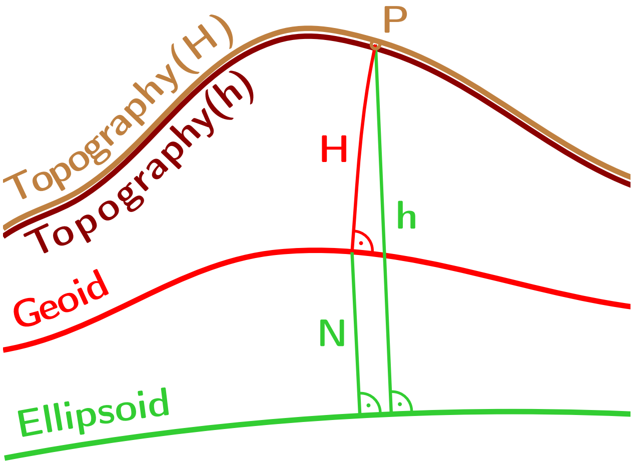
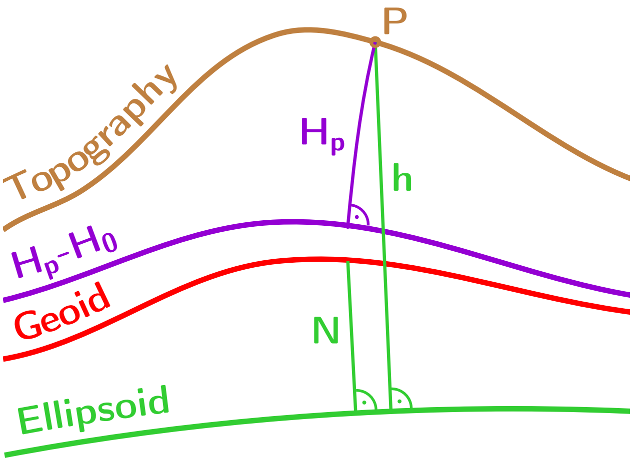
Requirement	**Present status**
Ellipsoidal heights *h* and (quasi-)geoid heights *N* must be given with respect to the same ellipsoid; i.e., the same ellipsoidal parameters have to be used • for the transformation of geocentric Cartesian coordinates into ellipsoidal coordinates, • as reference field 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* given in different tide systems; e.g, – the mean-tide system in oceanography, satellite altimetry, levelling, – the conventional tide-free system in ITRF positions, GRS80, some (quasi-)geoid models, – the 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.





constraints. The main constraint is that the gravitational potential V must vanish at infinity; i.e., $V_\infty = 0$. Consequently, this constraint is the primary convention for the realisation of the physical component of the IHRS. In this context, the potential values W_P may be obtained using a global gravity model of high degree (GGM-HD) or by estimating the anomalous potential T_P after solving the GBVP. The potential values are given by $W_\mathrm{P} = U_\mathrm{P} + T_\mathrm{P}$, where U is the potential of an appropriately selected reference ellipsoid.

The availability of GGM-HD, like the EGM2008 model (Pavlis et al. 2013, 2012) or the EIGEN-C series (e.g., Förste et al. 2015), makes it possible to carry out a direct computation of W_P by introducing the ITRF coordinates $\vec{X}$ of any point into the spherical harmonic expansion equation representing a GGM-HD. However, in areas with few terrestrial gravity data, the higher degrees of the GGM-HD do not contain the full signal of the Earth's gravity field and the so-called omission error increases strongly. According to Rummel et al. (n.d.), the expected accuracy after applying one of these models is $\pm 40\,\mathrm{cm}^2\mathrm{s}^{-2}$ to $\pm 60\,\mathrm{cm}^2\mathrm{s}^{-2}$ (equivalent to ±4 cm to ±6 cm) in well surveyed regions, and about $\pm 200\,\mathrm{cm}^2\mathrm{s}^{-2}$ to $\pm 400\,\mathrm{cm}^2\mathrm{s}^{-2}$ (±20 cm to ±40 cm) with extreme cases of $\pm 10\,\mathrm{m}^2\mathrm{s}^{-2}$ (±1 m) in sparsely surveyed regions. In addition, different GGM-HD deliver different potential values for the same position $\vec{X}$. This is probably a combined effect of including different gravity data of high-resolution (terrestrial, airborne and marine gravity data) and applying different standards, models and procedures in the estimation of the harmonic coefficients. As the realisation of the IHRS demands the best possible accuracy of the potential values (target is the sub-centimetre level $\approx \pm 10\,\mathrm{cm}^2\mathrm{s}^{-2}$), the direct application of GGM-HD for the IHRS realisation is still considered to be inappropriate.

