IAG Strategy 2019

Content:

1. Introduction

The IAG Strategy 2019 is based on the IAG Guiding Document 2016, summarizing the IAG Retreat 2016 in Potsdam, Germany, April 25-26, 2016. Members of the IAG Executive Committee performed the review with Gerhard Beutler (past IAG president) as moderator. Key elements for the IAG strategy for the next 10-15 years were identified.

The 2016 Retreat started with a 2-hour introduction on Monday, April 25 to be continued with a one-day review and workshop on Tuesday, April 26. A *Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis* of about half a day stood in the centre of the retreat. This analysis was performed in two groups with nine members per group. Both groups were given the same task, namely to perform a SWOT analysis for IAG. The outcome was *discussed* and *harmonized* by all retreat participants. The findings of the retreat were summarized in the IAG guiding document 2016 (Beutler, 2016).

A first draft of the IAG structure document was written by Beutler in March 2017; the IAG Executive Committee reviewed this draft on the occasion of its meeting on April 28, 2017, in Vienna. The comments by the IAG Executive Committee members were taken into account, to the extent possible, for the next version of this document, which was discussed at the IAG Scientific Assembly in Kobe, in July/August 2017.

Based on the comments received in Kobe, the document was reviewed once more, also with respect to a proposal of the Chinese National Committee suggesting (1) to establish regional IAG sub-organizations, (2) to set up a new IAG commission on Marine Geodesy, and (3) to establish a GGOS working group of geodetic nomenclature. The IAG Executive Committee (EC) discussed this at its meeting in Vienna, April 2018. The final version shall be presented for approval to the IAG Council at the IAG General Assembly 2019 in Montreal, Canada.

2. IAG development and embedding

Table 1 (Drewes, 2012) lists the development of the IAG structure after the World War II. Starting with the General Assembly in Oslo 1948, Tab. 1 lists the names of the Sections, re-named as *Commissions* at the General Assembly in 2003 Sapporo, when in essence IAG's current structure was put in place: five sections were mapped onto four Commissions and the Inter-Commission Committee on Theory (ICCT), meant to stimulate theoretical developments in the commissions. The ICCT was put on the same level as the four commissions including executive committee representation at the general assembly in Prague 2015. At the general assembly in Perugia in 2007 the Global Geodetic Observing System (GGOS), IAG's observing system encompassing in essence the geometry- and gravity-related IAG services, was put on the same level as the four Commissions, with executive committee representation.

General Assembly	I	II	III	IV	V
1948 Oslo	Triangulation	Levelling	Geodetic Astronomy	Gravimetry	Geoid
1951 Brussels	Triangulation	Levelling	Geodetic Astronomy	Gravimetry	Geoid
1954 Rome	Triangulation	Levelling	Geodetic Astronomy	Gravimetry	Geoid
1957 Toronto	Triangulation	Levelling	Geodetic Astronomy	Gravimetry	Geoid
1960 Helsinki	Triangulation	Levelling	Geodetic Astronomy	Gravimetry	Geoid
1963 Berkeley	Geodetic Positioning	Levelling and Crustal Motion	Geod. Astronomy & Artif. Satellites	Gravimetry	Physical Geodesy
1967 Lucerne	Geodetic Positioning	Levelling and Crustal Motion	Geod. Astronomy & Artif. Satellites	Gravimetry	Physical Geodesy
1971 Moscow	Control Surveys	Space Techniques	Gravimetry	Theory and Evaluation	Physical Interpretation
1975 Grenoble	Control Surveys	Space Techniques	Gravimetry	Theory and Evaluation	Physical Interpretation
1979 Canberra	Control Surveys	Space Techniques	Gravimetry	Theory and Evaluation	Physical Interpretation
1983 Hamburg	Positioning	Advanced Space Technology	Determination of the Gravity Field	General Theory & Methodology	Geodynamics
1987 Vancouver	Positioning	Advanced Space Technology	Determination of the Gravity Field	General Theory & Methodology	Geodynamics
1991 Vienna	Positioning	Advanced Space Technology	Determination of the Gravity Field	General Theory & Methodology	Geodynamics
1995 Boulder	Positioning	Advanced Space Technology	Determination of the Gravity Field	General Theory & Methodology	Geodynamics
1999 Birmingham	Positioning	Advanced Space Technology	Determination of the Gravity Field	General Theory & Methodology	Geodynamics
2003 Sapporo	Reference Frames	Gravity Field	Earth Rotation and Geodynamics	Positioning and Applications	Inter-Commission Cm’tee on Theory
2007 Perugia	Reference Frames	Gravity Field	Earth Rotation and Geodynamics	Positioning and Applications	Inter-Commission Cm’tee on Theory
2011 Melbourne	Reference Frames	Gravity Field	Earth Rotation and Geodynamics	Positioning and Applications	Inter-Commission Cm’tee on Theory
2015 Prague	Reference Frames	Gravity Field	Earth Rotation and Geodynamics	Positioning and Applications	Inter-Commission Cm’tee on Theory

Table 1: *Development of the internal IAG structure (Drewes, 2012, updated 2015)*

Figure 1 (Drewes, 2012), shows in the upper part the parent organizations of IAG, which is one of eight associations of IUGG, established in 1919. IUGG recently issued a strategic plan (IUGG, 2017), which was consulted when writing this document. There are many points of contact between IAG and IUGG. GGOS is, e.g., listed as a current program in the IUGG strategic plan. Also, the newly established IUGG Union Commission on Planetary Sciences (UCPS) (http://www.iugg.org/about/commissions/ucps.php) is of vital interest to IAG. It was initiated and is chaired in the period 2015-2019 by an IAG officer. IUGG is in turn member of ICSU. The ICSU platform *Future Earth* is of potential interest to IAG, as well. ICSU was merged in 2018 with the International Social Science Council (ISSC) to the International Science Council (ISC, https://council.science/).

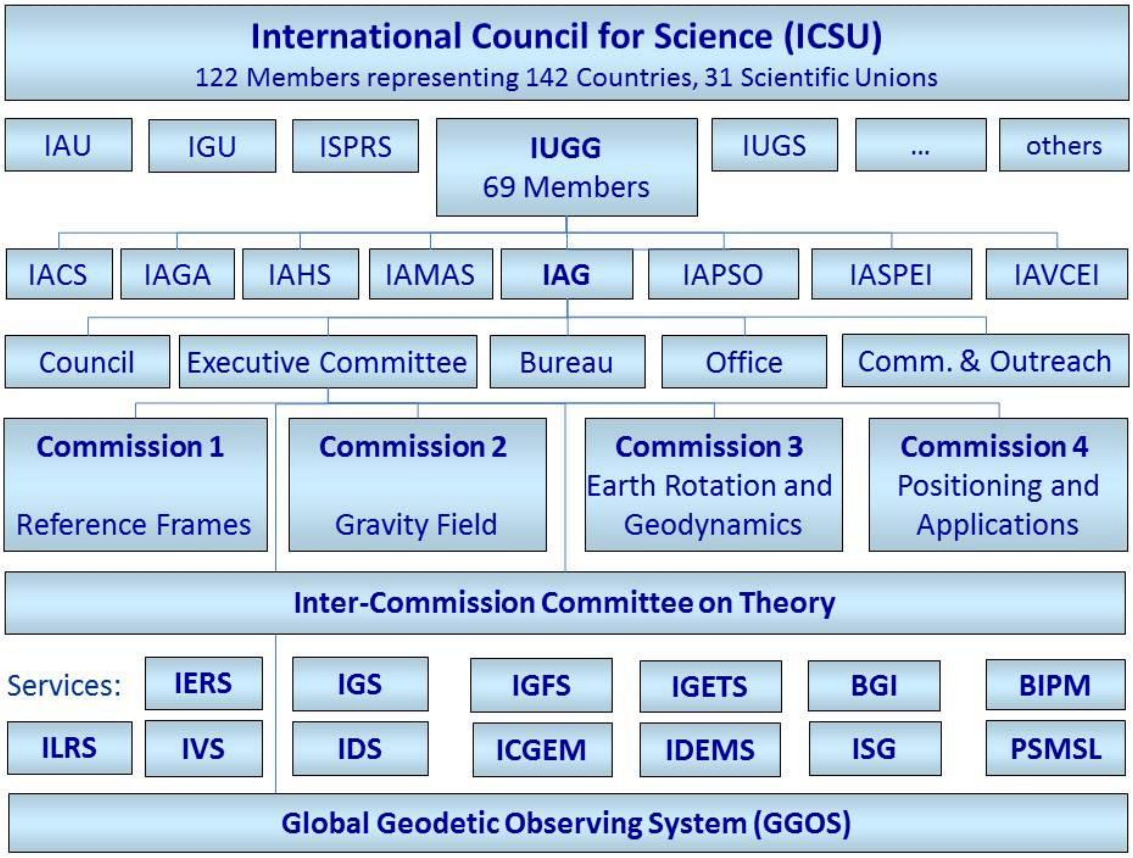

Figure 1: *IAG, current structure, and parent organizations IUGG and ICSU (Drewes, 2012, updated 2015)*

