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COMMISSION 19 ROTATION OF THE EARTH

ROTATION DE LA TERRE

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TRIENNIAL REPORT 2009–2012

1. Introduction

The Commission supports and coordinates scientific investigations about Earth rotation and related reference frames. Above all C19 encourages and develops 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). The Commission serves the astronomical community by linking it to the official organizations providing the International Terrestrial and Celestial Reference Systems/Frames (ITRS/ITRF and ICRS/ICRF) and Earth orientation parameters (EOP): International Association of Geodesy (IAG), International Earth Rotation and Reference System Service (IERS), International VLBI Service for Geodesy and Astrometry (IVS), International GNSS Service (IGS), International Laser Ranging Service (ILRS), International DORIS Service (IDS). Among the most important activities are the development of methods for improving the accuracy and understanding of Earth orientation and related reference systems/frames. Further, C19 ensures the agreement and continuity of the reference frames used for Earth orientation with other astronomical reference frames and their densifications and provides means of comparing observational and analysis methods and results to ensure accuracy of data and models.

During the 27th IAU General Assembly in Rio de Janeiro the Organizing Committee (OC) of C19 has been re-structured and filled with new members. It consists of three ex-officio members (Commission President, Vice-President, Past President), three representatives from international services related to Earth rotation (International Association of Geodesy (IAG), International Earth Rotation and Reference Systems Service (IERS), International VLBI Service for Geodesy and Astrometry (IVS)) and five elected members of which all are in their first of two possible terms. Furthermore the position of a Commission Secretary has been established.

During the past triennium a new commission website has been established (www.iau-comm19.org). It lists the Commission's terms of reference as well as information on upcoming scientific meeting and the history of C19. In addition it provides the members'

list of the Commission. During the past triennium the members' directory has been updated. It is now on an up-to-date status after former members were removed who are not active and/or interested in Earth rotation research any more.

A brief description of the most important developments in the fields related to C19 is given below. The following sections contain the reports of cooperating services/institutions. The list of references comprise only the most important papers which have been published in the past years; an extended list of references provided by the members of C19 will be posted at the Commission website. Two review works on Earth rotation shall be mentioned here that were published in the past triennium: A book chapter by Seitz and Schuh (2010) and a section in an encyclopedia by Schuh and Böhm (2011).

2. Scientific sessions, workshops and special publications within the past triennium

Three special workshops about Earth orientation variations were held during the past triennium: (1) a joint Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas (DynaQlim)/Global Geodetic Observing System (GGOS) workshop on 'Understanding Glacial Isostatic Adjustment' was held in Espoo, Finland during June 23-26, 2009; (2) an IERS workshop on 'EOP Combination and Prediction' was held in Warsaw, Poland during October 19-21, 2009; and (3) a joint GGOS / IAU Commission 19 workshop on 'Observing and Understanding Earth Rotation' was held in Shanghai, China during October 25-28, 2010. The joint DynaQlim/GGOS workshop included discussions of the importance of Earth orientation measurements to both constrain GIA models and to verify and validate those models. The proceedings of the workshop will be published as a special issue of the journal *Physics and Chemistry of the Earth*. The IERS workshop included discussions of the determination, combination, and prediction of Earth orientation variations. The proceedings papers of the workshop have been published in volume 45 of the journal *Artificial Satellites*. The joint GGOS/IAU C19 workshop included discussions of all aspects of the Earth's rotation, including the observations and theory of the Earth's time varying rotation, the causes of the observed variations, the consistency of Earth rotation observations with global gravity and shape observations, and the combination of Earth rotation, gravity, and shape observations to gain greater understanding of the mass load acting on the surface of the solid Earth. The proceedings of the workshop will be published as a special issue of the *Journal of Geodynamics*. Further scientific sessions on Earth rotation which can be reported here are sessions at the annual General Assembly of the European Geosciences Union (EGU; Vienna, Austria), as well as at the Journées 'Systemes de reference spatio-temporels' in 2010 (Paris, France) and in 2011 (Vienna, Austria).

3. Report of national projects and individual institutions

3.1. *Report of activities in Australia*

By *O. Titov*. Activities in Australia the field of the Earth rotation during 2008-2011 focused on the following topics:

- New VLBI network included three AuScope radio telescopes (Hobart, Yarragadee, Katherine) started operation in 2011, particularly, in IVS-R1, R4 sessions.
- General IVS meeting held in Hobart, Tasmania, in February, 2010, hosted by the University of Tasmania (UTAS).

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• Observational program for identification of the reference sources in radio/optics started in 2008 (PI: Oleg Titov). This program focuses on the future link between radio reference frame produced by VLBI and optical reference frame which will be produced by GAIA, and comprises several large optical facilities: The 3.5 meter New Technology Telescope (NTT, ESO) in Chile, the 6-meter Big Telescope Azimuthal (BTA, SAO) in Russia, and the two 8 meter Gemini Telescopes in Chile and Hawaii. Spectroscopic observations in optics of the reference radio sources to determine redshifts, and, thus, confirm their extragalactic nature are undertaken. Observational programs on all four telescopes are continuing at this stage. A proposal was submitted to reserve observing time at the 10 meter Gran Telescope Canarian (GTC) in Spain. The program is performed in collaboration with scientists from Russia, Australia, Germany, France, Spain and the USA. Redshifts of 50 reference radio sources have been measured by date.

• Indication of the Galactocentric aberration which is measured as 'secular aberration drift' from a global set of geodetic VLBI data may affect the future IAU Resolutions/IERS Recommendations.

• A significant investment in ground GNSS infrastructure over the last four years has included the expansion of the Australian GNSS network through federal government investment in geospatial infrastructure through AuScope. This funding has seen the construction of 48 GNSS sites with another 52 under construction. Significant research has also been undertaken by a number of Australian researchers investigating systematic error sources and mitigation strategies within analyses of global GNSS networks. This data from the Australian GNSS network is made available to the International GNSS Service and contributes to the IGS Earth Orientation parameter estimates.

