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COMMISSION 19 ROTATION OF THE EARTH

ROTATION DE LA TERRE

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TRIENNIAL REPORT 2006–2009

1. Introduction

The Commission supports and coordinates scientific investigations in the Earth rotation and related reference frames. Several changes had been introduced to the structure of Commission 19 since the IAU XXVI General Assembly in Prague, 2006. The Organizing Committee of Commission 19 has been substantially reduced. It consists now of six ex-officio members, the Commission president, vice-president, past president and representatives from the International Association of Geodesy (IAG), International Earth Rotation and Reference Systems Service (IERS), International VLBI Service for Geodesy and Astrometry (IVS), and five members at-large who are nominated by the OC, selected by the Commission members and elected by the IAU GA for a maximum of two terms. The modified terms of reference of Commission 19, the list of members and other details can be found at the Commission website <iau-comm19.cbk.waw.pl/>.

A brief description of the most important developments in the related field is given in Section 2, while Sections 3 - 5 contain the reports of cooperating services/institutions. The list of references comprise only the most important papers which have been cited in the report; an extended list of references provided by the members of Commission 19 will be posted at the Commission website.

2. Developments within the past triennium

The activities related to Commission 19 are mostly developed in the different institutions, at scientific meetings and in the WGs of Division I. The most important developments are described below.

(1) Establishment of the Global Geodetic Observing System (GGOS):
An important part of GGOS is related to the activity of Commission 19 and much has been done already in this field; for details see <www.ggos.org> and <geodesy.unr.edu/ggos/ggos2020/>.

(2) Developments of the observation techniques:

Ring laser gyroscope: an advantage of this emerging technique is that a single instrument is capable to determine the polar motion of the instantaneous rotation axis. However, the measurements are still not stable over periods longer than a few days. Therefore only the diurnal and subdiurnal variations can be estimated. Further progress has been attained in the analysis and interpretation of the ring laser measurements made in Wettzell.
VLBI 2010: a new VLBI system based on small antennas (10–12 m diameter) has been proposed by the IVS WG3. The following three performance goals have been identified: a) accuracies of 1 mm for site position and below 1 mm/year for velocity (TRF); b) continuous measurement of EOP; c) rapid generation and distribution of the IVS products.

(3) *GRACE*:
The *GRACE* observations allow the determination of the excitation functions, derived from changes in the gravity field. Such excitation functions can be compared with those derived from individual geophysical fluids, and also with the geodetically-determined polar motion excitations. The utility of *GRACE* fields in measuring polar motion excitation is now comparable to what can be obtained directly from the geophysical fluids.

(4) Development of the global circulation models of geophysical fluids:
Progress has been attained in modeling the atmospheric circulation (e.g., new re-analysis model ERA40; experimental models with hourly resolution) and the land hydrology (several new models become available, including those based on *GRACE* data).

(5) Reference frames and EOP:
The implementation of the IAU 2006 Resolutions related to Earth's orientation and reference systems has been prepared. IAU 2006 Resolution B1 adopted the P03 precession model as a replacement to the precession part of the IAU 2000A precession-nutation in order to be consistent with both dynamical theories and the IAU 2000 nutation (Hilton *et al.* 2006). EOP series have been reprocessed since 1984. Pole coordinates are now fully consistent with ITRF2005. The nutation offsets and UT1 are made consistent with the International Celestial Reference Frame (ICRF) through the IVS combined solution. Working groups have been established by the IAU, IERS and IVS with the goal of presenting the second realization of the ICRF at the IAU General Assembly in 2009.

(6) IERS Conventions:
Much has been done in order to present a consistent set of the IERS Conventions, in agreement with the current state of knowledge, and to have it actually put into practice by analysis centers. The IERS Conventions Center has worked on updating the IERS Conventions (2003), since 2005 with the help of an Advisory Board on IERS Conventions Update. A workshop on the IERS Conventions has been organized at the BIPM in September 2007.