3. Elements of the current IAG Structure

The current structure and mission of the Association, including the creation of GGOS were initially discussed at the IAG Section II Symposium in Munich in 1998, further developed in a review process in the IAG period 1999-2003, and applied for the first time in the period 2003-2007 (Beutler, 2004).

The lower part of Figure 1 shows the complete structure of today's IAG and indicates how its entities should interact: Commission 1 deals with the geometry-related part of geodesy, Commission 2 with the gravity-related part, Commission 3 with the motion of the Earth as a finite and deformable body, including the Earth's atmosphere and oceans, and Commission 4 with special applications of geodesy. The ICCT is meant to stimulate the work in the four commissions using theory (mathematics) as the common tool.

Table 2 shows how the IAG services originally developed in IAG. The last three lines of Figure 1 list the thirteen IAG services, which are today under the umbrella of GGOS, representing IAG's observing system. Ten of the thirteen services were created recently, the IERS in 1987 replacing the IPMS (the IERS is a service of IUGG and IAU, but IUGG transferred responsibility to IAG), the IGeS in 1991 (now ISG), the IGS in 1994, the ILRS in 1998, the IVS and the IDEMS in 1999, the ICGEM and the IDS in 2003, the IGFS in 2004. The IGS was the prototype for the space-technique-specific services ILRS, IVS, and IDS.

No	Acronym	Name of the IAG Service (and Address of the Homepage)		Year of Formation
1	**BGI**	Bureau Gravimetrique International / *http://bgi.omp.obs-mip.fr*		1951
2	**BIPM**	Bureau International des Poids et Mesures – Time Department / *http://www.bipm.org*		1875
3	**ICGEM**	International Centre for Global Earth Models / *http://icgem.gfz-potsdam.de/ICGEM*		2003
4	**IDEMS**	International Digital Elevation Models Service / http://*TBD*		1999
5	**IDS**	International DORIS Service / *http://ids.cls.fr*		2003
6	**IERS**	International Earth Rotation and Reference Systems Service / *http://www.iers.org*		1987
7	**IGETS**	International Geodynamics and Earth Tide Service / *http://igets.u-strasbg.fr/*		2015
8	**IGFS**	International Gravity Field Service / *http://www.igfs.net*		2004
9	**IGS**	International GNSS Service / *http://igscb.jpl.nasa.gov*		1994
10	**ILRS**	International Laser Ranging Service / *http://ilrs.gsfc.nasa.gov*		1998
11	**ISG**	International Service for the Geoid / *http://www.iges.polimi.it*		1991
12	**IVS**	International VLBI Service for Geodesy and Astrometry / *http://ivscc.gsfc.nasa.gov*		1999
13	**PSMSL**	Permanent Service for Mean Sea Level / *http://www.psmsl.org/*		1933
		Historical IAG Services		
	BIH	Bureau International de l'Heure	(1987 integrated into IERS)	1912
	ICET	International Center for Earth Tides	(2015 integrated into IGETS)	1956
	ILS	International Latitude Service	(1962 International Polar Motion Service, IPMS)	1899
	IPMS	International Polar Motion Service	(Successor of ILS, 1987 integrated into IERS)	1962

Table 2: *Development of IAG Services (from The Geodesist's Handbook 2016)*

Today the BGI, the ICGEM, the ISG, the IGETS, and the IDEMS are part of the IGFS, the gravity-related umbrella service of IAG created in 2004. Figure 1a illustrates the internal structure of the IGFS.

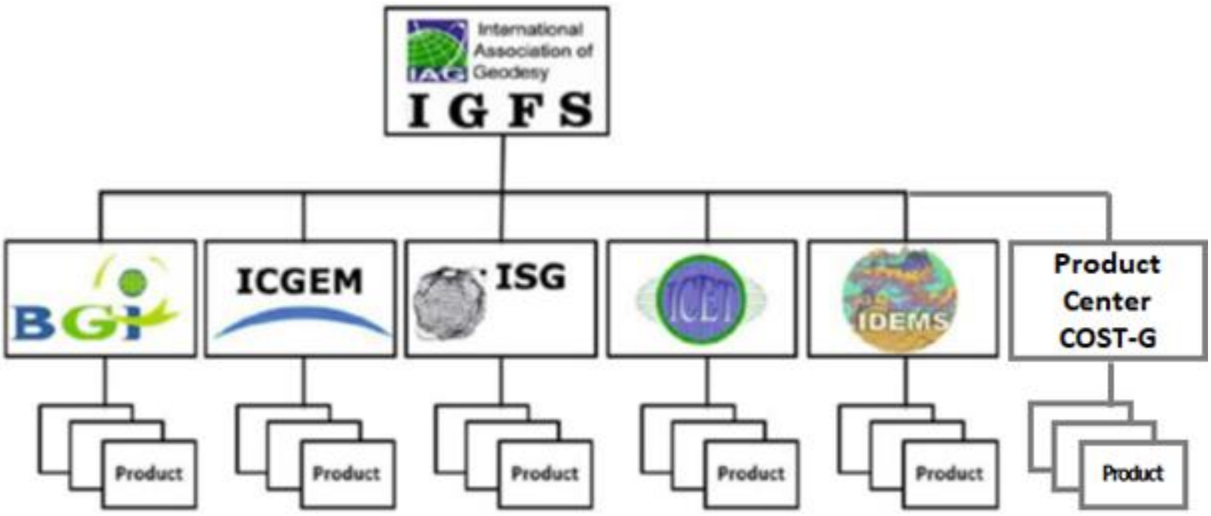

Figure 1a: *Internal Structure of the IGFS*

Figure 1b illustrates the GGOS structure. On the working level it consists of the Bureau of Networks & Observations (Director Mike Pearlman), the Bureau of Products and Standards (Director Detlef Angermann), and the four Focus Areas Unified Height System (Chair Laura Sánchez), Geohazards Monitoring (Chair John Labrecque), Sea Level Change (Chair Tilo Schöne), Geodetic Space Weather Research (Chair Michael Schmidt).

