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On the eve of the 100th anniversary of IAU Commission 19/A2 "Rotation of the Earth"

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Abstract. IAU Commission 19 began in 1919 with the birth of the IAU at the Brussels Conference, where Standing Committee 19 on Latitude Variations was established as one of 32 standing committees. At the first IAU General Assembly in 1922, Standing Committee 19 became Commission 19 "Variation of Latitude". In the beginning, the main topic of the Commission was the investigation of polar motion. Later, its activities included observations and theory of Earth rotation and connections between Earth orientation variations and geophysical phenomena. As a result, in 1964 at the XII IAU General Assembly, the Commission was renamed "Rotation of the Earth". The investigation of Earth orientation variations is primarily based on observations of natural and artificial celestial objects. Therefore, maintenance of the international terrestrial and celestial reference frames, as well as the coordinate transformation between the frames and the improvement of the model of precession/nutation, have always been among the primary Commission topics. In 1987, the IAU through Commissions 19 and 31 "Time" established, jointly with the *International Union of Geodesy and Geophysics*, what is now known as the International Earth Rotation and Reference Systems Service. Commission 19 continued to work to develop methods to improve the accuracy and understanding of Earth orientation variations and related reference systems and frames as well as theoretical studies of Earth rotation. In 2015, Commission 19 was renewed as Commission A2 "Rotation of the Earth" continuing Commission 19's functions and linking the astronomical community to other scientific organizations such as the *International Association of Geodesy, International VLBI Service for Geodesy and Astrometry, International GNSS Service, International Laser Ranging Service* and *International DORIS Service*. During its entire history, IAU Commission 19/A2 has always worked in close cooperation with these and other related services to improve the accuracy and consistency of the Earth orientation parameters and celestial and terrestrial reference frames.

Keywords. Earth, astrometry, reference systems and frames, time, history and philosophy of astronomy, geodesy, geophysics

1. Introduction

Earth rotation is not uniform. The Earth's rotational speed is not constant and this fact leads to variations in the length of the day (LOD). The excess LOD, which is defined as the difference between the observed LOD and nominal value of 86 400 seconds, amounts to milliseconds. The rotation axis also moves with respect to the Earth's crust due to the unequal and variable distribution of mass, and this phenomenon is referred to as polar motion. Observed irregularities in the rotation of the Earth have complicated structure and show both secular and quasi-periodic variations at time scales ranging from subdaily to decadal. These variations are affected by processes acting within the interior of the Earth, such as core-mantle interaction and glacial isostatic adjustment and by processes acting at the surface of the Earth, such as fluctuations in the transport of mass within the atmosphere and oceans, called geophysical fluids. Studying the Earth's time varying rotation can therefore be used to gain greater understanding of global-scale processes.

In addition, the gravitational attraction of the Sun, Moon and planets acting on the Earth causes the rotation axis to change its orientation with respect to the celestial reference system. This motion is characterized by precession, the slow continuous change in orientation causing a circular trace of the projection of the Earth's axis in space with a period of 25 772 years, and nutation, the smaller, more rapid motion of the direction of the axis in space composed of a large number of periodic terms. All of these motions are described by the Earth rotation angle, the angular coordinates of the Earth's pole in a terrestrial reference frame, and the angular coordinates of the celestial pole in a celestial reference frame (precession-nutation angles). Together, these are referred to as Earth orientation parameters (EOP). For practical purposes, celestial pole offsets, which are the difference between actual position of the axis and its position predicted by an adopted model of precession-nutation, are computed and provided to users instead of the full precession-nutation angles.

The Earth rotation is studied with respect to the terrestrial and celestial coordinate systems. Reference systems are critical, not only for astronomers but also for geodesists. At its very beginning, IAU Commission 19 on Latitude Variations was established simultaneously with an analogous commission of the *International Association of Geodesy* (IAG), and both organizations supported the activities of the *International Latitude Service* (ILS). During its entire history IAU Commission 19 has worked in close cooperation with the *International Union of Geodesy and Geophysics* (IUGG), the IAG, and the *International Earth Rotation and Reference Systems Service* (IERS) and its predecessors, the ILS, IPMS, and the *Bureau International de l'Heure* (BIH), in order to improve the accuracy and consistency of the EOP and terrestrial and celestial reference frames. Knowledge of the EOP is needed to relate the terrestrial and celestial reference frames. The terrestrial reference frame is attached to the solid Earth and its orientation with respect to the celestial frame changes as the Earth rotates. Knowing the relative orientation of the terrestrial and celestial reference frames and how it varies in time allows the positions of both ground-based and Earth orbiting objects to be known in both frames.