(7) EOP predictions:
Predictions of the EOP are necessary for practical use, e.g., in space navigation. Currently, predictions of EOP are provided by the IERS Rapid Service/Prediction Center for Earth Orientation Parameters. The EOP Prediction Comparison Campaign has been organized between July 2005 an March 2008. The results have been presented at several international meetings including EGU General Assemblies 2007 and 2008, Journees 2007 and AGU Fall Meeting 2007, and will be published in *Journal of Geodesy*; see `<www.cbk.waw.pl/EOP_PCC/` for details. Another organization involved in the improvement of the EOP predictions is the IERS Working Group on Prediction.

Two important review of works on Earth rotation variations were published in 2007 in *Treatise of Geophysics, Vol.3: Geodesy, Elsevier*, Chapter 3.11 – Long Period Variations by R. Gross, and Chapter 3.12 – Nearly Diurnal Variations by V. Dehant and P. Mathews.

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3. Report of IERS (compiled by the IERS Central Bureau)

3.1. *Publications, websites, and workshops*

The following IERS publications and newsletters appeared between 2005 and 2008: J. Souchay and M. Feissel-Vernier (eds.), The International Celestial Reference System and Frame, 2006 (IERS Technical Note No. 34); IERS Annual Reports 2004, 2005, and 2006; IERS Bulletin A, B, C, and D (weekly to half-yearly); IERS Messages Nos. 76 to 131; ITRF Mail Nos. 63 to 76.

A new IERS Data and Information System (DIS) at the website `<www.iers.org>`, maintained by the Central Bureau, is running in operational mode since the end of 2005. It presents information related to the IERS and the topics of Earth rotation and reference systems. It provides tools for searching within the products (data and publications), working with the products and downloading them. The DIS provides also links to other servers, including about 20 websites run by other IERS components.

The following IERS Workshops were held: Combination, Potsdam, Germany, October 2005; Global Geophysical Fluids, San Francisco, USA, December 2006; Conventions, Sèvres, France, September 2007. The IERS also organized two GGOS Unified Analysis Workshops, at Monterey, USA, December 2007, and Vienna, Austria, April 2008. Abstracts and presentations of all these workshops are available at the IERS website.

3.2. *Activities of the IERS components*

From 2005 to 2008, the IERS Directing Board met twice each year. Summaries of the meetings are available in the Annual Reports and at the IERS website.

The Central Bureau concentrated its work on the development of the IERS Data and Information System. It also coordinated the work of the Directing Board and the IERS in general, organized workshops and issued publications.

The work of the Analysis Coordinator and of the Working Group on Combination focused on coordinating the Combination Pilot Project (CPP) for the generation of weekly inter-technique combination products, mainly EOP. Version 2.02 of the SINEX data format was developed. The major achievement of the CPP is that each of the Technique Centres (IGS, ILRS, IVS, except IDS) provides a combined solution based on the weekly SINEX files of the individual analysis centres on a routine basis.

The Rapid Service/Prediction Centre is responsible for providing Earth orientation parameters on a rapid turnaround basis and does so through the IERS Bulletin A and data sets made available through its website and ftp areas. For more information see report 5.12 below.

The IERS further increased the quality of their time series of Earth Orientation Parameters. Bulletin B and C04 series were recomputed and aligned to the EOP solution associated to the ITRF2005, resulting in the new EOP 05 C04 series. The system of Bulletin A was changed to match the system of this new series.

In October 2006, the ITRS Centre released the new ITRF2005 based on time series of station positions and Earth Orientation Parameters (Altamimi *et al.*, 2007).

Involvement by ICRS Centre personnel in the celestial reference frame VLBI program has continued, increasing the number of observations of ICRF quasars in the southern celestial hemisphere and continuing an extensive observing program in the northern hemisphere. This observing program will eventually result in a new realization of the ICRS, tentatively called ICRF 2 (see also the reports of Commission 8 and WG ICRF-2).

The Conventions Centre has made several modifications to the Conventions through the Conventions update web page including a complete rewrite of Chapter 9 (Tropospheric Model). Other chapters have been revised to make them more consistent with

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current IAU recommendations. A Conventions Workshop was held in September 2007 to prepare a new edition, expected to be produced in 2009.