Regarding the solution of the GBVP, there is a long list of different approaches depending on the observables available for the formulation of the GVBP (e.g., Heck and Seitz 1993): fixed GBVP (boundary surface known, 3D position of the observables available), scalar-free GBVP (boundary surface unknown, horizontal position of the observables available), or a vector-free GBVP (boundary surface unknown, position of the observables unavailable). As the existing gravity data banks mainly contain gravity anomalies with latitude and longitude values, the scalar-free GBVP is the most used formulation presently. Its solution is faced applying different methodologies, for instance, the Stokes integral or the Molodensky series with unmodified or modified kernel functions, least-squares collocation, radial basis functions, spectral modifications, etc. A common strategy in these different methodologies is a remove-compute-restore procedure (Schwarz et al. 1990; Tscherning 1986). It allows the combination of the long-wavelength component provided by a satellite-only GGM with gravity observables of high-resolution (terrestrial, airborne and marine gravity data, deflections of the vertical, terrain gravity effects, etc.).

A rigorous standardisation of the method to solve the GBVP seems to be not suitable because (1) it exists different data availability and different data quality around the world (e.g. terrestrial gravity data, terrain models, GPS/levelling, etc.), and (2) regions with different characteristics require particular approaches (e.g. modification of kernel functions and size of integration caps depending on the terrestrial gravity data availability, or geophysical reductions like glacial isostatic adjustment effects, which are very much larger in polar regions than in equatorial zones). One possibility to overcome this issue would be a centralised computation of the potential values W_P in a similar way as the IERS combination centres determine the ITRF. However, this option is still unviable due to the restricted accessibility to terrestrial gravity data. To exploit at maximum the existing data to get as accurate as possible potential values, national/regional experts in the gravity field (or geoid) modelling should be involved in the determination of the IHRS/IHRF coordinates. They have access not only to terrestrial gravity data but also to terrain models of high-resolution, GNSS/levelling data, etc. The idea is that they utilise all the data they have available to determine the potential values using the computation approaches they have implemented for their regions. However, to minimise discrepancies and to obtain as similar and compatible results as possible with the different methods, a basic set of standards should be set up.

To advance in this purpose, during the Joint Scientific Assembly of the International Association of Geodesy (IAG) and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) (Kobe, Japan, Aug 2017), it was agreed to initiate an empirical experiment (Sánchez 2019) towards:

- the computation of IHRF coordinates, geoid heights and height anomalies using exactly the same input data and the own methodologies (software) of colleagues involved in the gravity field modelling, and
- the comparison of the results, to highlight the differences caused by disparities in the computation methodologies and to identify a set of standards that allow to get as similar and compatible results as possible.