Earth rotation is therefore an interdisciplinary topic that bridges astronomy, geodesy and geophysics. Precise Earth orientation parameters are needed to position and navigate objects on Earth and in space, and the analysis of Earth rotation variations provides important information about the interactions among the various components of the Earth system. This paper briefly describes the organizational history and scientific activity of IAU Commission 19 during its nearly 100-year-long history. It is mainly based on the IAU Reports for the period from 1922 through 2015 (IAU Transactions 1922–2015).

2. Overview of Commission history and activity

The story of IAU Commission 19 begins in 1919 at the Brussels Conference where the IAU, comprised of 32 Standing Committees on different branches of astronomy, was established. One of the 32 was Standing Committee 19 on *Latitude Variations* chaired by Hisashi Kimura, Director of the International Latitude Observatory, Mizusawa, Japan. In 1922, at the first IAU General Assembly, all Standing Committees became Commissions and thus IAU Commission 19 *Variation of Latitude* was established.

During its first years, the main topic of the Commission was the investigation of polar motion, primarily using observations made at the International Latitude Service (ILS) stations located at the latitude $39°08'$ N, referred to as the North parallel. According to the first Commission 19 charter, the main tasks were: continuation of observations on the North parallel, compilation of programs of observations, unification of reduction methods, development of new instruments and methods for future observations, and providing financial support for these activities. The main scientific problems discussed at Commission meetings were non-polar astronomical latitude variations, station motion, atmospheric impact on the results of latitude observations, improvement of astronomical models affecting the ILS results such as nutation, precession and aberration, and improvement of star positions used for the computation of latitudes. Many of these tasks remain of interest today, despite revolutionary changes in the observational techniques used for Earth rotation studies.

In the beginning of the 20th century, polar motion was the only irregularity in the Earth rotation that could be measured reliably. As it became clear that there was a wide spectrum of variations in the rotational speed, routine observations of the Earth rotation began to be made by determining adjustments to mechanical clocks based on optical star observations. The BIH became responsible for the coordination of these time observations, and in 1955 began to make its own determination of polar motion in order to improve the observations of astronomical time. In 1962 the ILS was superseded by the International Polar Motion Service (IPMS) in recognition of the contributions to polar motion made by stations other than those of the original ILS. More detail on the history of the ILS and IPMS can be found in Yokoyama, Manabe & Sakai (2000).

The Commission's activities expanded to include the effects of polar motion on the time observations, to manage the increasing number of stations performing latitude and time observations and to develop the theory of Earth rotation. The connection between variations in the Earth rotation and various geophysical phenomena and integrating geophysical and meteorological data in the analysis and prediction of EOP also came to be one of the most important topics of the Commission's discussions. As a result, in 1964 at the XII IAU General Assembly, the Commission was renamed *Rotation of the Earth* and included several functions of Commission 31 *Time* relating to the determination of Universal Time.

Until the 1970s, the optical astronomical observation of stars was the only technique available to determine polar motion and Universal Time used to describe the Earth rotation. After that, new observing techniques based on observations of artificial satellites, such as Doppler satellite tracking, Global Positioning System (GPS), Satellite and Lunar Laser Ranging (SLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), as well as Lunar Laser Ranging (LLR) and observation of extragalactic radio sources with Very Long Baseline Interferometry (VLBI) were developed that soon proved to be capable of determining the EOP and realizing reference systems much more accurately. In the 1980s members of Commission 19 were instrumental in organizing Project MERIT to compare the possible contributions of the developing techniques. To coordinate these efforts, a new service, the IERS (known then as the International