The eight Special Bureaus of the Global Geophysical Fluids Centre provide data sets reflecting the mass transport of geophysical fluids, which are important for Earth rotation studies. A plan for improving the GGFC data and activities is being developed.

The activities of the ITRS Combination Centres at DGFI and at IGN concentrated on the computations for the ITRF2005 and on its evaluation. For information regarding the work of the Combination Research Centres see the reports 5.1, 5.5 and 5.11 below.

Three new working groups (WG on Prediction, WG on Site Survey and Co-location, IERS/IVS WG on the Second Realization of the ICRF) were established to support the work of the IERS product centres.

3.3. *Report of IVS (compiled by IVS Coordinating Center)*

The IVS continued to fulfill its role as a service within the IAU by providing necessary products for the densification and maintenance of the celestial reference frame as well as for the monitoring of Earth orientation parameters, in particular UT1 and nutation, with two 24-hr sessions per week.

UT1 Intensive measurements are continued on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA) and on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan). In August 2007 a third Intensive series (Int3) started to fill the 36-hour gap in the data series between Int1 and Int2.

The VLBI 2010 Committee was formed to work on designing and implementing the next generation VLBI system. In November 2007 the first fringes were found with proof-of-concept hardware installed at the Goddard Geophysical and Astronomical Observatory.

For the second half of August 2008 a continuous VLBI campaign (CONT08) is being organized that will have 15 days of continuous observations on an 11-station network. With a recording rate of 512 Mbps and a time period that avoids the transitional months of March and October, CONT08 is expected to yield a high signal level in the atmospheric excitation functions for high temporal resolution Earth rotation investigations.

4. **Report of SOFA** (chair: Patrick Wallace)

The SOFA Review Board provides an authoritative set of fundamental-astronomy algorithms through a website (<www.iau-sofa.rl.ac.uk>) hosted by the UK Hydrographic Office and operated by Her Majesty's Nautical Almanac Office. SOFA's third issue of software was made in August 2007; it contained 161 Fortran routines (an increase of 40), including definitive implementations of the IAU 2006 precession models and related items, plus a 38-page explanatory document covering the Earth attitude algorithms. A fourth issue occurred in March 2008, comprising minor corrections and improvements. A second implementation of SOFA, this time using the C programming language, was completed in June 2008 and is being prepared for release. The Fortran SOFA already has some users in the aerospace industry, and the new C version is likely to increase interest. SOFA is increasingly coordinating its work with the IERS Conventions effort, with the object of eliminating unnecessary overlaps and evolving common standards.

5. Report of the individual institutions and national projects

5.1. *SYRTE Department of Paris Observatory*

Implementation of the IAU 2006 Resolutions: Various ways of forming the IAU 2000/2006 precession-nutation matrix have been discussed by Capitaine & Wallace (2006) and the corresponding precession-nutation procedures have been provided by Wallace & Capitaine (2006). Simplified implementations have also been proposed (Capitaine & Wallace 2008); these offer different compromises between size and precision and take advantage of the use of the celestial coordinates of the CIP instead of using the nutation angles in longitude and obliquity. The 'IAU 2006 Glossary' produced by the IAU WG on 'Nomenclature for Fundamental astronomy' (Capitaine *et al.* 2008a) was made available on the WG website (<syrte.obspm.fr/iauWGnfa>) providing the definitions corresponding to the IAU 2000 Resolutions and IAU 2006 Resolutions B1, B2 and B3. This includes, in particular the appropriate terminology for the pole, the Earth's angle of rotation, the longitude origins and the related reference systems and corresponding time scales.