The input data for this experiment were provided by the US National Geodetic Survey (NGS) and contain terrestrial gravity data (59,303 points), airborne gravity data (41 lines in E-W direction and 7 lines in N-S direction), GNSS/levelling data (510 points) and a digital terrain model for an area of about 500 km x 800 km in Colorado, USA. The experiment is conducted under the cooperation of

- GGOS-JWG: Strategy for the Realisation of the IHRS (chair: L. Sánchez, Germany)
- IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y. M. Wang, USA)
- IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren, Sweden)
- ICCT JSG 0.15: Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy (chair: J. Huang, Canada)

The Colorado data were distributed in Feb. 2018, together with a document summarizing a minimum set of basic requirements (standards) for the computations (see section 4.6.6). Ten different groups delivered solutions and the results were discussed during the Gravity, Geoid and Height Systems (GGHS2018) Symposium (Copenhagen, Denmark, Sep 2018). Main conclusions are (Sánchez et al. 2018b; Wang et al. 2018):

- Two solutions were declared as outliers. They present large discrepancies (at the 1.5 m level) in (quasi-)geoid heights as well in the potential numbers with respect to the other solutions.
- In the geoid comparison, six solutions agree within 3 cm to 10 cm in terms of standard deviation with respect to the mean value.
- In the quasi-geoid comparison, the same six solutions agree within 1 cm to 4 cm in terms of standard deviation with respect to the mean value.
- In the comparison of the potential values, four solutions agree within 1 cm to 2 cm in terms of standard deviation with respect to the mean value.
- The discrepancies present a high correlation with the topography.

Possible sources of discrepancy are:

- Different handling of terrain corrections/reductions.
- Inconsistent use of the zero-degree term.
- Precision degradation due to the conversion of height anomalies to geoid heights and vice versa.
- Uncertainties in the processing of the airborne gravity data.

To refine the results, a second computation for the Colorado experiment was completed in Apr 2019. In total, 14 solutions were delivered. At present, the comparison of geoid heights, height anomalies and potential values is going on.

4.6.6 Preliminary standards for the IHRS realisation

This section summarises the basic agreements outlined for the computation of station potential values as IHRS coordinates, geoid undulations and height anomalies within the Colorado experiment.
They have been prepared by L. Sánchez (Deutsches Geodätisches Forschungsinstitut, Technical University Munich, Germany), J. Ågren (Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden), J. Huang (Natural Resources Canada, Canada), Y. M. Wang (NOAA's National Geodetic Survey, USA), and R. Forsberg (National Space Institute, Denmark), see (Sánchez et al. 2018a).

Basics

- The determination of station potential values W_P as IHRS coordinates is straightforward if the disturbing potential T_P is known: $W_\mathrm{P} = U_\mathrm{P} + T_\mathrm{P}$.
- The potential values realising the IHRS coordinates must be determined at the reference stations; i.e., at the Earth's surface and not at the geoid.
- According to the IHRS definition, the station coordinates have to be given in the mean-tide system. To be consistent with the GBVP definition, it is recommended to perform the computations in the zero-tide system and afterwards, to transfer the coordinates to the mean-tide system at the very end, using simplified formulas. This keeps the computations consistent with the gravity/geoid work in zero-tide without introducing many transformations and corrections.
- For these first experiments, we assume the Earth's gravity field to be stationary; i.e., time changes are disregarded so far.

Standards

General constants (numerical values needed for the solution of several equations):

- Constant of gravitation (G)
  $6.67428 \times 10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}}$
- Geocentric gravitational constant (GM)
  $3.986004415 \times 10^{14}\ \mathrm{m^3s^{-2}}$ (including the Mass of the Earth's Atmosphere)
- Nominal mean angular velocity of the Earth (ω)
  $7.292115 \times 10^{-5}\ \mathrm{rad\,s^{-1}}$
- Conventional reference potential value (W_0)
  $62\,636\,853.4\ \mathrm{m^2s^{-2}}$
- Average density of topographic masses (ρ)
  $2670\ \mathrm{kg\,m^{-3}}$. This topographic density shall be assumed when computing the geoid height.

Reference ellipsoid (to be used for the computation of gravity anomalies, disturbing potential, ellipsoidal coordinates, geoid heights, height anomalies, etc.):

- GRS80 parameters published by Moritz (2000). Previous publications contain some typos in the normal gravity formulae.
- Atmospheric reduction has to be applied on the (terrestrial and airborne) gravity data.