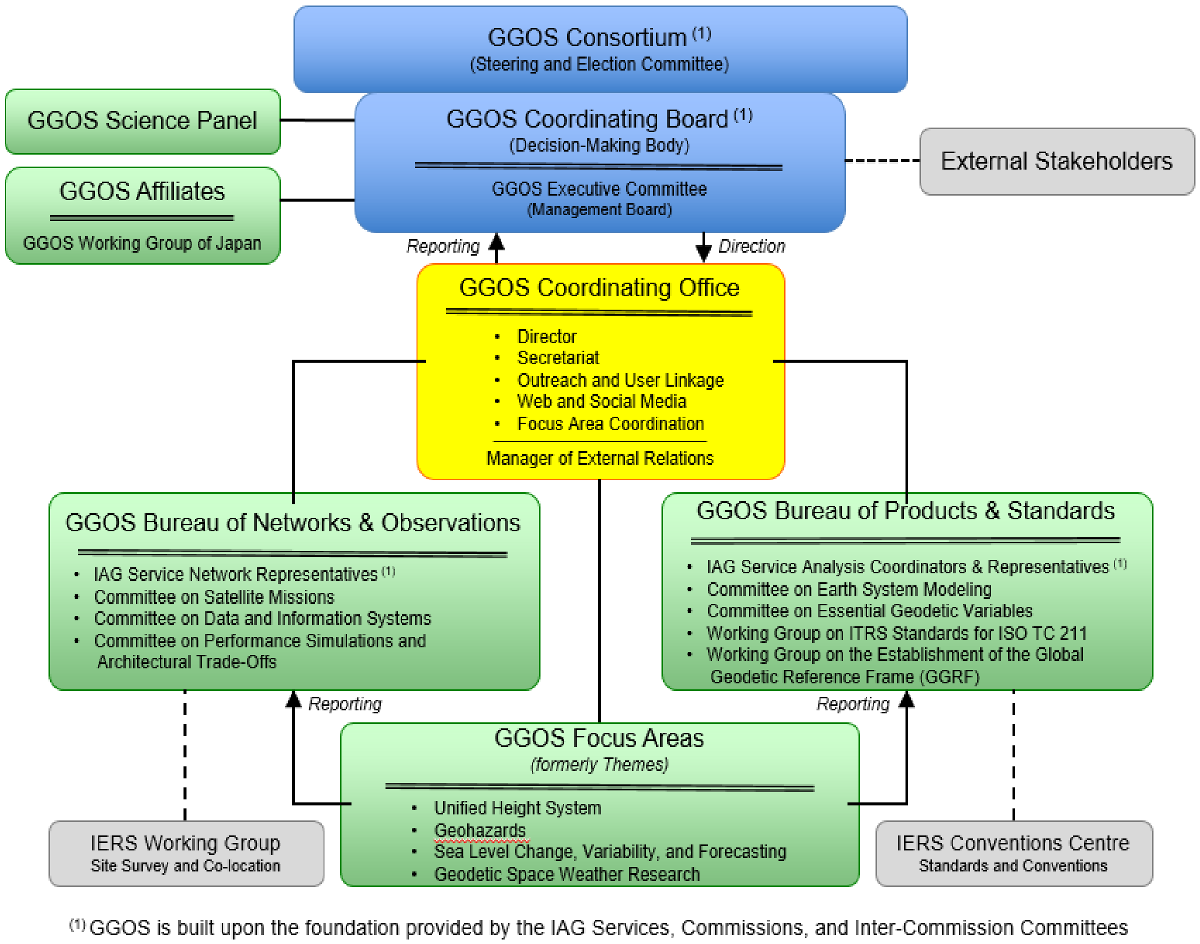

Figure 1b: *GGOS organizational chart*

The 2016 statutes (Drewes et al., 2016) summarize the key elements of the Association:

- *IAG mission*: The Mission of the Association is the advancement of geodesy. The IAG implements its mission by furthering geodetic theory through research and teaching, by collecting, analyzing, modelling and interpreting observational data, by stimulating technological development and by providing a consistent representation of the figure, rotation, and gravity field of the Earth and planets, and their temporal variations.
- *IAG structure*: The Association's structure comprises a small number of components: Commissions, the Inter-Commission Committee on Theory (ICCT), Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).
- According to http://www.ggos.org/ the key elements of GGOS are: *GGOS* is the Observing System of the IAG. GGOS works with the IAG components to provide the geodetic infrastructure necessary for monitoring the Earth system and for global change research. It provides observations of the three fundamental geodetic observables and their variations, that is, the Earth's shape, the Earth's gravity field, and the Earth's rotational motion.

Figure 1b shows the current GGOS organizational chart). For more information related to GGOS consult (Beutler and Rummel, 2011) and (Plag and Pearlman, 2009).

4. Key findings of the 2016 IAG Retreat

Strengths of IAG: IAG comprises the *top experts* in the field of geodesy and offers an open, friendly, and supportive environment. IAG is based on contributions, which are funded by national and institutional resources. *The services make the Association strong among the IUGG and other scientific associations.* IAG is *truly international* thanks to the about 70 member countries. IAG Commissions and the ICCT are ideal to work on new methodologies by involving the best experts in the respective fields. IAG offers well-established schools and, through its services, products relevant to science *and* society. IAG is interdisciplinary and contributes, e.g., to weather forecast, global change, natural hazards, and sea level rise.

Weaknesses of IAG: IAG has a low *visibility* to policy-makers, geo-sciences, educational institutions, and the general public. *Research areas of vital interest*, e.g., SAR and altimetry, are *not sufficiently covered* in IAG. IAG cannot always enforce its declared goal, *free access to original data*, because in general the Association does not own the data. Many IAG activities are based on *voluntary contributions*, which may occasionally endanger some of its components.

GGOS, more than ten years after its creation, is not yet working as originally intended. Insufficient communication among IAG components and overlap of commission work with GGOS were mentioned as part of the problem. The relation between IAG and GGOS should be clarified, and the overlaps minimized.

Opportunities of/for IAG: IAG is pivotal to achieve *quantitative results* in many areas relevant to society, e.g., related to global change, sea level change, exploration of variations of the global water cycle. Governments and space missions depend *on* geodetic products like reference frames and gravity field models. Projects with the focus on water in all its phases (water, ice, water vapour) – are of societal relevance, in particular water resources, sea level change, ice sheet melting, and atmospheric monitoring.

The *UN GGRF* initiative is a great platform to publicize geodesy to a broad public, and to involve developing countries in geodesy. GGRF has the potential to improve/optimize the global geodetic infrastructure.

ICSU initiatives, e.g., *Future Earth* and the project *Research Data Alliance* have a great potential for the future, as well. The IAG relations to these initiatives should be strengthened. The cooperation with other IUGG associations should be strengthened.

Promising *technological and/or scientific developments*, e.g., optical clocks, quantum technologies, are relevant for geodesy and should be developed by IAG together with fundamental physics institutes.

Threats to IAG: The UN initiative GGRF might also become a threat to IAG because a new governance structure outside IAG might emerge. IAG needs in any case its place in a future governmental structure with UN participation, which might result in a *Geodetic Commission* under UN auspices.

IAG is not attractive enough to early-career scientists, to engineers, and other members of the community. Maintaining and developing the global infrastructure for IAG-type research is a problem, because IAG can only try to convince national institutions and space agencies to provide support to the geodetic infrastructure.

The IAG structure was found to be weak by some retreat participants.

Additional important aspects came up in the discussions following the SWOT analysis:

Balance of representation in the IAG EC: the IAG *Executive Committee should have the broadest possible representation*, country-wise and geographically; an over-representation of particular countries and regions should be avoided, an issue which can only be influenced by the nomination committee. The election process should, however, not be burdened by too many optimization criteria.

GGOS2020: The reference (Plag and Pearlman, 2009) was published in 2009 and offers a comprehensive overview of geodesy's contribution to science and society around 2010. According to its preface the book wishes to serve two purposes: (1) to inform users of Earth observations (in particular, GEO https://www.earthobservations.org/index.php) of the potential of GGOS, and (2) to ensure that the GGOS community is aware of the users' needs and requirements so as to integrate GGOS into GEOSS for maximum mutual benefit. A successor of the document is required and must be developed in parallel to the IAG strategic plan.

Planetary geodesy: With the successful NASA mission GRAIL, plus recent, current, and future planetary missions with geodetic elements, *planetary geodesy will be an important future research issue*. IAG should work with the IUGG UCPS, which was established in 2015.

IAG and Commercial companies: IAG traditionally maintains good relationships with instrument manufacturers, e.g., the producers of GNSS receivers. However, many *commercial companies* like, e.g., Google, *use IAG products without acknowledging*, or contributing to, IAG. In this context it should be emphasized that products generated by GGOS or its components are also IAG products.

Activities on IUGG or ICSU level: ICSU describes *Future Earth* as follows: Future Earth is a global platform for international scientific collaboration, providing the knowledge required for societies in the world to face risks posed by global environmental change and to seize opportunities in a transition to global sustainability (http://www.futureearth.org). Large projects like IGBP, WCRP, ESSP, shall work under this umbrella in future. IAG must contribute to such activities.