Earth Rotation Service) was established in 1987 by the IAU and IUGG combining the operations of the IPMS and the Earth Rotation Section of the BIH (Wilkins 2000). In recognition of the importance of accurate reference systems in studying the Earth rotation the IERS was renamed the *International Earth Rotation and Reference Systems Service* in 2003. The IERS plays an important role in the operational and long-term determination and dissemination of the EOP and in the establishment and maintenance of the terrestrial and celestial reference systems and frames based on space geodesy observations. By the end of the 1990s, specific technique services were established, such as the *International GPS Service* (IGS, now International GNSS Service), *International VLBI Service for Geodesy and Astrometry* (IVS), *International Laser Ranging Service* (ILRS) and *International DORIS Service* (IDS). From the beginning of their activities, Commission 19 has worked in close cooperation with these technique services.

Describing Earth orientation variations requires clear and accurate definitions of the terrestrial and celestial coordinate systems and frames in which the Earth motion is given. The Commission has always been active in this area and plays a leading role in maintaining the *International Celestial Reference Frame* (ICRF) and the International Terrestrial Reference Frame (ITRF) in partnership with the IERS and IAG. For example, in 1967 the concept of the *Conventional International Origin* (CIO) was adopted by the IAU and IUGG. More recently, commission members have contributed to the maintenance of the celestial reference system and frame. In 1997, the new ICRS definition and its realization, ICRF, were adopted by the XXIII General Assembly of the IAU, followed by ICRF2 in 2009. ICRF3, the latest realization of the ICRS, was completed in 2018 and adopted by the XXX General Assembly of the IAU in August, 2018.

The investigation of Earth orientation variations is primarily based on observations of natural and artificial celestial bodies, such as stars, extragalactic radio sources, and artificial Earth satellites. Therefore, the accuracy of the coordinate transformation between terrestrial and celestial reference systems is of primary importance. For this reason, improving the model of precession/nutation has always been among the Commission's discussion topics. During its first decades, latitude observations were used to improve the nutation constant. In the 1970s, IAU Commission 19 and the IERS jointly promoted the new IAU 1980 nutation theory. In the 2000s, the IAU2000/2006 model of precession/nutation was adopted (IAU Resolutions 1922–2018). This model currently provides the best accuracy for relating the conventional reference frames, namely ICRF and ITRF.

Today, the Commission's objectives include:

- Encouraging and developing cooperation and collaboration in observation and theoretical studies of Earth orientation (the motions of the pole in the terrestrial and celestial reference systems and the rotation about the pole).
- Linking the astronomical community to the official organizations providing the ITRS, ITRF and EOP: IAG, IERS, IVS, IGS, ILRS and IDS.
- Developing methods for improving the accuracy and understanding of Earth orientation and related reference systems/frames.
- Ensuring agreement and continuity of the reference frames used for determination of EOP with other astronomical reference frames and their densification.
- Providing means of comparing observational and analysis methods and results to ensure accuracy of data and models.

Following the reorganization of the IAU adopted at its XXIX General Assembly in 2015, Commission 19 was abolished and Commission A2 with the same name *Rotation of the Earth* was established.

The Commission has been chaired by many distinguished scientists. Figure 1 presents all the Presidents of IAU Commission 19/A2 during its history.

Figure 1. Presidents of IAU Commission 19/A2.

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IAU Commission 19/A2 has organized, co-organized and participated in many IAU and inter-union working groups relevant to its field of interest. Each working group serves as a platform for discussions and interactions of specialists on the most important topics of the Commission. During the last 20 years these are:

- Joint IAU/IAG Working Group "Theory of Earth rotation and validation" (2015–).
- Joint IAU/IAG Working Group "Theory of Earth rotation" (2012–2015).
- IAU Working Group "Third Realization of ICRF" (2012–2018).
- IAU Working Group "Second realization of ICRF" (2003–2009).
- IAU Working Group "Nomenclature for Fundamental Astronomy" (2003–2006)".
- IAU Working Group "Numerical Standards for Fundamental Astronomy" (2006–).
- IAU Working Group "Definition of Coordinated Universal Time" (2001–2006).
- IAU Working Group "Precession–nutation" (2000–2003).
- IAU Working Group "Reference Systems" (1997–2000).
- Joint IAU/IUGG Working Group "Nonrigid-Earth Nutation Theory" (1994–2000).