Global Gravity Model (GGM):

- Since the disturbing potential should be estimated with high-precision, it is proposed to compute (a) the long wavelength component (about d/o < 200...250) using a satellite-only GGM and (b) the short wavelength component (d/o > 200...250) by the combination of terrestrial (airborne, marine and land) gravity data and detailed terrain models.
- The GGM should be at least based on the combination of SLR (satellite laser ranging), GRACE and GOCE data, due to the improvement offered by these data to the long wavelengths of the Earth's gravity field modelling. Suggested models are the latest GOCO releases, i.e.,
  GOCO05s, d/o=280 (Mayer-Gürr and GOCO Team 2015);
  GOCO06s, d/o=300 (Kvas et al. 2019).
- Although, the use of a satellite-only GGM is preferred, the possibility of using a combined GGM is open (combined means including terrestrial gravity data). It is important that the satellite-only component of the combined model is based on the combination of SLR, GRACE and GOCE data.
- If required, the conversion between the zero-tide system and the tide-free system should be made using:

$$\bar{C}_{20}^{\mathrm{TF}} - \bar{C}_{20}^{\mathrm{ZT}} \;=\; 3.11080{\cdot}10^{-8} \times 0.3/\sqrt{5}$$

First-degree terms: The first-degree coefficients ($C_{10} = C_{11} = S_{11} = 0$) are assumed to be zero to align the Earth's centre of masses with the origin of the geometric coordinate system (ITRS/ITRF). In this way, the disturbing potential T is given by (cf. Eq. 2-170 Heiskanen and Moritz 1967):

$$\begin{aligned} T(\vartheta,\lambda) \;&=\; T_0 + T_1(\vartheta,\lambda) + \sum_{n=2}^{\infty} T_n(\vartheta,\lambda) \\ \text{with}\quad T_1(\vartheta,\lambda) \;&=\; 0 \end{aligned} \tag{4.3}$$

Zero-degree term: The zero-degree term should be dealt with as follows:

- For the disturbing potential (T): The zero-degree term T_0 has to include the difference between the GGM and reference ellipsoid's GM constants (cf. Eq. 2-172 Heiskanen and Moritz 1967):

$$\begin{aligned} T_0 \;&=\; \big(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}}\big)/r_\mathrm{P} \;= \\ &=\; \big(3.986004415 \times 10^{14}\,\mathrm{m^3s^{-2}} \\ &\qquad - 3.98600 \times 10^{14}\,\mathrm{m^3s^{-2}}\big)/r_\mathrm{P} \end{aligned} \tag{4.4}$$

  with r_P beeing the geocentric radial distance of the computation point P.

- For the quasi-geoid (ζ) or the geoid (N): In addition to the difference between the two *GM* values, the difference between the reference potential W_0 value adopted by the IHRS and the potential U_0 on the reference ellipsoid has to be considered (cf. the generalised Brun's formula in Eq. 2-178, and also Eq. 2-182 Heiskanen and Moritz 1967):

$$\zeta_0 = \frac{\left(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}}\right)}{r_{\mathrm{P}} \cdot \gamma_{\mathrm{Q}}} - \frac{\Delta W_0}{\gamma_{\mathrm{Q}}} \tag{4.5}$$

$$N_0 = \frac{\left(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}}\right)}{r_{\mathrm{P}_0} \cdot \gamma_{\mathrm{Q}_0}} - \frac{\Delta W_0}{\gamma_{\mathrm{Q}_0}} \tag{4.6}$$

with

$$\begin{aligned}\Delta W_0 &= W_0 - U_0 = \\ &= 62\,636\,853.4\,\mathrm{m}^2\mathrm{s}^{-2} - 62\,636\,860.850\,\mathrm{m}^2\mathrm{s}^{-2} \\ &= -7.45\,\mathrm{m}^2 s^{-2}\end{aligned}$$

Figure 4.1 shows the positions of P, Q, P_0 and Q_0.