IAG and other national or international organizations: Projects like the EU-funded project *COST-G*, and current space missions such as *GRACE-FO* with heavy involvement of institutions represented in IAG, are of interest to other IUGG associations. COST-G is working under the much larger EU program Copernicus, which has elements of potential interest to IAG. *New inter-association activities* should be considered in the fields of seismo-geodesy, gravity/magnetic interpretation, mass transport, satellite altimetry, meteorology, volcanology, ionosphere/space weather, Tsunami Early Warning, and climate modelling / research. IGS products and Earth monitoring are of interest to the International Committee on Global Navigation Satellite Systems (ICG of the UN), a link which should be strengthened.

5. Geodetic challenges of the next decade

The new IAG structure, with its *Commission- and service-related parts*, has to cope with the challenges of the next decade. These challenges emerge from the developments in the previous 25 years: today's space-geodetic techniques replaced optical astrometry for the definition of the terrestrial and celestial reference frames and for the determination of the transformation between the two frames. The same statement holds for time and frequency transfer, where the progress was even more obvious.

Modern space-geodetic techniques have reached maturity and a high organizational level: SLR is coordinated by the ILRS, VLBI by the IVS, the use of GNSS for high-accuracy geodetic and geophysical applications, in particular for science, by the IGS, and the use of DORIS for geodetic purpose by the IDS.

Figure 2 shows the global tracking networks of the four geometry-related IAG services, which are the basis for the realization and maintenance of the ITRF by the IERS. With more than 500 sites, the IGS network in Figure 2 (top, left) is by far the one with most sites. In addition, the global network is densified by regional networks (Africa, Antarctica, Asia-Pacific, Europe, North America, South and Central America) with more than 1000 sites, which are coordinated by the IGS Regional Network Associate Analysis Centres. The IGS network tracks today four GNSS, namely the United States' GPS with 30-32 satellites (since the first IGS test campaign in 1992), the Russian GLONASS with 24 satellites (first attempts towards the end of the 20th century), the Chinese BeiDou with currently 18 satellites (13 of which are geostationary or geosynchronous, optimizing the regional use), and the European Galileo with currently 12 satellites. In addition there are two regional systems, the Japanese QZSS with currently one and the Indian IRNSS with 7 geostationary or geosynchronous satellites. The regular IGS products are based on GPS and GLONASS, with currently 56 satellites. More than 80 satellites are routinely tracked and analysed by the IGS in its MGEX program. The IGS collocates the sites of the other space-geodetic networks by routinely analysing GNSS data on the sites of the other networks in Figure 2.

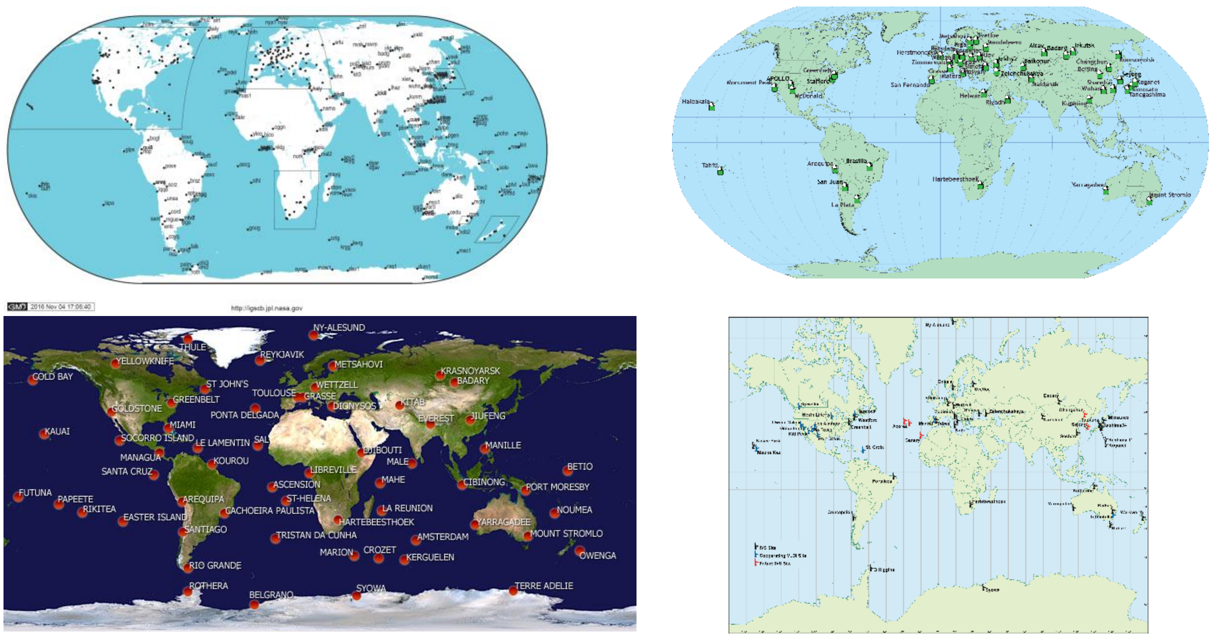

Figure 2: *Global tracking networks of IGS (top, left) and IDS (bottom, left), and of ILRS (top, right) and IVS (bottom, right)*

Figure 2 (top, right) shows the permanent ILRS tracking network consisting of over forty stations in 23 countries. A few stations are also capable of LLR tracking. The ILRS is indispensable for gravity field determination, in particular for determining the low degree and order terms, including the geocentre. SLR is the only independent tool for calibrating GNSS-derived orbit models. The ILRS network tracks an agreed-upon selection of GNSS satellites, providing independent calibrations of the IGS-derived GNSS orbits. This latter task may be performed, because the signal delays of the optical SLR signals caused by the Earth's atmosphere can "easily'' be taken care of, on the mm-level, by using in situ meteorological measurements at the SLR sites.

Figure 2 (bottom, left) shows the IDS network based on the French DORIS: each site is transmitting signals (beacons), which are received by LEOs equipped with DORIS receiving equipment. Since 1994, and thanks to its more than fifty permanent beacon network, DORIS contributes to the IERS activities for the realization and maintenance of the ITRF. According to the IDS, six satellites are currently equipped with DORIS receiving equipment. The IDS operates probably the most uniform of all global space-geodetic tracking networks.

Figure 2 (bottom, right) shows the IVS network of more than thirty sites equipped with radio telescope(s) tracking Quasars. The IVS coordinates the only space-geodetic technique, which is not based on Earth orbiting satellites. The IVS observes Quasars in the microwave band using interferometric methods. Because the same object has been observed simultaneously by at least two sites, scheduling of the observations is much more demanding than for the other space techniques. As the Quasars are extremely far away and do not show any significant proper motion on the celestial sphere, VLBI is the only modern space technique capable of defining the celestial reference frame on the (sub-)μas (microarcsecond) level and of determining the absolute motion of the Earth's rotation axis in space, in particular to determine UT1-UTC, precession and nutation which is an essential external input to all satellite techniques.

Figure 3 illustrates typical (not all) products emerging from the four geometry-related services IDS, IGS, ILRS, and IVS, and from the combination of the technique-specific results. All four services generate the coordinates and velocities of their tracking networks, polar motion time series and LoD with daily resolution, which are combined by the IERS.

Figure 3 (top, left), from Drewes (2012), shows the velocities of the Earth's geophysical plates, as emerging from geophysical models (PB2002) and from the ITRF (APKIM2008D, version 2008 in this case). It is thus based on the positions and velocities of the four geometry-related services.

Figure 3 (top, right) shows the global distribution of the mean electron density in the Earth's upper atmosphere, reconstructed from one hour of dual-frequency observations to all GPS- and GLONASS-satellites made by about 250 tracking sites the IGS network. The figure implies that microwave observations of celestial objects *also* contain information about the Earth's atmosphere. The figure illustrates only one of the atmosphere-related IGS products: the GNSS signals may also be used to extract the water vapour content in the troposphere, either by making use of (comparably) dense arrays of GNSS receivers, or by the so-called atmosphere limb-sounding technique based on front- or aft-looking spaceborne GNSS receivers on LEOs. The atmosphere-related activities are a logical continuation of refraction studies based on optical (astrometric) observations, e.g., made at Pulkovo in the 19^{th} century. The troposphere products are also used for weather prediction.