• Satellite Laser Ranging (SLR) at the Mount Stromlo (Canberra) and Yarragadee (Western Australia) facilities have continued throughout the 2007-2011 period. In 2008, $80K of AuScope funding was used to upgrade the power of the laser in the Mt. Stromlo SLR system. This allows ranging to high Earth orbit satellites such as GNSS. The Australian systems were operated by Electro Optic Space Systems under contract to Geoscience Australia. The two SLR observatories contribute to the International Laser Ranging Service (ILRS) and subsequently their Earth Orientation parameter estimates. In 2007, Geoscience Australia became accredited as an associate analysis centre of the ILRS.

3.2. *Report of activities at the Institute of Geodesy and Geophysics (IGG) of the Vienna University of Technology, Austria*

By *T. Nilsson, M. Schindelegger and S. Böhm.* The main research area at IGG is the study of short-period and episodic variations in Earth rotation and the estimation of these effects using the very long baseline interferometry (VLBI) and other space geodetic techniques. Hourly Earth rotation parameters (ERP) estimated from the two-week long VLBI campaigns CONT02, CONT05, and CONT08, have been compared to estimates of GPS as well as to the IERS model for high frequency ERP variations (Nilsson *et al.*, 2010). Furthermore, time series of polar motion and DUT1 with sub-daily resolution estimated from all available geodetic VLBI observations have been used to create empirical models of the diurnal and sub-diurnal ERP (Böhm *et al.*, 2011). The obtained parameters have been compared to those derived from ocean tidal models, e.g. to the high frequency ERP variations as predicted by the IERS Conventions. Significant differences between the VLBI results and the IERS Conventions model were found at several tidal frequencies. The reasons for these discrepancies need further investigation. The possibility to combine data from the ring laser gyroscope 'G' in Wettzell with VLBI observations in order to estimate accurate hourly ERP have also been studied (Nilsson *et al.*, 2011a). The

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results show that a combination on the normal equation level is possible, although the contribution from the ring laser observations is presently very small since the accuracy of the VLBI data is about one order of magnitude higher.

Atmospheric excitations of Earth rotation at diurnal and sub-diurnal frequencies have been studied by analysing atmospheric angular momentum (AAM) functions calculated from numerical weather models. AAM series from a special set of hourly ECMWF analysis fields during the period of CONT08 (Schindelegger *et al.*, 2011a), from 3-hourly ECMWF delayed cut-off analysis fields (Schindelegger *et al.*, 2011b), and from the standard 6-hourly ECMWF operational analysis data, have been used. An interesting discovery from this investigation is that the excitations caused by atmospheric mass variations and those caused by winds tend to counteract each other. The reason for this counteraction has been carefully investigated. Changes in Earth rotation caused by the large Earthquakes in Chile, February 2010, and Japan, March 2011, have been studied. The expected variations in the ERP and the corresponding excitation values were calculated from a model. The changes are however so small, that it has presently not been possible to validate the model results using observations (Nilsson *et al.*, 2011b).

3.3. *Report of activities at the Royal Observatory of Belgium*

By *V. Dehant*. The main goal of the team 'Earth rotation' at the Royal Observatory of Belgium (ROB) is to better understand and model the Earth rotation and orientation variations, to study physical properties of the Earth's interior as well as the interactions between the solid Earth and the geophysical fluids. The work is based on theoretical developments as well as on the analysis of data from Earth rotation monitoring and general circulation models of the atmosphere, ocean, and hydrosphere. The scientists involved in this project work on the improvement of the processing of Very Long Baseline Interferometry (VLBI) and GNSS observations, on the determination of geophysical parameters from these data, and on analytical and numerical Earth rotation models. They study the angular momentum budget of the complex system composed of the solid Earth, the core, the atmosphere, the ocean, the cryosphere, and the hydrosphere at all timescales. This allows them to better understand the dynamics of all the components of the Earth rotation, such as Length-of-day variations (LOD), polar motion (PM), and precession/nutation, as well as to improve their knowledge and understanding of the system, from the external fluid layers to the Earth deep interior. In particular for the last years (2009–2011):

- ROB has developed a strategy for combining VLBI- and GPS-based normal equations in order to achieve a better accuracy and a better consistency in the resulting nutation series.
- ROB has performed an inversion of different VLBI nutation data sets in order to estimate parameters characterizing physical properties of the deep Earth. This inversion was performed using longer data sets and a new inversion strategy.
- ROB has analyzed the Earth's interior parameters inferred from the inversion of nutation observations in terms of existing models of the mechanical coupling at the boundaries of the fluid core. Estimations of physical properties of the deep Earth have been obtained.
- ROB has computed the topographic torque at the core-mantle boundary and its effects on nutations, and ROB has shown that some harmonics of the topography are enhanced due to the coupling of the nutation forcing and the topography itself.

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3.4. *Report of activities in the People's Republic of China*

By *C. Huang*. The dynamic coupling between magnetic field and nutation near core-mantle-boundary was discussed in a numerical integration approach. Results showed that the contribution from magnetic field is approximately one order of magnitude smaller than required to fill the differences of -1.0-year nutation and FCN period between theoretical value and observation (Huang *et al.* 2011). A generalized theory of the gravity potential and figure interior was developed and applied to study the global dynamic fattening (H) and nutation. It was shown that the traditional 1.1% difference between H_{PREM} and H_{obs} can be reduced by 2/3 (Huang and Liu, 2011). A triaxial Earth rotation theory to incorporate all relevant physical processes was studied. The dynamic equations are formulated and the normal modes for an Earth model with a triaxial anelastic mantle, a triaxial fluid core, and dissipative oceans are obtained (Chen *et al.*, 2009, 2010; Shen *et al.*, 2011).