Comparison between models and observations for the celestial motion of the CIP: A comparative study by Souchay *et al.* (2007) discussed the differences between the rigid Earth theory (REN 2000), the non-rigid Earth nutation theory (MHB 2000), and observational data. A detailed consideration by Mathews *et al.* (2007) of the ERA-2005 precession-nutation model that G. Krasinsky presented at the IAU 2006 General Assembly (JD16) made clear the fundamental differences in the main features of the IAU and the ERA-2005 precession-nutation models. This study showed severe deficiencies in the ERA-2005 model that were confirmed by Capitaine *et al.* (2008b) through further comparisons between the models as well as with the most recent VLBI observations.

The first step of the Descartes-nutation project devoted to the integration of the rotational equations developed as functions of the X, Y coordinates of the CIP in the geocentric celestial reference system (GCRS) were completed (Capitaine *et al.*, 2006) and the second step was started. A method has been developed by Zerhouni *et al.* (2008) for determining the GCRS CIP coordinates from the high accuracy LLR measurements over a 20-yr period.

Earth Rotation and geophysical excitation: Different studies have been conducted within the Earth orientation and Space geodesy group of the SYRTE Department, to study the relationship between the Earth rotation parameters (ERP) and the geophysical phenomena that affect Earth rotation. These concern the effects of the geophysical external fluids (Gambis *et al.* 2008; Seoane *et al.* 2008) and internal parts (Varga *et al.* 2007). Other effects include the solar activity (Chapanov & Gambis 2008). Observation of ERP are now available with an increased accuracy, i.e., 40 microarcseconds for pole components and 3 microseconds for UT1.

Journées 2007 on space and time reference systems: The Journées 2007 organized at Paris Observatory with the sub-title 'The Celestial Reference Frame for the future' included several sessions devoted to Earth rotation and reference systems.

5.2. *Royal Observatory of Belgium*

General objectives: The objectives of the work are to better understand and model the Earth rotation and orientation variations, and to study physical properties of the Earth's interior and the interaction between the solid Earth and the geophysical fluids. It is based on theoretical developments and on the analysis of data from Earth rotation monitoring and general circulation models of the atmosphere, ocean, and hydrosphere. We worked on the improvement of VLBI observations as well as of analytical and numerical Earth rotation models. The angular momentum budget of the complex system composed of the

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solid Earth, the core, the atmosphere, the ocean, the cryosphere, and the hydrosphere was studied, in order to better understand the dynamics of all components of Earth orientation.

Theory: We demonstrated that the contributions of Poisson terms in the tidal potential to long-periodic nutations are small but significant at the microarcsecond level and that the liquid core has an important contribution in that effect (Folgueira *et al.* 2007); (2) we computed the second-order torque on the tidal redistribution and the Earth's rotation (see Lambert and Mathews 2007); (3) we studied the electromagnetic coupling at the core-mantle boundary and its effects on the tides and nutation, using numerical integration; (4) we established an analytical method to compute the topographic coupling at the core-mantle boundary and its effects on nutations; (5) we showed that the atmosphere could globally excite the FCN but the atmospheric data could not reproduce the exact time variability of its amplitude (Lambert 2006); we estimated the time variable amplitude of the FCN from VLBI data and proposed our model for the IERS Conventions.

Observations and data interpretation: (6) precise VLBI-only EOP and reference frames determination is routinely done in collaboration with the Paris Observatory IVS Analysis Center; (7) analyzing VLBI data, we studied the influence of the analysis strategy on Earth EOP determination and showed that this can reach a few tens of microarcseconds in nutation amplitudes (Lambert *et al.*, 2008, Lambert and Dehant V., 2007); (8) we showed that using GPS-based determinations of the VLBI station positions could improve the determination of VLBI-only Earth rotation parameters; (9) we estimated time variable amplitude of FCN from VLBI data; our model showed that the atmosphere could globally excite the FCN; (10) using a Bayesian approach and VLBI observations in time domain, we estimated the limits within which the geophysical parameters may be expected to change, and to which extent the inner core parameters and precession may vary (Koot *et al.*, 2006 and 2008); we showed that the errors of the adopted parameter values were underestimated; (11) we estimated the FCN free mode and showed that both results are coherent; (12) we analyzed polar motion when the two main oscillations canceled each other (from November 2005 till February 2006); we explained the small centimeter level loops by atmospheric and oceanic contributions (Lambert *et al.*, 2006).