Figures 3 (bottom) illustrate time series of the two ERP types, which are accessible to all modern space geodetic techniques, namely polar motion in Figure 3 (bottom, left), LoD in Figure 3 (bottom, right). The lampion-like pattern of polar motion is caused by the beat signal with a period of about 6.2 years of the annual (365.25 days) and the Chandler periods (435 days). The LoD in Figure 3 (bottom, right) shows erratic decadal variations, a compelling argument for the permanent monitoring of LoD, of the order of several µs/year, as opposed to the mean increase of LoD caused by tidal friction and GIA of about 2.3 ms/century. The annual signal is caused by the interaction of the Earth's atmosphere with the solid Earth (annual variation of the jet streams).

The technique-specific products in Figures 3 (bottom) are used to generate combined ERP series, exactly as it is done for the ITRF in Figure 3 (top, left). Generating combined polar motion and UT1-UTC is performed by the IERS since its creation in 1987. The task needs a close collaboration between the IERS, the technique-specific services, and GGOS.

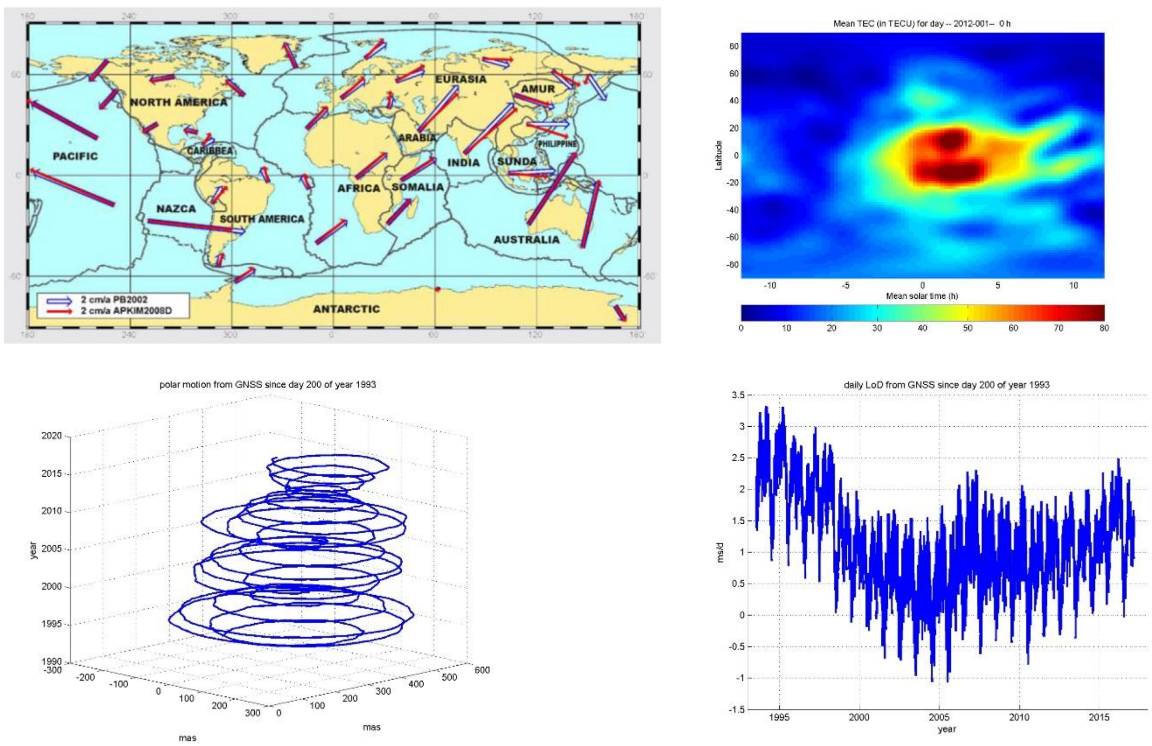

Figure 3: *Geometry-related products of the technique specific services ILRS, IVS, IGS, and IDS, and of their combination by the IERS, top, left: plate motion from geophysical models (PB2002) and from the ITRF2008, top, right: Mean electron density from IGS observations on January 1, 2012, 01^h-02^h, bottom, left: polar motion as a function of time from day 200 of 1993 to day 59 of 2017, bottom, right: LoD as a function of time from day 200 of 1993 to day 59 of 2017*

Having dealt with the geometry-related developments in the recent past, we have to review the gravity-related geodetic developments: the first fifteen years of the 21st century saw a revolution of gravity field determination. The three dedicated gravity missions CHAMP (2000-2010), GRACE (2002-2017), and GOCE (2009-2013), and GRACE Follow-on (2018-) tremendously improved our knowledge of the Earth's stationary and time-variable components of the Earth's gravity field. The German-USA mission CHAMP (Figure 4, (top, left)) was a pathfinder mission for the subsequent missions. CHAMP pioneered the use of spaceborne GNSS (GPS only, at that time) for precise orbit and gravity field determination, an element which was/is retained in the other two dedicated gravity missions.

The GRACE mission in Figure 4 (top right), with its µm-precise microwave link between the twin satellites, was optimized to determine the time-variable part of the gravity field, initially with a time resolution of one month. The time-invariable part of the GRACE gravity field model was also used in the EGM2008 (Pavlis et al., 2012), which is based on the best possible ground and space-information of the Earth's gravity field, available around 2008. A new version EGM2020 is announced to be available in 2020, which will be based on all satellite gravity data from GRACE and GOCE, and significantly improved ground data over continents and oceans. Ba means of a dedicated working group, IAG is currently deeply involved in the validation of preliminary versions of EGM2020.

The ESA mission GOCE in Figure 4 (bottom, left) was aiming at the highest spatial resolution of the gravity field using its gradiometer, consisting of a set of six accelerometers. Figure 4 (bottom, right) gives an impression of the quantum jump of knowledge of the steady-state part of the gravity field using difference-degree amplitudes w.r.t. EGM2008.