Prediction of EOP by artificial neural networks (ANN) has been studied by several colleagues. The accuracy for prediction over 60-360 days is quite good, and its accuracy for prediction of UT1 by integrated LOD is significantly improved for shorter lead times (Liao *et al.* 2011). The axial sequence of AAM is introduced into the forecasting model of ANN (Wang *et al.* 2008a); the operational prediction series of axial AAM is incorporated into the ANN model as an additional input in the real-time rapid prediction of LOD variations with 1-5 days ahead (Wang *et al.* 2008b); A non-linear ANN, general regression neural network (GRNN) model to forecast the LOD change was also studied (Zhang *et al.*, 2011). Different combinations of least squares(LS), ANN, autoregressive (AR) and Kalman filter (LS+ANN, LS+AR, and LS+AR+Kalman) in prediction of the EOP were studied (Xu *et al.*, 2010). The individual tropospheric and stratospheric wind contributions to the Earth's variable rotation were investigated. For the axial component these two terms are essentially additive; for the equatorial components these two terms cancel significantly (Zhou *et al.*, 2008).

The evidence of El Niño-related signals (sea-surface temperature anomalies) in earth rotation variation in interannual band was investigated (Zhao and Han, 2008). Plumb line (vertical) variations of the order of 0.2-0.4" has been found in North China, which are caused by the underground matter changes before and after an earthquake, and can be determined by ground astrometric techniques. It hints that the new application of this classical technique is expectable (Li and Li, 2009). A GGOS/IAU joint Science workshop *Observing and Understanding Earth Rotation* was held during Oct. 25–28, 2010 at the Shanghai Astronomical Observatory, China. There were 70 participants and 53 presentations.

3.5. *Report of activities in the Czech Republic*

By *J. Vondrák*. Long-periodic variations of Earth's rotation and their correlations with different geophysical phenomena were studied, in cooperation with Ya. Chapanov, Bulgaria (Chapanov *et al.*, 2008, 2009, 2010a,b, 2011). New celestial reference frame, as defined by our new star catalogue EOC-4 (Vondrák and Štefka 2010, Vondrák *et al.* 2010a), was used to reduce anew the classical astrometric observations to derive the Earth orientation parameters in the 20th century (Vondrák *et al.* 2010b, 2011c). New model of precession, valid for very long time intervals (J2000.0 ± 200 millenia), was derived in cooperation with N. Capitaine (France) and P. Wallace (UK). Its accuracy is comparable to the one of the present IAU 2006 model in the interval ± several centuries around the central epoch, J2000.0, and it deteriorates to several arcminutes at both ends of the interval studied (Vondrák *et al.* 2009, 2011a, b). The influence of geophysical (namely atmospheric and oceanic) excitation on nutation, including the excitation of the

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Free Core Nutation, was studied (Vondrák 2009, Vondrák and Ron 2009, 2010, Ron and Vondrák 2011, Ron *et al.* 2011). The non-rigorous method of combining observations of Earth orientation parameters by modern space techniques (VLBI, GNSS, SLR) was further developed and improved (Štefka 2010, 2011, Štefka *et al.* 2009, 2010), so that also station coordinates are estimated.

3.6. *Report of activities in France*

By *C. Bizouard*.

1. Paris Observatory/SYRTE department

EOP Determination: The Paris Observatory/SYRTE department is in charge of the IERS Earth Orientation Center, which collects solutions of Earth Orientation Parameters (EOP) of many institutes, delivers them after validation in IERS format through WEB/FTP, and produces the reference EOP solution IERS CO4 by combination of EOP series. Important tasks within the last four years have been the development of web services for the distribution of the Earth orientation matrix and EOP (http://hpiers.obspm.fr:eop-pc, Bizouard and Becker 2008) and the implementation of the new combined EOP solution C04 consistent with the International Terrestrial Reference Frame 2008 (Bizouard and Gambis 2008, Gambis and Bizouard 2010). These service activities are complemented by the long term project of combination at observational level. In cooperation with laboratories of the GRGS (Groupe de Recherche de Géodésie Spatiale), the Paris Observatory produces an EOP multi-technique solution from VLBI, GPS, SLR and DORIS normal equations since 2010 (Biancale *et al.*, 2011). In order to validate this multi-technique solution, GRGS and other European organizations have initiated the international campaign 'COL' (Combination at the Observation Level). The IERS working group COL has been created, which regularly examines the achieved progress and problems to be solved during international workshops. The third COL workshop was organized by the Paris Observatory in November 2011. The determination of EOP is also performed from individual techniques. The IVS center managed by Sébastien Lambert (and Anne-Marie Gontier, deceased in 2010) delivers SINEX normal equations that are included in the IVS EOP combined solution. The department also gives attention to Lunar Laser Ranging observations, which may improve the knowledge of multi-year variations of the celestial pole offsets (Zerhouni and Capitaine 2009).

Fundamental Research: Astro-geodetic work is strongly reinforced by theoretical works and EOP analysis. They concern both long term astrometric modeling of the Earth rotation (Vondrák *et al.*, 2011b) and geophysical analysis of its irregularities: the interpretation of the polar motion in light of the hydro-meteorological excitation (Zotov and Bizouard 2011, Bizouard *et al.* 2011, Bizouard and Seoane 2009) also in link with gravimetric GRACE data (Seoane *et al.* 2009, Seoane *et al.* 2011) and the consideration of asymmetric effects in the pole tide excitation (Bizouard 2011).

2. Research activities in the field of Earth rotation at other French institutions

While Paris Observatory/SYRTE department is the French reference for Earth rotation studies, many other French institutes or organizations deal with this subject. Especially, many groups are involved in the treatment of space geodetic observations (VLBI, GPS, SLR, LLR, DORIS), in particular for determining ERP: Observatoire de la Cte d'Azur (OCA), Observatoire Midi-Pyrénées/CNES, French private firm CLS, Bordeaux Observatory, and Institut Géographique National (LAREG department). Most of these groups together with Paris Observatory are federated within GRGS. One also finds geophysical

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institutes or universities, where some colleagues develop theoretical aspects of the Earth rotation in the light of geophysical processes (e.g., M. Leftz and O. de Viron in the Institut de Physique du Globe de Paris, Y. Rogister in the Institut de Physique du Globe de Strasbourg, J. Laskar at Paris Observatory/IMCEE department).

