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DIVISION I FUNDAMENTAL ASTRONOMY

ASTRONOMIE FONDAMENTALE

Division I provides a focus for astronomers studying a wide range of problems related to fundamental physical phenomena such as time, the inertial reference frame, positions and proper motions of celestial objects, and precise dynamical computation of the motions of bodies in stellar or planetary systems in the Universe.

DIVISION I COMMISSIONS

Commission 4	**Ephemerides**
Commission 7	**Celestial Mechanics and Dynamical Astronomy**
Commission 8	**Astrometry**
Commission 19	**Rotation of the Earth**
Commission 31	**Time**
Commission 52	**Relativity in Fundamental Astronomy**

DIVISION I WORKING GROUPS

Division I WG	**Nomenclature for Fundamental Astronomy,**
Division I WG	**Astrometry by Small Ground-Based Telescopes**
Division I WG	**Natural Satellites**
Division I WG	**Standards of Fundamental Astronomy (SOFA)**

INTER-DIVISION WORKING GROUPS

Division I-III WG	**Cartographic Coordinates and Rotational Elements**
Division I-III WG	**Natural Satellites**

TRIENNIAL REPORT 2009–2012

1. Introduction

The goal of the division is to address the scientific issues that were developed at the 2009 IAU General Assembly in Rio de Janeiro. These are:

- •Astronomical constants
  - —Gaussian gravitational constant, Astronomical Unit, GM_{Sun}, geodesic precession-nutation

•Astronomical software
•Solar System Ephemerides
—Pulsar research
—Comparison of dynamical reference frames
•Future Optical Reference Frame
•Future Radio Reference Frame
•Exoplanets
—Detection
—Dynamics
•Predictions of Earth orientation
•Units of measurements for astronomical quantities in relativistic context
•Astronomical units in the relativistic framework
•Time-dependent ecliptic in the GCRS
•Asteroid masses
•Review of space missions
•Detection of gravitational waves
•VLBI on the Moon
•Real time electronic access to UT1-UTC

In pursuit of these goals Division I members have made significant scientific and organizational progress, and are organizing a Joint Discussion on *Space-Time Reference Systems for Future Research* at the 2012 IAU General Assembly. The details of Division activities and references are provided in the individual Commission and Working Group reports in this volume. A comprehensive list of references related to the work of the Division is available at the IAU Division I website at http://maia.usno.navy.mil/iaudiv1/.

2. Developments within the past triennium

The Journées 2010 meeting "New challenges for reference systems and numerical standards in astronomy" (http://syrte.obspm.fr/journees2010/)organized by the Paris Observatory and co-sponsored by the IAU was held September 2010, in Meudon, France. Among the topics was new information on the latest fundamental solar system ephemerides from JPL (Pasadena), IMCCE (Paris), and IAA (St. Petersburg). Links to all three ephemerides can be found at the Commission 4 web site.

The Journées 2011 meeting "Earth rotation, reference systems and celestial mechanics: Synergies of geodesy and astronomy" (http://info.tuwien.ac.at/hg/meetings/journees11/), organized by the Technical University of Vienna and co-sponsored by the IAU was held in September, 2011 in Vienna, Austria. It focused on issues related to recent developments in fundamental astronomy, time and relativity, plans for the next generation of space-time reference systems, astronomical space and time reference systems, Earth rotation and global geodynamics, celestial mechanics of solar system bodies, space observations and dedicated missions for geodesy and astronomy.

Thanks to a joint initiative by members of the Working Group on Astrometry by Small Ground Based Telescopes and astronomers from France (IMCCE), Turkey (Tubitak Obs.), Ukraine (Nikolaev Obs.) and China (Shanghai Obs. and Jinan Univ. of Guangzhou), a Summer School on Astrometry was held in Antalya (Turkey), on September 5-9, 2011. The purpose was to encourage students to do research in astrometry and to study new astrometric methods. Nineteen students and young astronomers attended lectures and

observing sessions. A workshop "Astrometry Now and in the Future" was organized at the end of the school.

2.1. *Science*

Members of Commission 4 continued their work in the computation of fundamental solar system ephemerides and practical astronomical data, including geocentric and topocentric coordinates of stars and solar system objects; the prediction of astronomical phenomena, parameters describing the apparent orientation and illumination of solar system objects; and various quantities used to transform directions among standard reference systems. The Commission established a Working Group on Standardizing Access to Ephemerides. It is to provide guidance on a consistent format for ephemerides of solar system bodies for the astronomical community. The working group has tentatively decided to recommend the Spacecraft and Planetary Kernal (SPK) file format used in the SPICE Library written and maintained by the Navigation and Ancillary Information Facility (NAIF) of the Jet Propulsion Laboratory, but this depends on NAIF providing a detailed specification of those portions of the format needed for the ephemerides and a standalone routine for reading SPK files.

There is some uncertainty in how almanac-producing institutions will respond to a possible change in the definition of Coordinated Universal Time (UTC)if approved by the International Telecommunications Union in 2012. While this would not represent a major obstacle to Commission 4 affiliated institutions, it would require decisions on providing data to users in the future. Also, institutions computing fundamental solar system ephemerides will have to respond to the potential change in the definition of the astronomical unit.