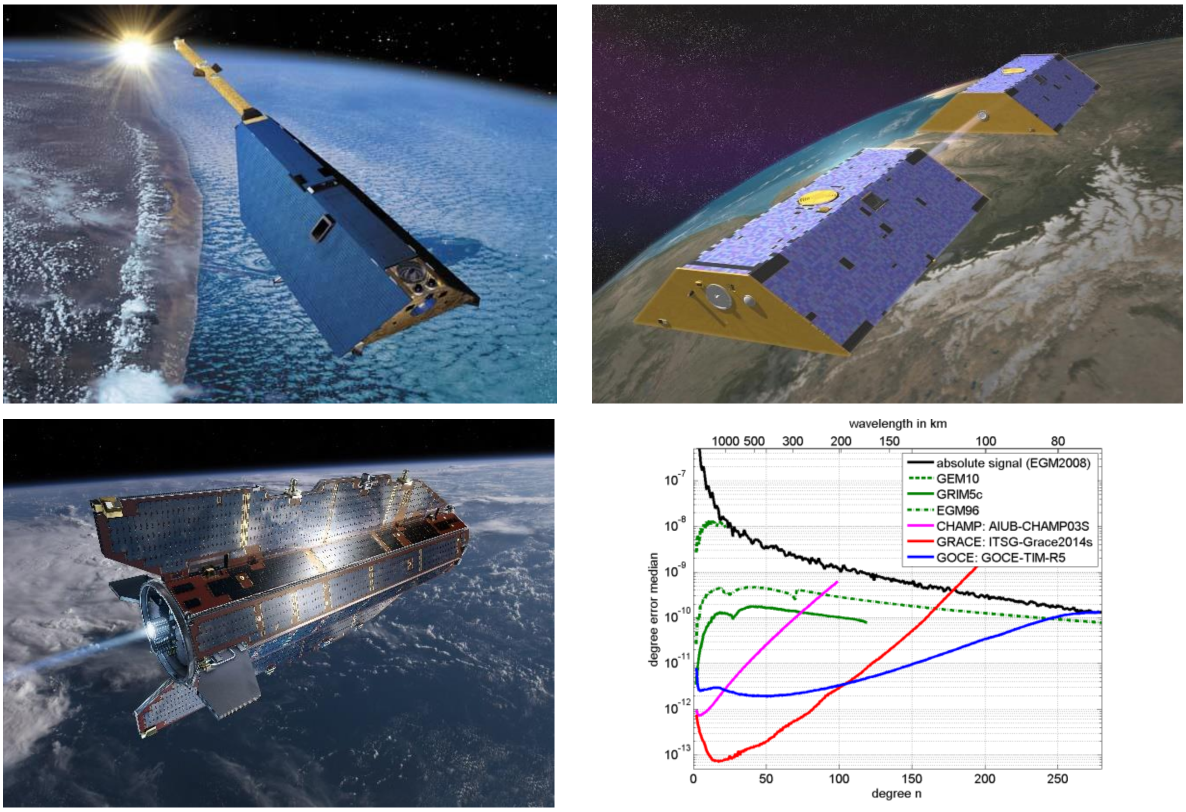

Figure 4: *The first three dedicated gravity field missions and their impact on gravity field determination. (Top, left): CHAMP; (top, right): GRACE; (bottom, left): GOCE; (bottom, right): degree error medians of different global gravity models: (a) GEM10, (b) GRIM5c, (c) EGM96, (d) CHAMP-derived field, (e) GRACE-derived field, (f) GOCE-derived field.*

Figure 4 might give the impression that gravity field determination with dedicated missions was "only" an episode in the history of geodesy. Problems related to global change, sea level rise, the global water cycle in the system Earth, etc., require permanent monitoring of the Earth's gravity field on the highest possible accuracy and resolution (in space and time) by dedicated space missions.

With the follow-on mission GRACE-FO (successfully launched in May 2018), this requirement will be met in the next decade. GRACE-FO is based on the same technology as GRACE, i.e., on spaceborne GNSS receivers for precise absolute orbit and gravity field determination and on a microwave link between satellites for ultra-precise differential orbit and gravity field determination. GRACE-FO also operates an experimental Laser-link between its satellites, measuring the inter-satellite distance with a much higher accuracy than with the microwave link. It will be a challenge to exploit the potential of this new measurement technique in the analysis.

Next-generation gravity field missions beyond GRACE-FO, science and user needs were defined by international expert panels under the umbrella of IUGG (Pail et al. 2015), and the strong need for a sustained gravity field observation from space was emphasized by the corresponding IUGG resolution no. 2 adopted by the IUGG Council, Prague 2015.

The Geodesist’s Handbook (Drewes et al., 2016) says that geodesy is the discipline dealing with the measurement and representation (geometry, physics, and temporal variations) of the Earth and other celestial bodies. This task includes the gravity field determination. Traditionally, the Earth was in the centre of the geodesists’ interests - and this will remain true for a long time, certainly for the next decade. In recent years, however, space missions to planets and moons of planets often had “geodetic” components, i.e., they used geodetic measurement and analysis methods to retrieve the geometric and gravitational properties of other celestial bodies than the Earth. The NASA mission GRAIL was even a dedicated gravity mission to the Moon, and it was based on the GRACE technology-heritage.

Figure 5 (left) shows the gravity anomalies of the Moon, as emerging from GRAIL (Arnold et al, 2015), Figure 5 (right) contains an artists’ views of three Venus missions, namely Venus Express (top, left), Pioneer Venus Orbiter (bottom, right) and Magellan (top, right), where the latter two had geodetic components, and one of the resulting gravity field models (without Venus Express), again expressed in terms of gravity anomalies. Mars missions (historic or planned) or the mission BepiColombo to Mercury might have been used as examples, as well.

The analysis of the geodetic part of past and future planetary missions will be more than an exotic side issue in the next decade and IAG should use its expertise and knowhow for the geodetic exploration of our planetary system.

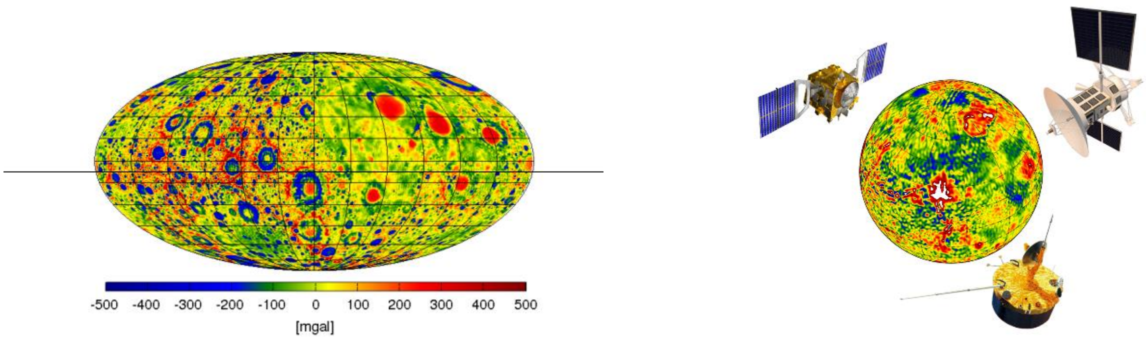

Figure 5: *Left: Gravity anomalies of the Moon, near-side of the Moon on the right-hand side, far-side on the left-hand side (Arnold et al., 2015); right: gravity anomalies of Venus and artists views of the three Venus missions.*

Technology always played a key role in geodesy, therefore also in IAG. Key developments of technology were identified at the IAG retreat 2016: Optical clocks, quantum technologies, e.g., for dedicated gravity field missions, are relevant for geodesy and should be studied/considered by IAG, e.g., for future space missions, in collaboration with fundamental physics institutes.

6. IAG Strategy 2019

The proposed IAG strategy 2019 is based on the outcome of the SWOT analysis performed at the 2016 IAG Retreat, on recent and anticipated future developments summarized in Sec. 5, and on aspects, which came up during the discussion in the IAG EC meetings.

First of all, we believe that the Association should consist in future, as in the past, of four Commissions, of the ICCT, of the Services, of the GGOS, and of the COB, as stated in article 5(a) of the IAG Statutes. The establishment of further ICCs is currently in preparation.

We thus believe that no *fundamental* changes are required in the IAG Statutes and Bylaws (Drewes et al., 2016, pp. 921-924), but that the degrees of freedom offered by the IAG Statutes and Bylaws should be exploited to go into new directions. Modifications emerging from the proposed strategy can be put in place by applying article 16(a) of the IAG Statutes. We will propose modifications, offer visions for improvements, and propose options for modifications, when we believe that additional investigations, e.g., by a planning committee, are required before implementing a proposed change.

The IAG services are a unique asset of IAG in comparison to the other IUGG associations. They are long-lasting (several decades at least) and they are related to the Earth monitoring with geodetic tools. The work in the services is based on an intensive, yet friendly competition, which very much helps to improve the quality of the services' products.

This chapter deals with GGOS and the services in Sec. 6.1, with the Commissions and the ICCT in Sec. 6.2, and it summarizes the proposed modifications to the IAG Statutes and Bylaws, the Visions, and the options for new IAG Projects in Sec. 6.3.

6.1 GGOS and the Services

Let us summarize the *status quo* of the IAG services:

1. There are *geometry-related* services, like the IGS, *gravity-related services*, like the BGI, pure *combination services*, like the IERS, *umbrella services*, like the IGFS, and services of *mixed* type, like the ILRS, which generates geometry- and gravity-related products.
2. The geometry-related and mixed IAG services, i.e., the four services illustrated by Figure 2, rely on expensive ground infrastructure, which is of vital importance for, but not owned by IAG.
3. Thanks to the UN-GGRF it is nowadays generally acknowledged that a "geometry-related monitoring" of the Earth is indispensable. "Gravity-related monitoring", e.g. for all mass displacements in global change, still has to be developed. Let us mention at this point that the IAG EC has adopted a position paper on the understanding of the GGRF as an integrated frame of geometry and gravity.
4. The gravity-related IAG services rely on a relatively expensive terrestrial infrastructure as well, e.g., the network of absolute gravimeters, but also on very expensive space missions (Figure 4) put into orbit by space agencies like NASA, ESA, in collaboration with big research centres like the GFZ.