3.7. *Research activities in the framework of the DFG-Research Unit FOR584/2 in Germany*

By *J. Müller*. For the integrated study of Earth rotation and related global dynamic processes, the joint research initiative *Earth Rotation and Global Dynamic Processes* with partners from Germany, Austria and Switzerland has now been working for more than 5 years. There, 10 inter-related sub-projects (with 12.5 co-workers from 11 universities and research institutions) are funded by the German Research Foundation (DFG). Goal was the consistent modelling, analysis and interpretation of all relevant features related to Earth rotation (observation techniques, data processing, the geophysical processes in the Earth system, etc.) covering all essential time scales. The inter-disciplinary research group comprises competences from geodesy, geophysics, meteorology and oceanography. The complete project with a funding line of 3 + 3 years started in 2006 and has now entered the last phase.

The scientific challenges (for each of them, one or more projects have been defined) have been:

- Relativistic modelling of rotation, better nutation theory
- Consistent modelling and interactions of geophysical fluids relevant for EOP research
- Un-explained signals in laser gyros + combination with other techniques
- Lunar Laser Ranging modelling/analysis insufficient
- Consistent combined processing and analysis (techniques and parameters)
- Close internal and external cooperation, sustainable data and EOP tools

Some highlights of the past research years were

- Extension of the post-Newtonian nutation/precession theory to a non-rigid earth
- Determination of long term EOP parameters (precession/nutation as well as trends in UT and polar motion) from the analysis of lunar laser ranging data
- Assimilation of Earth rotation and GRACE parameters into ocean models
- Improved forward modeling for core/mantle interaction (electromagnetic, topographic and gravitational coupling)
- Analysis of climate variability from fully coupled atmosphere-hydrosphere models and its influence on EOP, evaluation of NAO index values determined from various input quantities
- Inversion of a dynamic Earth system model for the estimation of physical Earth parameters from EOP, determination of Love number k2
- Analysis and interpretation of observations of ringlaser gyros (including sub-daily and episodic variations of Earth rotation, development of a 3-D FEM topographic model for surface deformation)
- Earth rotation parameters with hourly resolution estimated from the combination of VLBI and ring laser data
- Study on the impact of earthquakes on Earth rotation
- Simultaneous estimation of consistent high-quality time series of EOP and TRF parameters from integrated VLBI, SLR, and GNSS analysis

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• Combination of EOP and 2nd-degree harmonic gravity field coefficients for the separation of single mass contributions and motion effects as well as for mutual cross-validation

• Determination of tidal terms in diurnal and semi-diurnal polar motion and UT1 using VLBI and GPS

• Studying a possible coupling of non-linear changes of station coordinates into EOP

• Further development of the Earth Rotation Information System (ERIS) for providing EOP data, excitation functions, interactive analysis tools for Earth rotation studies

More information about the work of the research unit FOR584 and related publications can be found at its website www.erdrotation.de.

3.8. *Report of activities in the Space Research Centre of the Polish Academy of Sciences*

By *A. Brzeziński, J. Nastula, B. Kołaczek, M. Paśnicka, W. Kosek, M. Kalarus, T. Niedzielski and W. Popiński* Modeling perturbations in Earth rotation with subdaily to seasonal periods: We studied perturbations in Earth rotation caused by the influence of external fluid layers, the atmosphere, the oceans and the land hydrology, by using the available time series of the global angular momentum of those fluids, AAM, OAM and HAM, respectively. An important part of this work concerned the seasonal balance of excitation (Brzeziński *et al.*, 2009; Dobslaw *et al.*, 2010). A separate study had been devoted to the geophysical excitation of the free Chandler wobble (Brzeziński *et al.*, 2011). We also investigated the possibility of modeling and observation of the perturbations in Earth rotation having very short periods, daily and subdaily. The so-called complex demodulation technique (Brzeziński, 2011b) appeared to be very useful tool for studying such high frequency geophysical effects (Brzeziński, 2009; 2011a). In addition, we developed analytical model of the so-called libration in UT1/LOD, the semidiurnal variation due to the lunisolar torque on the triaxial figure the Earth (Brzeziński and Capitaine, 2010).

Research on the geophysical excitation function of polar motion: Contributions to polar motion excitation determined from HAM models and harmonic coefficients of the Earth gravity field obtained from GRACE mission were analyzed. These contributions are different for different HAM models. None of the HAM functions closes the excitation budget of polar motion (Brzeziński *et al.*, 2009; Nastula *et al.*, 2011a, 2011b; Seoane *et al.*, 2009a, 2009b, 2011). Geodetic residuals of polar motion excitation computed by removing the atmospheric and oceanic effects from geodetic determinations of polar motion are different for different ocean models. These differences are of the order of hydrological excitation of polar motion (several mas) and prove deficiencies of ocean models (Kołaczek *et al.*, 2012; Paśnicka *et al.*, 2012a). In addition regional variations of AAM, OAM and HAM (computed either from hydrological models or from gravimetric GRACE data) were computed and widely analyzed (Nastula *et al.*, 2009; Nastula and Salstein, 2011; Nastula *et al.*, 2012). Our attention was focused on two cases of regional distribution of OAM: in seasonal spectral band and in the wide band around the Chandler period.