5.3. *Research unit 'Earth rotation and global dynamic processes' in Germany (chair: Jürgen Müller)*

In order to organize joint research activities in 'Earth rotation and global dynamic processes' in Germany, since the beginning of 2006 ten related sub-projects are supported by the German research funding organization DFG (Deutsche Forschungsgemeinschaft) in the frame of a research unit (Müller *et al.* 2005). Based on the general survey of Schuh *et al.* (2003), the main objective of this coordinated project is a comprehensive description and explanation of underlying physical phenomena contributing to variations of Earth rotation. Such an integral treatment of Earth rotation became possible by combining experts of observational techniques, data processing and analysis as well as in particular modelling. The research unit with participating scientists and institutions from geodesy, geophysics, meteorology, and oceanography will provide significant contributions to international programs such as GGOS and GMES (Global Monitoring for Environment and Security).

In close cooperation with the research unit a complex Earth system model is developed in a research project supported by DFG. The dynamical system model couples numerical models of the atmosphere, of ocean tides and circulation as well as of continental discharge considering consistent mass, energy and momentum fluxes between these near-surface subsystems of the Earth in order to allow for explanations and interpretations of geodetically observed variations of global parameters of the Earth. More information on the DFG Research Unit FOR584 can be obtained from `www.erdrotation.de`.

5.4. *Space Research Centre of the Polish Academy of Sciences*

Atmospheric and oceanic excitation of Earth rotation (Aleksander Brzeziński). A successful attempt has been made to retrieve the diurnal and semidiurnal components of polar motion and UT1 from analysis of the routine observations by VLBI (Brzeziński & Bolotin 2006). These components are expressed by a time series beginning in 1984, which can be interpreted by comparison with geophysical determinations of the excitation functions. Brzeziński (2007) developed and implemented the computational algorithm of the so-called geodetic excitation of nutation based on VLBI observations. Korbacz *et al.* (2008) performed detailed analysis of the new high resolution atmospheric and oceanic angular momentum data (AAM – from ERA40 reanalysis project, OAM – Ocean Model for Circulation and Tides forced with ERA-40 data). They estimated the corresponding perturbations in EOP and compared them to earlier results based on different AAM and OAM data sets. A separate part of this analysis was devoted to the atmospheric thermal tide S1 occurring at exactly the frequency of 1 cycle per solar day (Brzeziński, 2008).

Geophysical excitation functions of polar motion (Barbara Kołaczek & Jolanta Nastula). Gravimetric polar motion excitation functions computed from the data derived from the Gravity Recovery and Climate Experiment (GRACE) differ from the mass terms of geodetic observations and from the geophysical excitation functions of polar motion of seasonal time scales up to 20 mas. Thus gravimetric excitation functions need further improvements for studies of polar motion (Nastula *et al.* 2007; Nastula *et al.* 2008). Hydrological excitations of polar motion are not able to explain the residual excitations. The differences between amplitudes of the seasonal oscillations of hydrological excitation of the polar motion computed from various hydrological models are of the order of 5 mas (Nastula *et al.* 2006; Nastula *et al.* 2008). Study of the regional patterns of atmospheric variability was continued in a fine-resolution network of sectors over an extended 60-yr period at annual time scales. (Salstein & Nastula 2006). Spectral characteristic of polar motion along loops during 2005 - 2006 and 1999 - 2000 were studied by Nastula & Kołaczek (2007).

Modeling and prediction of the Earth Orientation Parameters (Wieslaw Kosek). The time frequency analyses methods were used to detect wideband oscillations in the EOP data, which were then used to construct the EOP model data. Prediction of such a model reveals the influence of the most energetic oscillations on the forecast errors of the EOP data (Kosek *et al.* 2006; 2008). The mean prediction errors for various prediction algorithms and techniques were calculated during the Earth Orientation Parameters Prediction Comparison Campaign (Kalarus *et al.* 2008). The combination of least-squares extrapolation and univariate or multivariate autoregressive prediction was used to predict UT1-UTC (Niedzielski & Kosek 2007) as well as local and global sea level anomaly data from TOPEX/Poseidon and Jason-1 altimetry (Niedzielski & Kosek 2005).