IAU Commission 19/A2 also organized or co-organized with other IAU Commissions and other communities and institutions many IAU sponsored and co-sponsored scientific meetings, such as

- Journées "Systèmes de Référence et de la Rotation Terrestre" (2017).
- Joint IAU/IAG/IERS Symposium "Geodesy, Astronomy & Geophysics in Earth Rotation" (2016).
- 23 Journées "Systèmes de Référence Spatio-Temporels" (1988–2014).
- Joint Discussion 7 at the XXVIII IAU General Assembly (2012).
- Joint IAU/GGOS Workshop "Observing and Understanding Earth Rotation" (2010).
- Joint Discussion 16 at the XXVI GA (2006).
- Joint Discussion 16 at the XXV IAU General Assembly (2003).
- Joint Discussion 2 at the XXIV GA (2000).
- IAUC 180: Towards models and constants for sub-microarcsecond astrometry (2000).
- IAUC 178: Polar Motion: Historical and Scientific Problems (1999).
- IAUS 156: Developments in Astrometry and their Impacts on Astrophysics and Geodynamics (1992).
- IAUC 127: Reference Systems (1990).
- IAUS 141: Inertial Coordinate System on the Sky (1989).
- IAUS 128: Earth's Rotation and Reference Frames for Geodesy and Geodynamics (1986).
- IAUC 63 : High-Precision Earth Rotation and Earth-Moon Dynamics (1981).
- IAUC 56 : Reference Coordinate Systems for Earth Dynamics (1980).
- IAUS 82 : Time and the Earth's Rotation (1978).
- IAUS 78 : Nutation and the Earth's Rotation (1977).
- IAUC 26 : On Reference Coordinate Systems for Earth Dynamics (1974).
- IAUS 48 : Rotation of the Earth (1971).
- IAUS 13 : The Future of the International Latitude Service (1960).
- IAUS 11 : The Rotation of the Earth and Atomic Time Standards (1958).

As a result of these scientific discussions and working group activities, the Commission initiated or supported tens of recommendations and IAU Resolutions related to its field of interest and responsibility. These resolutions relate to the organization of Earth orientation observations, computation of the EOP, and development of astronomical models, reference systems and frames, and time scales. Through the IAU resolutions proposed or supported by the Commission, such organizations as the ILS Central Bureau, IPMS and IERS were established or maintained, new precession-nutation models were adopted, three ICRF realizations were endorsed, new dynamical time scales along with barycentric

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and geocentric space-time coordinates were defined and the concept of Non-Rotating Origin (NRO) was introduced.

3. Conclusion and outlook

IAU Commission 19/A2 has a long and proud history of active involvement in the IAU. Starting with investigations of latitude variations, mostly based on astronomical observations taken at stations on the 39°08′ North parallel. Now, at its 100th anniversary the Commission has extended its activities to many topics related to the investigation of all aspects of the theory and observations of Earth rotation and the establishment and maintenance of the terrestrial and celestial reference systems and frames as well as time scales. Summarizing the Commission's activities during the nearly 100-year length of its history, we can say that:

- IAU Commission 19/A2 has played and continues to play an important role in the IAU's activity of coordinating international cooperative efforts to improve our knowledge of the Earth rotation and to establish and maintain the international terrestrial and celestial reference systems and frames.
- IAU Commission 19/A2 initiated or supported many important resolutions related to the theory of precession-nutation, terrestrial and celestial reference systems and frames, time scales, and other topics of general scientific and practical interest.
- IAU Commission 19/A2 co-organized and collaborates with several international services such as the IERS, IGS, IVS, ILRS and IDS.
- IAU Commission 19/A2 organized or co-organized many working groups including inter-commission and inter-union ones.
- IAU Commission 19/A2 works in close cooperation with other international organizations such as the IUGG and IAG and thus provides the necessary link between these organizations and the IAU.

The Commission will continue to work closely with the services, commissions, inter-commission committees and *Global Geodetic Observing System* (GGOS) of the IAG as it has in the past. In this manner, the astronomy community is kept abreast of progress made by the geodetic community in observing and understanding the Earth's rotation, and vice versa.

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