Modeling, statistical analysis and prediction of Earth rotation: The EOP Prediction Comparison Campaign showed that ensemble prediction of pole coordinates data errors are less than the errors of the individual prediction techniques and the Kalman filter which involves short term prediction of axial component of the AAM is the most accurate prediction technique of UT1-UTC (Kalarus *et al.* 2010). The combination of the least squares and the multivariate autoregressive method involving axial component of the AAM was proposed to predict UT1-UTC (Niedzielski and Kosek 2011). It was found that pole coordinates data prediction errors are caused by wide band short period oscillations

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in joint ocean and atmospheric excitation functions (Kosek *et al.* 2009, Kosek 2010, 2011). Using semblance filtering the common oscillations were found in the geodetic and joint atmospheric-ocean excitation functions of polar motion (Kosek *et al.* 2011). The semblance showed that addition of the hydrology excitation function to the joint atmospheric-ocean excitation of polar motion improves the agreement of these functions in the annual frequency band (Kosek *et al.* 2011). The probability distribution of the EOP has also been studied (Niedzielski *et al.* 2009, Sen *et al.* 2009).

3.9. *Report of activities in Russia*

By *Z. Malkin*. Five institutes in Russia have been working on processing of space geodesy observations: Institute of Applied Astronomy, Institute of Astronomy, Institute of Time and Space Metrology (VNIIFTRI), Pulkovo Observatory, Sobolev Astronomical Institute (St. Petersburg State University), Sternberg Astronomical Institute (Moscow State University). Derived results are EOP , terrestrial and celestial reference frames, troposphere delays and geocenter motion. Most of the solutions are regularly submitted to IERS, IVS and IDS. More than 20 permanent VLBI, GPS and SLR stations are included in the IVS, IGS, EPN and IDS networks and used for derivation of IERS, IVS, IGS, EUREF, and IDS products and TRF densification. The Institute of Applied Astronomy started in regular (currently weekly) EOP determination on the Russian Quasar VLBI network (Finkelstein *et al.* 2011). Both Russian VLBI and GPS/GLONASS networks are used for EOP determination in the framework of the Russian State EOP Service (Kaufman and Pasynok 2010).

Several groups are working on investigation of Earth rotation variations at different time scales from intra-day to decadal and their geophysical causes. Akulenko *et al.* (2010, 2011) improved an Earth rotation model and used it to investigate the interconnection between fluctuations in the Atmospheric Angular Momentum and LOD variations, and improve the accuracy of interpolation and prediction of the Earth's axial rotation. Malkin and Miller (2010) and Miller (2011) investigated Chandler wobble variations using a 165-year IERS Polar motion series and a 170-year series of the Pulkovo latitude variations respectively. Gorshkov (2010) analyzed several EOP series to investigate LOD variations with periods of 2-7 years and their connection with various geophysical phenomena. Various aspects of improvement of Polar motion and UT1 predictions are discussed in Malkin (2010a) and Tissen *et al.* (2010). The accuracy of the celestial pole offset prediction has been assessed in Malkin (2010b). The impact of the Celestial Pole Offset modelling on the VLBI UT1 Intensive results was investigated in Malkin (2011a). Gubanov (2010) analyzed the Free Core Nutation period and amplitude variations. Malkin (2011b) estimated the impact of the Galactic aberration on precession and long-term nutation parameters derived from VLBI observations.

3.10. *Report of activities in United States of America*

By *R. Gross*. During the past triennium, investigations in the U.S. of the Earth's time varying rotation followed a number of themes, including theoretical studies (Gross, 2011), tidal variations (Gross, 2009a, 2009b, 2009c; Dickman, 2010; Dickman and Gross, 2010; Gross and Dickman, 2011), glacial isostatic adjustment (Matsuyama *et al.*, 2010; Mitrovica and Wahr, 2011), effects of global geophysical fluids (Dey and Dickman, 2010; Dickey *et al.*, 2010; Landerer *et al.*, 2009; Marcus *et al.*, 2010; Nastula *et al.*, 2009; Schindelegger *et al.*, 2011;), effects of earthquakes (Gross and Chao, 2010), effects of the core (Buffett, 2010a, 2010b; Buffett *et al.*, 2009; Dickey and de Viron, 2009; Dickey *et al.*, 2011), comparisons with gravity measurements (Cheng *et al.*, 2011; Gross *et al.*, 2009; Jin *et al.*, 2010, 2011), and improving predictions (Chin *et al.*, 2009; Gambis and Luzum, 2011;

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Gambis *et al.*, 2011; Kalarus *et al.*, 2010; Luzum, 2010; Luzum and Nothnagel, 2010). Attention has been given to the use of atmospheric models to investigate the changes in Earth rotation that might be expected due to climate variability and possible secular changes (Salstein *et al.*, 2011).

3.11. *Report of activities related to Earth rotation in the International Association of Geodesy (IAG)*

By *Z. Malkin*. IAG continued to develope the Global Geodetic Observing System (GGOS) to provide 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 integrating different techniques.

IAG Commission 1 *Reference Frames* coordinated, in particular, researches in several directions related to the investigation of the Earth rotation. Three sub-commissions participated in this activities are:

- SC 1.1 Coordination of Space Techniques (President M. Rothacher)
- SC 1.2 Global Reference Frames (President C. Boucher)
- SC 1.4 Interaction of Celestial and Terrestrial Reference Frames (President H. Schuh)

The most important IAG meetings held in 2009–2011 were:

- IAG General Assembly at the IUGG 2011, Melbourne, Australia, 28 June-7 July 2011. Three symposia at this meeting discussed various matters related to the Earth rotation and reference frames: JG05 Integrated Earth Observing Systems; G01 Reference Frames from Regional to Global Scales; G03 Monitoring and Modelling Earth Rotation.
- IAG Commission 1 Symposium 2010 on Reference Frames for Applications in Geosciences (REFAG2010), Marne-La-Vallee, France, 4–8 October 2010.

3.12. *Report of the International VLBI Service for Geodesy and Astrometry (IVS)*

By *H. Schuh*. The IVS continued to fulfill its role as a service within the IAU as well as within the IAG, International Association of Geodesy. A main task of the IVS is the provision of products for the Earth orientation parameters, in particular UT1 and precession/nutation, as well as for the realizations of the celestial reference system (by the ICRF-2, the International Celestial Reference Frame) and the terrestrial reference system (by the ITRF, the International Terrestrial Reference Frame). More details about the IVS and about VLBI2010, the next generation VLBI system, are given in the Report of IAU Division I and can also be found on http://ivscc.gsfc.nasa.gov.