5.5. *Astronomical Institute, Academy of Sciences of the Czech Republic and Faculty of Civil Engineering, Czech Technical University, Prague*

The new combined astrometric catalogue EOC-3 (Earth Orientation Catalogue) has been provided by the combination of astrometric observations of latitude/universal time with astrometric catalogues (ARIHIP, TYCHO-2). The new catalog contains also quasi-periodic terms reflecting orbital motion of stars (Vondrák & Štefka 2007). The new solution of EOP from optical astrometry in 1899.7 - 1992.0 in the system of this new

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catalogue was derived by Vondrák *et al.* (2008). The atmospheric and oceanic excitation of free core nutation, the stability of its period and the quality factor were studied by Vondrák & Ron (2006, 2007, 2008).

A method of non-rigorous combination of different techniques to obtain simultaneously station coordinates and Earth orientation parameters was developed and tested. Basically, three approaches were studied - the short-term, e.g., monthly, and the long-term combinations (Pešek & Kostelecký 2006a), and, as a response to a call for producing weekly combinations, the method of non-rigorous combination was slightly modified to produce such very short-term solutions (Pešek & Kostelecký 2006b). We also started to use the new constraints to ensure the continuity and smoothness of EOP of the non-rigorous combination (Štefka & Pešek 2007; Štefka *et al.* 2008). A more effective algorithm for sparse systems from the GNU Gama package (`<www.gnu.org/software/gama>`) was implemented, decreasing the necessary computation time by one order. Other information on our activities is available at the web pages of the Center for Earth Dynamics Research (`<pecny.asu.cas.cz/cedr¿`), joining five Czech institutions active in astronomy and geosciences research.

5.6. *Institute of Geodesy and Geophysics (IGG) of the Vienna University of Technology*

One main research area at IGG focuses on sub-daily and episodic variations of Earth rotation. Hourly polar motion and universal time was estimated in an optimal and consistent manner from Very Long Baseline Interferometry (VLBI) observations (Englich *et al.* 2008) and compared with results obtained from GPS. So far, no significant signal could be seen at the terdiurnal band. The relative Sagnac frequency variation of a new emerging technology, the ring laser gyroscope, was investigated for sub-daily signals of Earth rotation (Mendes Cerveira *et al.* 2008b). As it is envisaged to combine high-resolution ring laser data with VLBI observations, the ring laser gyroscope theory was carefully investigated (Mendes Cerveira *et al.* 2008a).

Uncertainties of the atmospheric excitation of Earth rotation were evaluated w.r.t. the diverse possible calculation options. Forecast data of the ECMWF was used to increase the temporal resolution (Boehm *et al.* 2008). The largest uncertainty arises from the adopted numerical weather model itself. An investigation was conducted on the improvement of a combination of nutation rates from GPS and GLONASS with nutation offsets from VLBI (Kudryashova *et al.* 2008). The potential benefit of including the future European satellite system GALILEO was studied, too.

5.7. *Central Astronomical Observatory at Pulkovo RAS (Pulkovo Observatory)*

The following topics were investigated: determination of the EOP from VLBI observations; Free Core Nutation (Malkin 2007; Malkin & Miller 2007); connection of the Earth rotation with other geophysical phenomena (Gorshkov 2007); assessment and improvement of the celestial reference frame (Sokolova & Malkin 2007; Malkin 2008). An IVS Analysis Center PUL was organized in 2006. Related info and results can also be found at `<www.gao.spb.ru/english/as/ac_vlbi/>`. A permanent GPS station PULK has been included in the EPN network and is used for the EOP determination in the Russian State EOP Service (in cooperation with NAVGEOCOM, Moscow). Group members participated in the several Working Groups of IAG, IERS and IVS.