As it was stated above that the geoid/quasi-geoid should be consistent with the IHRS reference level W_0 and that GRS80 is to be used as normal gravity field/ellipsoid, it is concluded:

1) To compute the quasi-geoid: compute starting with $n = 2$ and then add Eq. (4.5).
2) To compute the geoid: compute N starting with $n = 2$ and then add Eq. (4.6).

*Potential values W_{P} as IHRS/IHRF coordinates:*To determine the potential value W_{P} at the stations located on the Earth's surface, consistency with the approach used for the estimation of the disturbing potential should be ensured. If the quasi-geoid is computed, the disturbing potential is determined at the point P on the Earth's surface (see Fig. 4.1) and the estimation of W_{P} is straightforward:

$$W(\mathrm{P}) = U(\mathrm{P}) + T(\mathrm{P}) = U(\mathrm{P}) + \left(T_0 + \sum_{n=2}^{\infty} T_n(\mathrm{P})\right) \tag{4.7}$$

or

$$W(\mathrm{P}) = U(\mathrm{P}) + \gamma\zeta(\mathrm{P}) + \Delta W_0\,. \tag{4.8}$$

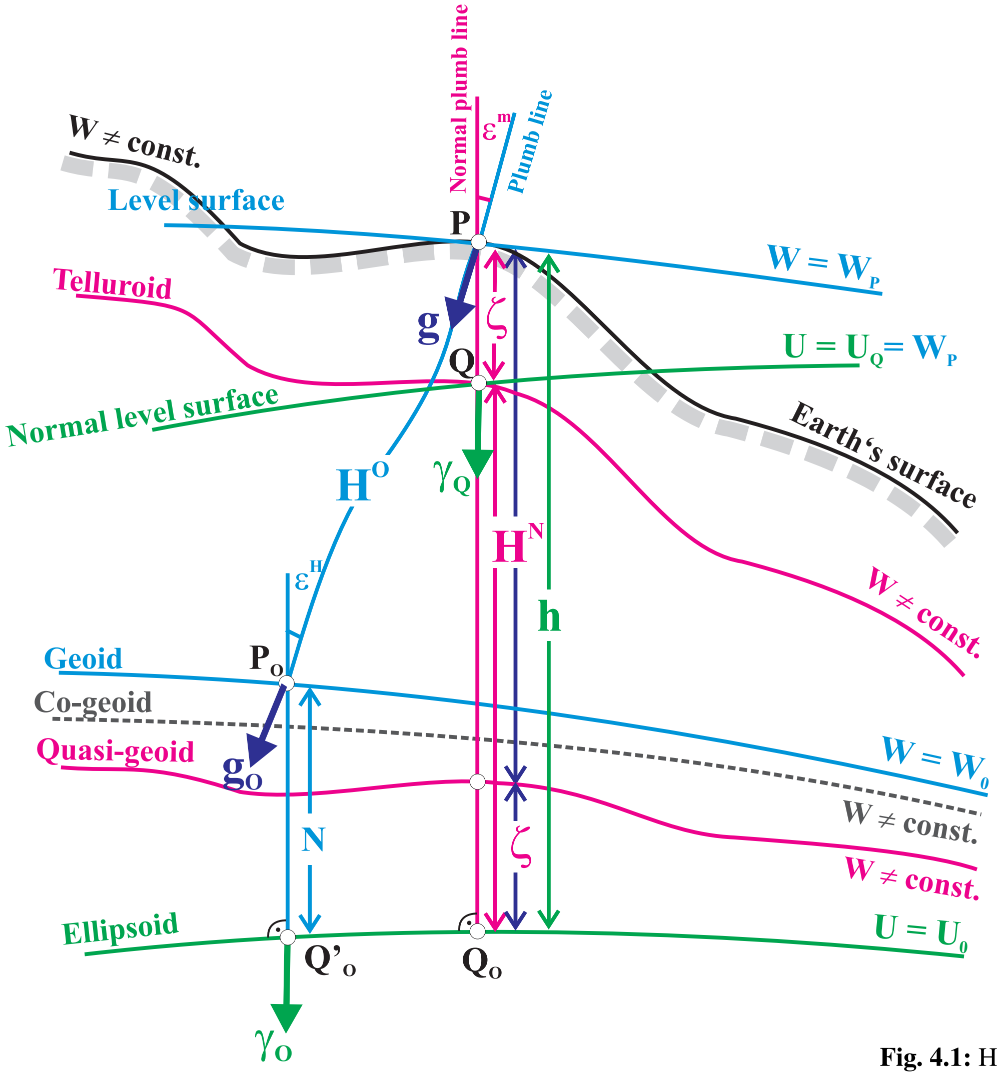


Fig. 4.1: Heights and reference surfaces

When the geoid is computed, the disturbing potential is determined at the point P_0 on the geoid (inside the Earth's topographic masses, see Fig. 4.1) and an upward continuation would be necessary to estimate W_P on the Earth's surface. This upward continuation must be consistent with the hypotheses applied to reduce the gravity values from the Earth's surface to the geoid. Therefore, it is strongly recommended to start from the quasi-geoid or disturbing potential at surface and then to infer the potential values W_P using Eq. (4.7) or (4.8). If the geoid computation is preferred, it would be necessary to transform N to ζ and then to infer the potential values W_P with (4.7) or (4.8). The transformation from N to ζ must be consistent with the hypotheses applied for the geoid computation. As this transformation produces a precision degradation, it is not desired for the computation of the potential values W_P.

As mentioned in Section 4.6.5, these standards will be refined in agreement with the results of the on-going Colorado experiment.

4.6.7 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 Unified Height System: to assess its requirements for the definition and realisation 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 modelling.

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 recognise 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 modelling (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.

4.6.8 Open problems and recommendations