3.13. *Report of the International Earth Rotation and Reference Systems Service (IERS)*

By *W. Dick and C. Ma*. The International Earth Rotation and Reference Systems Service continued to provide Earth orientation data, terrestrial and celestial references frames, as well as geophysical fluids data to the scientific and other communities. Work on new realizations of the International Terrestrial Reference System (ITRF2008) and the International Celestial Reference System (ICRF2) was finished. In 2009, Bulletin B was revised following a survey which was made among the community. In order to be consistent with ITRF2008, the IERS EOP C04 was revised again in 2011. The new solution 08 C04 is the reference solution which started on 1 February 2011. The system of the Bulletin A was changed to match the system of the new 08 C 04 series. The IERS Conventions (i.e. standards etc.) have been updated regularly; a new revised edition was published at the end of 2010. The Global Geophysical Fluids Centre (GGFC) restructured to allow for

the establishment of operational products. A new Working Group on Combination at the Observation Level was established in October 2009.

The following IERS publications and newsletters appeared between 2008 and 2011: A.L. Fey, D. Gordon, and C.S. Jacobs (eds.): The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, 2009 (IERS Technical Note No. 35); G. Petit and B. Luzum (eds.): IERS Conventions (2010), 2010 (IERS Technical Note No. 36); IERS Annual Report 2007; IERS Bulletin A, B, C, and D (weekly to half-yearly); IERS Messages Nos. 132 to 196. The central IERS web site www.iers.org and about 15 individual web sites of IERS components have been updated, improved and enlarged continually.

The following workshops were held, two partially co-organized with GGOS: IERS Workshop on EOP Combination and Prediction, Warsaw, Poland, 19–21 October 2009; Second GGOS Unified Analysis Workshop, San Francisco, CA, USA, 11–12 December 2009; Third GGOS Unified Analysis Workshop, Zurich, Switzerland, 16–17 September 2011. Abstracts and presentations of all these workshops are available at the IERS web site.

4. Closing remarks

The last three years have shown great progress in Earth rotation research in terms of quality of the observations (accuracy, time resolution, time from observation until results) as well as in modeling the causes of variations of Earth rotation and in prediction of the EOP. This interesting field of research interfacing astronomy and geodesy has provided extremely useful output for many related disciplines such as meteorology, climatology, oceanography and other Earth sciences. As it has also attracted many young scientists working on Earth rotation, an ongoing goal is to include this new generation of Earth rotation researchers in the activities of Commission 19.

Florian Seitz
Secretary of Commission 19

Harald Schuh
President of Commission 19

References

Akulenko L., Markov Yu., Perepelkin V., & Rykhlova L., 2010, *Astronomy Reports*, 54(3), 260
Akulenko L., Markov Yu., Perepelkin V., & Rykhlova L., 2011, *Astronomy Reports*, 55(9), 849
Biancale R., Gambis D., Richard J. Y., & Bizouard C., 2011, *IAG Symposia*, in pess.
Bizouard, C., 2011, *Proc. Journées 2011*, submitted
Bizouard C. & Becker O., 2008, *Proc. 5th IVS General Assembly*, 199
Bizouard, C. & Gambis, D., 2008, *IAG Symposia*, 134
Bizouard C., Rémus F., Lambert S., Seoane L., & Gambis D., 2011, *A&A*, 526, A106
Bizouard C. & Seoane L., 2010, *J. Geodesy*. 84, 19
Böhm S., Brzeziński, A., & Schuh, H., 2011, *J. Geodynamics*, in press
Brzeziński A., 2009, *Proc. Journées 2008*, 89
Brzeziński A., 2011a, *Proc. Journées 2010*, 131
Brzeziński A., 2011b, *J. Geodynamics*, in press
Brzeziński A., N. Capitaine, 2010, *Proc. IAU*, Vol. 5, H15, 217
Brzeziński A., H. Dobslaw, R. Dill, M., & Thomas M., 2011, *IAG Symposia*, 136, 497
Brzeziński A., J. Nastula, & B. Kolaczek, 2009, *J. Geodynamics*, 48, 235
Buffett, B., 2010a, *Nature*, 468, 952
Buffett, B., 2010b, *EPSL*, 296, 367
Buffett, B. A., J. Mound, & A. Jackson, 2009, *GJI*, 177, 878
Capitaine N., Mathews P. M., Dehant V., *et al.*, 2011, *Celest.Mech.Dyn.Astr.*, 103, 179

https://doi.org/10.1017/S1743921312002608 Published online by Cambridge University Press