5.8. *Institute of Applied Astronomy of the Russian Academy of Sciences (IAA)*

During the last three years IAA has continued to support the EOP Service including daily processing of VLBI, SLR and GPS observations. The CONT05 VLBI data have been analyzed to determine subdiurnal variations of EOP and other parameters (Finkelstein

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et al. 2006). Significant improvements to the AC software were maid. A new version of the VLBI data processing software QUASAR (Gubanov *et al.* 2007) is now used for global EOP + TRF + CRF solutions on regular basis. Quasar VLBI Network observations are processed to support GLONASS (Finkelstein *et al.* 2007). The period and phase of FCN data obtained from VLBI observations have been analyzed (Gubanov 2008). The analysis of radio source position time series has been performed in the framework of the IVS WG on ICRF (Kurdubov & Skurikhina 2008). The secular decrease of the Earth's dynamical ellipticity has been derived from the analysis of VLBI data (Krasinsky 2008).

5.9. *Sternberg Astronomical Institute of Moscow State University, Moscow*

A new program package ARIADNA for processing VLBI observations has been developed and tested. It is planned that beginning in July 2008 it will be used for the processing of VLBI observations. Research continued on the modeling VLBI delay both for ground and space-ground interferometers (Radioastron mission). This package was used to improve the data set of stable and potentially stable sources for the next radio ICRF. The theory of apparent motion of the 'stable' radio sources, based on the analysis of VLBI-derived time series of their coordinates, was developed. A new approach for the realization of the new radio ICRF was developed.

Five new GPS/GLONASS stationary points have been installed (two in Moscow and three in the North Caucasus region). GPS/GLONASS data are used both for monitoring the point motions and EOP estimation.

5.10. *Universities of Alicante and Valladolid, Spain*

The groups of the universities of Alicante and Valladolid (Spain) continued investigating the accurate modeling of the non-rigid Earth rotation. The efforts were focused on extending the analytical Hamiltonian theory up to the second order, both in the sense of perturbation theory and in the case of contributions previously disregarded. Some examples are illustrated in (Ferrándiz *et al.* 2007) and (Escapa *et al.* 2008). In addition, we participated in the IAU Division I WG on *Precession and the Ecliptic* (Hilton *et al.* 2006).

Theoretical studies on the rotation of other celestial bodies of the Solar System (Moon, Mercury, etc.) and on some fundamentals of the rotational motion have been initiated (e.g., Efroimsky & Escapa 2007; Ferrándiz & Barkin 2007; Barkin & Ferrándiz 2006), often in cooperation with scientists from other centers such as National Aeronautics and Space Administration (USA), National Astronomical Observatory of Japan, US Naval Observatory (USA), Royal Observatory of Belgium and Sternberg Astronomical Institute. (Russia).

These investigations have been partially supported by Spanish projects AYA2004-07970, AYA2007-67546, *Junta de Castilla y León* project VA070A07, and also by the Descartes Prize Nutation consortium.

5.11. *Jet Propulsion Laboratory (JPL), USA*

JPL continued to investigate Earth orientation variations including their excitation by earthquakes (Gross and Chao 2006), by atmospheric winds (Dickey *et al.* 2007; Gross *et al.* 2008a), and by ocean tides (Gross, 2008). The consistency of Earth orientation, gravity, and shape measurements was evaluated by comparing them both with each other and with models of surface geophysical fluids (Gross *et al.* 2008b). A review of the theory of Earth orientation variations, the techniques used to measure them, and their causative mechanisms was published (Gross 2007a). JPL also continued to support tracking and navigation of interplanetary spacecraft by acquiring and reducing VLBI, GPS and LLR data and by using a Kalman filter to both combine these with other Earth orientation measurements in order to produce optimal estimates of past variations in the Earth's orientation and to predict its future evolution (Gross 2007b).