A main result of the Colorado experiment should be a document similar to the IERS conventions; i.e., a sequence of chapters describing the different components to be considered for the realisation of the IHRS and its practical utilisation. Based on these conventions, a first solution for the IHRF should be computed. The aim of this first solution is to evaluate the achievable accuracy under the present conditions (data availability, computation methods, etc.) and to identify key actions to improve the determination of the IHRS/IHRF coordinates. These key actions include an investigation about the best way to establish an IHRS/IHRF element within the IGFS to ensure the maintenance and availability of the IHRF. This implies regular updates of the IHRFyy to take account for new stations, coordinate changes with time, improvements in the estimation of coordinates (more observations, better standards, better models, better computation algorithms, etc.), geodetic products associated to the IHRF (description and metadata), and the organisational and operational infrastructure to ensure the IHRF sustainability.

To improve the standardisation 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 modelling, 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 standardised 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 organisational 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 standardisation 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 modelling, the minimal requirements to be used for stations should be outlined.

Recommendation 6.4: The GGOS Focus Area Unified Height System, the IAG Commission 2 (Gravity Field) and the IGFS should investigate the best way to establish an IHRS/IHRF element within the IGFS to ensure the maintenance and availability of the IHRF and its products.

5 Summary

The GGOS Bureau of Products and Standards (BPS) has compiled an inventory of standards and conventions used for the generation of IAG products. The first version of this document has been published in the Geodesists Handbook 2016. During the last four years, the inventory has been updated to incorporate the changes and new developments concerning standards, conventions and the generation of IAG products. This second version of the document has been prepared for the publication in the Geodesists Handbook 2020.

According to its Terms of Reference, a key activity of the BPS is to assess the standards and conventions 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 work has been performed in cooperation with the IAG Services and the other entities involved in standards and conventions, such as IAU, ISO, CODATA and the UN-GGIM Subcommittee on Geodesy. The overall objective of this inventory is to evaluate the present status concerning standards and geodetic products, to identify gaps and shortcomings, and to provide recommendations for improvements. In this way, the BPS supports IAG in its goal to obtain geodetic products of highest accuracy and consistency.