Aspect (2) was a key argument to initiate GGOS. It would be most valuable for IAG to have a similarly prominent link to the major space agencies (NASA, ESA, JAXA, DLR, etc.) to assure a permanent monitoring of the Earth's gravity field through an uninterrupted series of dedicated gravity missions. The Committee on Satellite Missions in the GGOS Bureau of Observations and Standards (Figure 1b) already could provide such a link.
The space missions under (4) are realized based on suggestions by the scientific community, e.g., (Pail et al., 2015). Some IAG members are represented in these advisory committees like mission advisory boards. Their expertise and influence should be systematically used by IAG.
The IAG Services were internally evaluated by IAG in the years 2013 to 2015 ("IAG Service Assessment"). This assessment helped to identify some weaknesses of the services and helped to improve their performance. Nevertheless, there is still space for increasing efficiency and professionalism of almost all of the existing services.

The IAG services and GGOS should follow their definitions in the IAG Statutes and in the IAG Bylaws (Drewes et al., 2016) as closely as possible. The definitions are, with the essential elements highlighted:
Article 13(a) of the IAG Bylaws: IAG Services *generate products, using their own observations* and/or observations of other services, relevant for geodesy and for other sciences and applications. Accuracy and robustness of products, quality control, timeliness, and state of the art quality are the essential aspects of the Services.
Article 15(b) of the IAG Bylaws: GGOS works with other IAG components, such as the IAG Services and the IAG Commissions, as well as the Inter-commission Committees, *to provide unique, mutually consistent, and easily accessible geodetic products* (including the geometric reference frames and the gravity field) *and the relevant geodetic constants for science and society*.

To clarify responsibilities and to reduce frictions Modification #1 of the IAG Bylaws is proposed in Sec. 6.3.

Geometry- and gravity- related products should be mutually consistent. The GGOS Bureau of Products and Standards (Figure 1b) plays an essential role to accomplish this task.

The *geometry-related part* of the work of GGOS and the services may be summarized as follows:

- SLR, VLBI, GNSS, and DORIS are today's relevant space-geodetic techniques. Organization and scheduling of the observations, deployment and maintenance of the technique-specific networks, and the generation of technique-specific products, are performed by the four IAG services ILRS, IVS, IGS and IDS.
- The work of the ILRS, IVS, IGS, and IDS related to the observations and to the collocation of the technique-specific networks is coordinated by the GGOS Bureau of Networks & Observations.
- The IERS combines the geometry-related technique-specific products and issues releases of the ITRF and of ERP series.
- The IERS is not directly an IAG Service, but acts as an IAG Service, in this structure. A close collaboration between the IERS and the GGOS, with its technique-specific services, ensures a correct understanding and use of both, the technique-specific and the combined products.

The geometry-related part of the IAG services is working very well for the generation and maintenance of the classic ITRF and of ERP-time series with a daily time resolution.

There is, however, no obvious reason to retain a resolution of products with only 24h, in particular for the ERPs. This is why Vision#1 is proposed in Sec. 6.3.

Three of the four services illustrated by Figure 2 are satellite-geodetic services, but only the ILRS is regularly used for gravity field determination. There are no compelling reasons why the other two satellite-geodetic services (IDS and IGS) are not following the example of the ILRS and implement schemes to solve for the low-degree and-order harmonics of the gravity field, which would allow it, e.g., to study the gravitational aspects of the tides. Such modifications do not make sense for day-to-day products, but for reprocessing events. We therefore formulate Vision#2 in Sec. 6.3.

Other improvements, e.g., those related to the full deployment of GNSSs, other than GPS, or those related to more "DORIS satellites" are at least equally important, but they are not emphasized here, because they will be implemented anyway.

The *gravity-related part* of the work (Sec. 5) in GGOS and the services may be summarized as follows:

- Gravity field and geoid models emerging from past, present and future space missions are not generated by IAG services, but they are central issues for IAG.
- The IAG Service ICGEM, working under the umbrella of the IGFS, gives easy access to all gravity fields generated by institutions inside and outside IAG in its repository.
- The IAG/IGFS Product Center COST-G delivers consolidated time-variable global gravity models and user-friendly derived products by combining solutions from individual gravity analysis centers.

There are other components of the IGFS, dealing with important aspects of the gravity field. We believe, however, that the following aspects are currently missing and should be taken care of as soon as possible:

- *Combined* gravity field and geoid models emerging from past, present and future space missions, and gravity field models including terrestrial gravity *should be generated by and/or validated through the IGFS*, as it is foreseen in the IGFS terms of reference.
- The IGFS or the GGOS Bureau of Products and Standards should identify the "best'' gravity field and geoid model(s) for general (non-specialists') use.

Gravity field models resulting from different missions, the combination of mission-specific gravity data, and the combination of gravity field models based on mission-specific and terrestrial data are central issues for the IAG strategy 2019. Such tasks should be handled by dedicated and permanent IGFS entities. This is the reason for Vision#3 in Sec. 6.3.

The GGOS terrestrial observing network actually should include the stations of the global tracking networks (Figure 2), the global (absolute) gravity network, and the global (physical) height network. All of them have to be monitored in time. The geometrical coordinates are those available in / represented by the ITRF, the gravity values shall be given in the Global Absolute Gravity Reference Frame (IAG Resolution No. 2, Prague 2015), and the physical heights (or geopotential numbers) in the International Height Reference Frame (IHRF, IAG Resolution No. 1, Prague 2015). All three networks should have a significant number of co-located stations on a global and a regional scale. These considerations underlie Vision#4 of Sec. 6.3.

The book GGOS2020 (Plag and Pearlman, 2009) served as the handbook in GGOS in the decade 2010-2020. As the title implies, it cannot serve the same purpose in the next decade.

GGOS2020 shall be revised according to Vision#5 in Sec. 6.3, which is in turn based on the procedure agreed upon at the IAG Retreat 2016.

6.2 Commissions and the ICCT

The roles of the IAG Commissions and the Inter-commission Committees are defined in the IAG Bylaws (Geodesist's Handbook 2016):
Article 4, IAG Bylaws: *Commissions* shall promote the advancement of science, technology and international cooperation in their field. They establish the necessary links with sister disciplines and with the relevant Services. Commissions shall represent the Association in all scientific domains related to their field of geodesy.
Article 17, IAG Bylaws: *Inter-commission Committees* shall handle well defined, important and permanent tasks involving all Commissions.

These definitions shall remain the same in the IAG structure 2019.

The current IAG structure allows it to establish more than one ICC, as long as all ICCs handle permanent tasks involving all commissions. Since the implementation of the new structure in 2003, "only" the ICCT seemed to meet the criteria mentioned above. At the Prague General Assembly, the outgoing IAG President characterized the ICCT as follows (***from Presidential address at XXIV IUGG General Assembly in Prague):*** The mission of the ICCT is to interact actively and directly with other IAG entities, in particular Commissions and GGOS, in order to further the objectives of the ICCT:
• to be the international focal point of theoretical geodesy
• to encourage and initiate activities to further geodetic theory in all branches of geodesy, and
• to monitor research developments in geodetic modelling. Such a definition for the ICCT is missing in the current IAG Bylaws and Statutes. For these reasons, the Modification#2 of the IAG Bylaws is proposed in Sec. 6.3.

The IAG thus has a powerful tool to define new focal points by establishing an additional ICC to put the emphasis on an important topic, which it believes to last for more than one four-year period. The IAG also may propose one or more ***IAG Projects***, listed as long-term IAG subcomponents in Art. 1(f) of the IAG Bylaws, and defined by Articles 16 (a, b):

Article 16, IAG Bylaws (a): IAG Projects are flagship long-term projects of a broad scope and of highest interest and importance for the entire field of geodesy.
Article 16, IAG Bylaws (b): Planning for the creation of an IAG Project shall be carried out by a planning group established by the Executive Committee.