5.12. *U.S. Naval Observatory (USNO), USA*

The USNO serves the community as: the IERS Rapid Service/ Prediction Center; the co-host of the IERS Conventions Center along with the Bureau International des Poids et Mesures; the co-host of the IERS ICRS Center along with the Paris Observatory; a VLBI Correlator Center, an Operations Center, an Analysis Center and Analysis Center for Source Structure for the IVS; and an Analysis Center for the IGS. USNO has improved the quality of its EOP combination by using improved data sets and reducing the smoothing applied to the data. The predictions have been improved by using a new polar motion prediction algorithm and improved AAM forecasts. USNO is preparing for the upcoming release of the next registered edition of the IERS Conventions, anticipated to be released in the next year. The VLBI correlator is undergoing a modernization of the control computer and the addition of playback units which promises to improve the processing of large VLBI sessions. USNO also plays a significant role in the generation of the ICRF-2. The quality of the USNO GPS solutions has improved through the use of better antenna phase center models.

5.13. *National Geospatial-Intelligence Agency (NGA), Basic and Applied Research Office, USA*

Several research efforts have been initiated to improve Earth Orientation (EO) prediction. A new research project was begun with the Naval Research Laboratory to improve the atmospheric and oceanic model data available for EO research. This effort is focused on improving our understanding of excitation mechanisms of polar motion and length of day variations and on advancing techniques used for the prediction of EO parameters. This has resulted in an improved understanding of the angular momentum transfers between the atmosphere, oceans, and land, and how these interactions affect the excitation of high frequency polar motion (Johnson 2008). Currently, NGA's University Research Initiative (NURI) grant program is sponsoring academic research projects to improve atmospheric data products and prediction methods available for near real-time EO predictions. T. Johnson, formerly at the USNO, is now a project scientist in the NGA, coordinating these efforts.

5.14. *Related researches in China*

National Astronomical Observatory of China (NAOC) and National University of San Juan of Argentina (NUSJ) set up a cooperative 60 cm SLR station (ID 7406) in San Juan. It has started routine observations from the beginning of 2006, and contributes to the ITRF, etc. The daytime tracking function and a co-located GPS station will be realized. In the NAOC group, the secular variation of the Earth's rotation is studied using ancient astronomical observations (Li, 2006), while the variation of the vertical is also studied using observations of time and latitude (Han *et al.* 2007; Ma 2007).

Shanghai Astronomical Observatory (SHAO): an artificial neural networks (ANN) method has been applied to predict EOPs (x, y & LOD). An operational prediction series of the AAM has been incorporated into the ANN model as an additional input in the real time prediction of the LOD, and the results show that the LOD prediction is significantly improved in comparison with that obtained by using LOD data only (Wang *et al.* 2008). The coupling between the magnetic field near the core-mantle-boundary and Earth nutation is discussed in a numerical integration approach, and it is shown that the

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effect is one order of magnitude smaller than the gap of the out-of-phase part of the −1.0-year nutation between the observations and theoretical nutation models (Huang *et al.* 2007). The free oscillations of a 12-layers Earth model with rotation is studied by the Galerkin method, while boundary conditions are treated with the Tau method. It is shown that the Galerkin method is an alternative tool for such a study (Zhang *et al.* 2008). A new integrated formula to obtain the equilibrium figures of the Earth's interior to third-order accuracy has been developed, in which both the direct and indirect contribution of the anti-symmetric crust layer are included, i.e., all non-zero order and odd degree terms are included. Using this new potential theory and replacing the homogeneous outermost crust and oceanic layers in PREM with various real surface layers data, the global dynamic flattening (H) is obtained and it is shown that the 1% difference between H-PREM and H-obs can be removed by 2/3 (Liu & Huang 2008).

Wuhan Institute for Geodesy and Geophysics(WHIGG): the correlation between DLOD and ENSO is studied, and it is shown that the maximum appears around three-five-year timescales; weak correlation exists around the biennial timescales (Liu *et al.* 2005). The concept of the normal Morlet wavelet transform (NMWT) is developed and applied to polar motion (PM), and finds that the ocean always offsets the atmospheric effects on annual PM and that the observed Chandler wobble has only one instantaneous frequency all the time. (Liu *et al.* 2008).

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