Chapanov Ya., Vondrák J., & Ron C., 2008, *AIP Conference Proceedings*, 1043, 197
Chapanov Ya., Vondrák J., & Ron C., 2009, *Proc. Journées 2008*, 178
Chapanov Ya., Vondrák J., & Ron C., 2010a, *IAU Symposia*, 264, 407
Chapanov Ya., Vondrák J., & Ron C., 2011, *Proc. Journées 2010*, 149
Chapanov Ya., Vondrák J., Ron C., Štefka V., *et al.*, 2010b, *Akademperiodika*, 180
Chen, W. & W. Shen, 2010, *JGR*, 115, B12419
Chen, W., W. Shen, & J. Han, 2009, *Surv. Geophys.*, 30, 39
Cheng, M.-K., J. C. Ries, & B. D. Tapley, 2011, *JGR*, 116, B01409
Chin, T., R. Gross, D. Boggs, & J. Ratcliff, 2009, *Interplanetary Network Progr. Rep., 42-176*, JPL
Correia A., Levrard B., & Laskar J., 2008 *A&A* 488, L63
Dey, N. & S. R. Dickman, 20, *JGR*, 115, C09016
Dickey, J. O. & O. de Viron, 2009, *GRL*., 36, L15302
Dickey, J. O., S. L. Marcus, & O. de Viron, 2010, *GRL*, 37, L03307
Dickey, J. O., S. L. Marcus, & O. de Viron, 2011, *J. Climate*, 24, 569
Dickman, S. R., 2010, *JGR*, 115, B12407
Dickman, S. R., & R. S. Gross, 2010, *J. Geodesy*, 84, 457
Dobslaw H., R. Dill, A. Grötzsch, A. Brzeziński, & M. Thomas, 2010, *JGR*, 115, B10406
Finkelstein A., Salnikov A., Ipatov A., *et al.*, 2011, *Proc. 20th Meeting of the EVGA*, 82
Gambis D. & C. Bizouard, 2010, *Highlights of Astronomy*, 15, 207
Gambis, D. & B. Luzum, 2011, *Metrologia*, 48(4), 165
Gambis, D., D. A. Salstein, & S. Lambert, 2011, *J. Geod.*, 85, 435
Göttl, F. & Seitz, F., 2008, *IAG Symposia*, 133, 439
Gorshkov V. L., 2010, *Solar System Research*, 44(6), 487
Govind, R., F. Lemoine, J. Valette, D. Chinn, & N. Zelensky, 2010, *Adv. Space Res.*, 46, 1593
Gross, R. S., 2009a, *J. Geodyn.*, 48, 219
Gross, R. S., 2009b, *J. Geodesy*, 83(7), 635
Gross, R. S., 2009c, *Proc. Journées 2008*, 95
Gross, R. S., 2011, *IAG Symposia*, 137, in press
Gross, R. S. & B. F. Chao, 2010, *IAG Symposia*, 135, 643
Gross, R. S. & S. R. Dickman, 2011, *Proc. Journées 2010*, in press
Gross, R. S., D. A. Lavallee, G. Blewitt, & P. J. Clarke, 2008, *IAG Symposia*, 133, 463
Gubanov V. S., 2010, *Astronomy Letters*, 36(6), 444
Hense, A.; Sündermann, J.; Drewes, H. *et al.*, 2009, *German Geodetic Commission*, B317
Huang C. L., Dehant V., Liao X. H., Van Hoolst T., & Rochester M. G., 2011, *JGR*, 116, B03403
Huang C. L. & Liu Y., 2011, *Proc. IUGG GA*, submitted
Jin, S., D. P. Chambers, & B. D. Tapley, 2010, *JGR*, 115, B02403
Jin, S., L. J. Zhang, & B. D. Tapley, 2011, *GJI*, 184, 651
Kalarus, M., H. Schuh, W. Kosek, *et al.*, 2010, *J. Geodesy*, 84, 587
Karatekin Ö., de Viron O., Lambert S., *et al.*, 2011, *Planet. Space Sci.*, 59(10), 923
Kaufman M. & Pasynok S., 2010, *Artificial Satellites*, 45(2), 81
Kołaczek B., Paśnicka M., & Nastula J., 2012, *Proc. Journées 2011*, submitted
Koot, L. & Dumberry M., 2011 *EPSL*, 308(3-4), 343
Koot L., Dumberry M., Rivoldini A., de Viron O., & Dehant V., 2010, *GJI*, 182(3), 1279
Koot, L., Rivoldini A., de Viron O., & Dehant V., 2008, *JGR*, 113, B08414
Kosek, W., 2010, *Proc. 6th Orlov Conference*, 96
Kosek, W., 2011, *IAG Symposia*, 136, 511
Kosek W., Popiński W., & Niedzielski T., 2011, *Proc. Journées 2010* ,168
Kosek, W., Rzeszótko A., & Popiński W., 2009, *Proc. Journées 2008*, 168
Kudryashova, M., Lambert, S., Dehant, V., Bruyninx, C., *et al.*, 2011, *Proc. Journées 2010*, 202
Lambert, S., Dehant, V., & Gontier, A.-M., 2009, *A&A*, 481(2), 535
Landerer, F. W., J. H. Jungclaus, & J. Marotzke, 2009, *GRL*, 36, L17603
Li, Z. X. & Li, H. , 2009, *Studia Geophysica et Geodaetica*, 53(2), 185
Liao, D. C., Wang, Q. J., Zhou, Y. H., Liao, X. H., & Huang C. L., 2011, *J. Geodyn.*, submitted