This second version of the inventory includes an update of the GGOS structure and the BPS activities. It also comprises various updates in the field of standards and conventions, such as the newly released ISO standards by ISO/TC211 covering geographic information and geomatics, the activities of the GGRF Working Group "Data Sharing and Development of Geodetic Standards" within the UN-GGIM Subcommittee on Geodesy, the re-writing/revising of the IERS Conventions initiated by the IERS Conventions Centers, and the recently adopted resolutions by IAG, IUGG and IAU that are relevant for geodetic standards and products. An open problem is the current situation concerning numerical standards including time and tide systems. The fact that various definitions are in use within the geodetic community is a potential source for inconsistencies and even errors of geodetic products. The BPS recommends that these inconsistencies need be resolved and that a new Geodetic Reference System should be developed.

Since 2016, new IERS products have been released for the celestial and terrestrial reference frame as well as for the EOP, namely ICRF3, ITRF2014 and EOP 14C04. Although a significant progress has been achieved compared to the previous realisations, there are still some deficiencies and open problems that are addressed in this inventory, and recommendations are provided to further improve the accuracy and consistency of these products. Concerning GNSS satellite orbits the modelling has been improved and some missing information has been provided by the satellite operators, but there are still some remaining deficiencies. A remarkable progress has been achieved in the field of gravity and geoid related data and products, including the establishment of the IGFS Central Bureau and the development of a dedicated data and products portal based on online applications for the creation of metadata for gravity and geoid data. Finally, the latest developments in the field of height systems and their realisations are reported, open problems are discussed and recommendations towards the realisation of the IHRS are provided.

This inventory will be updated on a regular basis to incorporate the latest developments regarding standards and geodetic products. Thereby, also the ongoing activities of IAG towards the development of new products need to be incorporated in the updates of this inventory.

Glossary

AAM	Atmospheric Angular Momentum.
AC	Analysis Centre.
ACC	Analysis Centre Coordinator.
AGN	Active Galactic Nuclei.

BCRS	Barycentric Celestial Reference System.
BGI	Bureau Gravimétrique International.
BIH	Bureau International de l'Heure.
BIPM	Bureau International de Poids et Mesures.
BPS	GGOS Bureau of Products and Standards.
BSC	GGOS Bureau for Standards and Conventions.
BTM	Bathymetric Terrain Model.

CAO	Cabinet Office, Government of Japan.
CBE	Current Best Estimates.
CEOS	Committee of Earth Observation Satellites.
CIP	Celestial Intermediate Pole.
CIRS	Celestial Intermediate Reference System.
CM	Centre of Mass.
CODATA	Committee on Data for Science and Technology.
CODE	Center for Orbit Determination in Europe.
COST-G	International Combination Service for Time-variable Gravity Fields.
CPO	Celestial Pole Offset.
CSNO	China Satellite Navigation Office.
CTRS	Conventional Terrestrial Reference System.

DEM	Digital Elevation Model.
DGFI-TUM	Deutsches Geodätisches Forschungsinstitut, Technische Universität München.
DLR	Deutsches Zentrum für Luft- und Raumfahrt.
DOI	Digital Object Identifier.
DORIS	Doppler Orbit Determination and Radiopositioning Integrated by Satellite.

ECMWF	European Centre for Medium-Range Weather Forecasts.
ECOM	Empirical CODE Orbit Model.
EGM 2008	Earth Gravitation Model 2008.
EGV	Essential Geodetic Variables.
EOP	Earth Orientation Parameters.
EOSDIS	NASA's Earth Observing System Data and Information System.
EPN	EUREF Permanent GNSS Network.
EPOS	European Plate Observing System.
ERP	Earth Rotation Parameters.
ESA	European Space Agency.
EUREF	IAG Reference Frame Sub-Commission for Europe.

FCN	Free Core Nutation.
FGS	Forschungsgruppe Satellitengeodäsie.
FICN	Free Inner Core Nutation.
FK5	Fifth Catalogue of Fundamental Stars.
FOC	Full Operational Capability.