GGOS was established as an IAG Project in 2003 before it was put on a different level in 2007. Currently, there is no IAG Project. One may think of several potential IAG projects, which are provided in Sec. 6.3.

The IAG EC might wish to establish a planning group for a new IAG Project. Options 1-3 in Sec. 6.3 have been provided as examples, only. The establishment of a new IAG Project might be based on a Call for Proposals, to be issued at the 2017 IAG Scientific Assembly in Kobe, the proposal(s) might be publicly presented at the 2019 IAG General Assembly in Montreal, where one or more of the projects might be selected as new IAG Projects by the IAG EC.

Some of the above options, if not selected, might be selected as Commission projects. The creation of one or several planning groups for IAG Projects (or ICCs) is provided as Vision#6 in Sec. 6.3.

The IAG should make a serious attempt to attract young scientists. A possible way how to do that is proposed in Visions#7 and #8 of Sec. 6.3.

The IAG EC might consider establishing a planning committee at the IAG Scientific Assembly in Kobe to realize Visions #7 and #8 with the goal to organize the first special session in Montreal.

6.3 Modification of Bylaws, Visions, Options for IAG Projects

Modification #1* (*IAG Bylaws*)*:
Article 15(b): "GGOS works with the IAG Services *to provide unique, mutually consistent, and easily accessible geodetic products* (including the geometric reference frames and the gravity field models) *and the relevant geodetic constants for science and society*. GGOS takes the advice from Commissions and the ICCT concerning new developments, it keeps Commissions and ICCT informed of the work in GGOS.

Modification#2* (*IAG Bylaws*)*: The role of each established ICC should be defined in the IAG Bylaws, e.g., by a new article immediately after the current article 17:
18. Established ICC:
18.1 The Inter-commission Committee on Theory (ICCT), *followed by the above definition in the Presidential address*.
Other ICCs, should they be established one day, might be added as 18.2, etc. to this article. The current article 18 would then become article 19, etc.

Vision#1 for the IAG Strategy 2019 (geometry): The geometry-related services should strive for higher than daily, e.g., hourly, time resolution of their ERP series. High-resolution ERP series would allow it to improve the sub-diurnal polar motion and UT1/LoD models, but also to monitor polar motion in the inertial system.

Vision#2 for the IAG Strategy 2019 (geometry): All satellite-geodetic, geometry-related services are encouraged to develop tools to include gravity field parameters in their parameter estimation procedures.

Vision#3 for the IAG Strategy 2019: The IGFS should promote research and validation activities related to combining gravity field models emerging from one or several missions, e.g., by setting up a dedicated component within the IGFS for this purpose. It should in particular be easy to incorporate the service-like combinations performed routinely by the EGSIEM project of the EU using GRACE data.

Vision#4 of the IAG Strategy 2019: The GGOS terrestrial observing network should include the stations of the global tracking networks (Figure 2), the global (absolute) gravity network, and the global (physical) height network. All of them have to be monitored in time.

Vision#5 of the IAG Strategy 2019 (GGOS2020): A small task group shall review the document (Plag and Pearlman, 2009) with the goal to replace or amend this document in 2019 (at the latest). This task group should start working as soon as possible.

1. To avoid conflicts with the existing document (Plag & Pearlman, 2009) a new GGOS document should be written.
2. The new document, which might be called *GGOS Explanatory Supplement*, shall be much shorter than the old one; about 50 pages should be sufficient.
3. The new document shall clearly define the role of GGOS in IAG and w.r.t. science and society in general.
4. The GGOS Science Panel is responsible to coordinate the effort, implying that Richard Gross will be the lead editor. Co-editors might be Chris Rizos and Harald Schuh (ex officio).

Vision#6 of the IAG Strategy 2019 (IAG Project(s)): The IAG EC might wish to set up one or several Planning Groups at its meeting on April 28 in Vienna 2017 to further develop one or several of the IAG Projects listed below or of other IAG Projects.

Vision#7 of the IAG Strategy 2019: The IAG EC might consider attracting young scientists

(a) by awarding the IAG Bomford Prize for excellent young scientists every two years (instead of presently every four years),
(b) by letting the winner of the Bomford Prize organize a special session at the next IAG Scientific Assembly and/or at the next IAG General Assembly,
(c) where the organizing committee would be chaired by the previous prize winner(s) of the Bomford Prize and would include the recipients of the recent best paper awards in the organizing committee, and
(d) the Bomford Prize winners get free registration and a travel support to attend the Assembly.

Vision#8 of the IAG Strategy 2019: The attempt should/might be made to have the above prize(s) sponsored by “geodetic industry”.

Options for IAG Projects and Inter-Commission Committees in the IAG Strategy 2019:

Option#1: Planetary geodesy might be established as an IAG Project in close cooperation with the IUGG UCPS.

Option #2: Methodology for the establishment of a GGRF, based on the IAG position paper on the GGRF. This automatically included aspects of Option#2, such as how to achieve a good global reference gravity field and local densification as a basis for a unified height system, but extends to the integration of the latter with the geometry part (technically, standards and background models, ...).

Option#3: The use/implementation of new technologies like optical clocks, quantum technologies, new airborne instrumentation in geodesy might be established as an IAG Project.

Option#4: Marine Geodesy should be established as an IAG Project.

Option#5: Geodesy for climate research

Option#6: Seismo-Geodesy

Acronyms

BGI	Bureau Gravimétrique International
BIPM	Bureau International des Poids et Mesures
BeiDou	Chinese Satellite Navigation System
CHAMP	CHAllenging Minisatellite Payload
COB	Communication and Outreach Branch (of IAG)
COST-G	International Combination Service for Time-variable Gravity Field Solutions
DORIS	Doppler Orbitography by Radiopositioning Integrated on Satellite
EGM	Earth Gravitational Model (EGM96, EGM2008 referring to 1996, 2008)
EGSIEM	European Gravity Service for Improved Emergency Management
ERP	Earth Rotation Parameter
ESA	European Space Agency
GEO	Group on Earth Observation
GGOS	Global Geodetic Observing System
GIA	Global Isostatic Adjustment
GIAC	GGOS Interagency Committee
GNSS	Global Navigation Satellite Systems
GOCE	Gravity field and steady-state Ocean Circulation Experiment
GRACE	Gravity Recover and Climate Experiment
GRACE-FO	GRACE Follow On (launch scheduled 2018)
GRAIL	GRAvity recovery and Interior Laboratory (of the Moon)
IAG	International Association of Geodesy
IAS	International Altimetry Service
IAU	International Astronomical Union
ICET	International Center for Earth Tides
ICC	Inter-Commission Committee
ICCT	Inter-Commission Committee on Theory
ICGEM	International Center for Global Earth Models
ICSU	International Council for Science
IDEMS	International Digital Elevation Model Service
IDS	International Doris Service
IERS	International Earth Rotation and Reference Systems Service
IGeS	International Geoid Service
IGFS	International Gravity Field Service
IGS	International GPS Service
ILRS	International Laser Ranging Service
IPMS	International Polar Motion Service (predecessor of IERS)
ITRF	International Terrestrial Reference Frame
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service for Geodesy and Astrometry
IRNSS	Indian Regional Navigation Satellite System
LEO	Low Earth Orbiting satellite
LLR	Lunar Laser Ranging
LoD	Length of Day
MGEX	Multi-GNSS Experiment (of IGS)
NASA	National Aeronautics and Space Administration
Quasar	Quasi-stellar Object emitting microwave radiation
SAR	Synthetic Aperture Radar

SLR	Satellite Laser Ranging
SWOT	Strengths, Weaknesses, Opportunities, Threats
UCPS	Union Committee on Planetary Science (of IUGG)
UN	United Nations
UN-GGIM	UN-Global Geospatial Information Management
UN-GGRF	UN-Global Geodetic Reference Frame (UN-GGIM Working Group)
VLBI	Very Long Baseline Interferometry

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