Luzum, B., 2010, *Artificial Satellites*, 45(2), 107
Luzum, B. & A. Nothnagel,, 2010, *J. Geodesy*, 84, 399
Malkin Z., 2010a, *Artificial Satellites*, 45(2), 87
Malkin Z, 2010b, *Astronomy Reports*, 54(11), 1053
Malkin Z., 2011a, *J. Geodesy*, 85(9), 617
Malkin Z., 2011b, *Astronomy Reports*, 55(9), 810
Malkin Z. & Miller N., 2010, *Earth Planets Space*, 62(12), 943
Marcus, S. L., O. de Viron, & J. O. Dickey, 2010, *JGR*, 115, B12409
Maslennikov K., A. Boldycheva, Z. Malkin, & O. Titov, 2010, *Astrophysics*, 53, 147
Matsuyama, I., J. X. Mitrovica, A. Daradich, & N. Gomez, 2010, *JGR*, 115, B05401
Miller N., 2010, *Solar System Research*, 45(4), 342
Mitrovica, J. X., & J. Wahr, 2011, *Ann. Rev. Earth Planet. Sciences*, 39, 577
Mocquet, A., Rosenblatt, P., Dehant, V., & Verhoeven, O., 2011, *Planet. Space Sci.*, 59(10), 1048
Nastula, J., Gross, R., & Salstein, D., 2012, *J. Geodynamics*, submitted.
Nastula, J., Paśnicka, M., & Kołaczek B., 2011a, *Acta Geophysica*, 59(3), 561
Nastula, J., Paśnicka, M., & Kołaczek, B., 2011b, *Proc. Journées 2010*, 165
Nastula, J. & Salstein, D., 2011, *IAG Symposia*, 136
Nastula, J., D. Salstein, & B. Kołaczek, 2009, *JGR*, 114, B04407
Niedzielski, T. & Kosek, W., 2011, *IAG Symposia*, 137, 153
Niedzielski, T., Sen, A. K., & Kosek, W., 2009, *Artificial Satellites*, 44, 33
Nilsson, T., Böhm J., & Schuh, H., 2010, *Artificial Satellites*, 45(2), 49
Nilsson, T., Böhm J., & Schuh, H., 2011a, *J. Geodynamics*, submitted
Nilsson, T., Böhm J., & Schuh, H., 2011b, *Proc. Journées 2010*, 176
Paśnicka, M., Nastula, J., & Kołaczek, B., 2012, *J. Geodynamics*, submitted.
Ron, C. & Vondrák, J., 2011, *Acta Geodyn. Geomat.*, 8(3), 243
Ron, C., Vondrák, J., & Štefka, V., 2011, *Proc. Journées 2010*, 221
Salstein, D., K. Quinn, & R. Abarca del Rio, 2011, *EGU Research Abstracts*, EGU2011-5270-1
Schindelegger, M., Böhm, J., Salstein, D., & Schuh, H., 2011a, *J. Geodesy*, 85(7), 425
Schindelegger, M., Böhm, J., Schuh, H., & Salstein,, 2011b, *Proc. Journées 2010*, 180
Schuh, H. & Böhm, S., 2011, Earth Rotation, in: *Encyclopedia of Solid Earth Geophysics*, 1, 123
Seitz, F. & Drewes, H., 2009, *Proc. Journées 2008*, 123
Seitz, F., Kirschner, S., & Neubersch, D., 2012, *IAG Symposia*, Proc. QuGOMS'11, in press.
Seitz, F. & Schuh, H., 2010, Earth Rotation, in: *Sciences of Geodesy I*, 185
Seitz, F., Schuh, H., & Müller, J. *et al.*, 2010, *IAU Transactions B*, XXVIIB, 137
Sen A. K., Niedzielski T., & Kosek, W., 2009, *Proc. Journées 2008*, 105
Seoane, L., Nastula, J., Bizouard, C., & Gambis, D., 2009a, *GJI*, 178, 614
Seoane, L., Nastula, J., Bizouard, C., & Gambis, D., 2009b, *Proc. Journées 2008*, 149
Seoane, L., Nastula, J., Bizouard, C., & Gambis, D., 2011, *Int. J. Geophys.*, doi:10.1155/2011/174396.
Shen, W. B., Sun, R., & Chen, W, *et al.*, 2011, *Ann. Geophys.*, 54(4), 436
Štefka, V., 2010, *Acta Geodyn. Geomater.*, 7(3), 275
Štefka, V., 2011, *Acta Geodyn. Geomater.*, 8(3), 237
Štefka, V., Kostelecký, J., & Pešek, I., 2009, *Acta Geodyn. Geomater.*, 6(3), 239
Štefka V., Pešek I., Vondrák J., & Kostelecký J., 2010, *Acta Geodyn. Geomat.*, 7(1), 29
Tissen V. , Tolstikov A., Balahnenko A., & Malkin Z., 2010, *Artificial Satellites*, 45(2), 111
Titov, O., D. Jauncey, H. Johnston, R. Hunstead, & L. Christensen, 2011, *AJ*, 142, 165
Titov, O., S. Lambert, & A.-M. Gontier, 2011, *A&A*, 529, A91
Titov, O. & Z. Malkin, 2009, *A&A*, 506, 1477
Verhoeven, O., Mocquet, A., Vacher, P., Rivoldini, A., *et al.*, 2009, *JGR*, 114(B3), B03302
Vondrák, J., 2009, *Proc. VI Serbian-Bulgarian Astronomical Conference*, 9, 143
Vondrák, J., Capitaine, N., & Wallace, P., 2009, *Proc. Journées 2008*, 23
Vondrák, J., Capitaine, N., & Wallace, P., 2011a, *Proc. Journées 2010*, 24

Vondrák, J., Capitaine, N., & Wallace P., 2011b, *A&A*, 534, A22
Vondrák J. & Ron C., 2009, *Acta Geodyn. Geomat.*, 6(3), 217
Vondrák, J. & Ron C., 2010, *Acta Geodyn. Geomat.*, 7(1), 19
Vondrák, J., Ron, C., & Štefka, V., 2010b, *Acta Geodyn. Geomat.*, 7(3), 245
Vondrák, J., Ron, C., Štefka, V., & Chapanov, Ya., 2011c, *Proc. VII Bulg.-Serb. Astr. Conf.*, subm.
Vondrák, J. & Štefka, V., 2010, *Astron. Astrophys.*, 509, A3
Vondrák, J., Štefka, V., & Ron, C., 2010a, *Proc. 6th Orlov Conference*, 64
Wang, Q. J., Liao, D. C., Zhou, Y. H., & Liao, X. H., 2008a, *Chin Astron. Astrophys.*, 32, 342
Wang, Q. J., Liao, D. C., & Zhou, Y. H., 2008b, *Chinese Science Bulletin*, 53(7), 969
Winkelnkemper, T., Seitz, F., Min, S.-K., & Hense, A., 2008, *IAG Symposia*, 133, 447
Xu, X. Q. & Zhou, Y. H., 2010, *J. Spacecraft TT&C Tech.*, 29, 70
Zerhouni, W. & Capitaine N., 2009, *A&A* 507, 1687
Zhang, X. H., Wang, Q. J., & Zhu, J. J., 2011, *Chin Astron. Astrophys.*, in press
Zhao, J. & Han, Y. B., 2008, *Pure & Applied Geophys.*, 165(7), 1435
Zhou, Y. H., Chen, J. L., & Salstein, D. A., 2008, *GJI*, 174, 453
Zotov, L. & Bizouard, C., 2011, *J. Geodymics*, in pess