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.
GIAC	GGOS Inter Agency Committee.
GIS	Geographic Information System.
GLONASS	Globalnaja nawigazionnaja sputnikowaja sistema.
GMF	Global Mapping Function.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System.
GPT	Global Pressure and Temperature.
GPT2	Global Pressure and Temperature 2.
GRACE	Gravity Recovery And Climate Experiment.
GRACE-FO	Gravity Recovery And Climate Experiment – Follow On.
GRS	Geodetic Reference System.
GRS80	Geodetic Reference System 1980.
GSFC	Goddard Space Flight Center.
GSPM	GPS Solar Pressure Model.

IAG	International Association of Geodesy.
IAGBN	International Absolute Gravity Basestation Network.
IAPG	Ingenieurinstitut für Astronomische und Physikalische Geodäsie, Technische Universität München.
IAU	International Astronomical Union.
ICGEM	International Centre for Global Earth Models.
ICRF	International Celestial Reference Frame.
ICRF2	Second Realization of the International Celestial Reference Frame.
ICRS	International Celestial Reference System.
IDEMS	International Digital Elevation Model Service.
IDS	International DORIS Service.
IERS	International Earth Rotation and Reference Systems Service.
IGETS	International Geodynamics and Earth Tide Service.
IGFS	International Gravity Field Service.
IGFS CB	IGFS Central Bureau.

IGN	Institut National de l'Information Géographique et Forestiere, France.
IGS	International GNSS Service.
IGSN71	International Gravity Standardization Net 1971.
IGSO	Inclined Geo-Synchronous Earth Orbit.
IHRF	International Height Reference Frame.
IHRS	International Height Reference System.
ILRS	International Laser Ranging Service.
IOV	In-Orbit Validation.
IRNSS	Indian Regional Navigation Satellite System.
ISC	International Science Council.
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.
LEO	Low Earth Orbiter.
LLR	Lunar Laser Ranging.
LOD	Length of Day.
MEO	Medium Earth Orbit.
MGEX	Multi-GNSS Pilot Project.
MGWG	Multi-GNSS Working Group.
NAGU	Notice Advisory to Galileo Users.
NAGU	Notice Advisory to GLONASS Users.
NANU	Notice Advisory to NAVSTAR Users.
NAQU	Notice Advisory to QZSS Users.
NAREF	North American Reference Frame.
NASA	National Aeronautics and Space Administration.
NAVGEM	US Navy's Global Environmental Model.
NCEP	National Centers for Environment Prediction.
NGS	National Geodetic Survey.
NIST	National Institute of Standards and Technology.
NNR	No-Net-Rotation.
NSFA	IAU Division A Working Group Numerical Standards for Fundamental Astronomy.
OAM	Oceanic Angular Momentum.
OGC	Open Geospatial Consortium.
OHI	Operational History Information.
OMCT	Ocean Model for Circulation and Tides.
PCO	Phase Centre Offset.
PCV	Phase Centre Variation.
PREM	Preliminary Reference Earth Model.
PSMSL	Permanent Service for Mean Sea Level.
QZSS	Quasi-Zenith Satellite System.
SBAS	Space Based Augmentation System.
SCoG	Subcommittee on Geodesy (UN-GGIM).
SI	International System of Units.
SINEX	Solution INdependent EXchange format.
SIRGAS	Sistema de Referencia Geocéntrico para las Américas (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.
TIRS	Terrestrial Intermediate Reference System.
TRF	Terrestrial Reference Frame.
TRS	Terrestrial Reference System.
TT	Terrestrial Time.
UN	United Nations.
UN-GGIM	UN Committee of Experts on Global Geospatial Information Management.
USNO	United States Naval Observatory.
UTC	Coordinated Universal Time.
VLBI	Very Long Baseline Interferometry.
WGM	World Gravity Map.
WGRF	IAU Working Group on Reference Frames.
ZTD	Zenith Total Delay.

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