Members of Commission 7 produced papers considering methods of determining orbital class and degree of chaos. Most are based on the calculation of the Lyapunov characteristic exponents and their derivatives. The role of chaotic orbits in the evolution and dynamics of spheroids was considered in several papers. Work was also done to establish the influence of chaos, and in particular of 'sticky' or 'confined' orbits, on galactic structures. Manifolds, linked to the unstable periodic orbits around the L1 (L2) Lagrange points are proposed to explain both the spirals and the rings in barred galaxies.

The chaotic behavior of planetary orbits in the Solar System was discovered using numerical integration of averaged equations of motion. This chaotic behavior manifests itself in an exponential divergence of nearby trajectories, which limits the validity of the solutions to less than 100 Myr. A numerical integration of the Solar System motion over 5 Gyr can only be considered as a random sample of its possible evolution and statistical studies are required. The search for the best solution for the Earth's orbit over millions of years is motivated by the possibility of calibrating recent geological timescales by correlating the geological stratigraphic data to the computed variation of the insolation on Earth.

Around 1% of solar-type stars host Jupiter-mass planets with the semimajor axis a less than 0.1 AU. It is thought that these so-called *hot Jupiters*, did not form *in situ* because the region within 0.1 AU was too hot and rarefied for a Jupiter-mass planet to form. Instead, they probably formed several AU from their host stars, and later migrated inward due to their interaction with the protoplanetary gas disk from which they formed.

The ICRF2 containing accurate positions of 3414 compact, extragalactic radio sources on the system of the original ICRF was adopted by the IAU in 2009 as the new fundamental celestial reference frame. It has a noise floor of $\sim$40 μas, some 5-6 times better

than ICRF, and an axis stability of $\sim$10 μas, nearly twice as stable as ICRF. Alignment of ICRF2 with the International Celestial Reference System (ICRS) was made using 138 stable sources common to both ICRF2 and ICRF-Ext2. The UCAC project concluded with the publication of its 4th data release (all-sky, over 100 million stars). IAU Commission 8 (Astrometry) also reports that the astrometric satellite Gaia which is expected to achieve parallax accuracies of about 10 to 300 μas for 6 to 20 mag. is scheduled to be launched in 2013. The JASMINE (Japan Astrometry Satellite Mission for Infrared Exploration) project proposes to launch three satellites [Nano-JASMINE, Small-JASMINE and (Medium-sized) JASMINE. It willl launch the Nano-JASMINE satellite in 2012 and continue development of its other satellites which will complement the Gaia project. The Joint Institute for VLBI in Europe (JIVE), in cooperation with the European VLBI Network (EVN), EC FP7 EuroPlaNet and ESPaCE and other partners, continued developing VLBI applications for ultra-precise tracking of planetary and other space science missions. Its high accuracy enables multi-disciplinary applications including celestial mechanics and astrometry of the Solar System, fundamental physics and studies of interiors and atmospheres of planets. In the reporting period, the activities focused on the Planetary Radio Interferometry and Doppler Experiment (PRIDE)

The WG on Natural Planetary Satellites encouraged the making of astrometric observations of all planetary satellites. A campaign of observations of the mutual events of the main satellites of Jupiter and Saturn has been made in 2009. These photometric observations provide highly accurate astrometric positions. The WG encouraged also progress in astrometric reductions in order to prepare for the arrival of the Gaia star catalogue. The International Occultation Timing Association (IOTA) reports that over the reporting period some 400 high-precision relative astrometric positions of asteroids derived from occultation observations were reported to the Minor Planet Centre. Over the reporting period, profiles with a resolution of a few km were obtained for about 35 asteroids. This included the binary asteroid 90 Antiope, where the profiles of both components were well-resolved. Occultation results have been combined with light curve inversion models to obtain scaled 3-D models of 44 asteroids. All observations are archived with NASA's Planetary Data System (http://sbn.psi.edu/pds/resource/occ.html).

During the past triennium a new Commission 19 website was established providing the Commission's terms of reference, membership directory,information on upcoming scientific meeting and the history of the Commission. Three 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 in 2009; (2) an IERS workshop on "EOP Combination and Prediction' was held in Warsaw, Poland in 2009; and (3) a joint GGOS / IAU Commission 19 workshop on "Observing and Understanding Earth Rotation' was held in Shanghai, China in 2010. The proceedings of all of these meetings are to be published.

The proposal to eliminate leap seconds from Coordinated Universal Time (UTC) continues under discussion. Commission 31 members contributed to the discussion by the International Telecommunications Union Radiocommunications Section (ITU-R). Working Party 7A (Time Signals and Frequency Standard Emissions) of ITU-R met in Geneva on 5-11 October, 2010. During this meeting the possible revision of ITU-R Recommendation TF 460-6 to abolish leap seconds was discussed. Prior to this meeting, the IAU was requested to report on whether or not it supported this proposal. A poll of Commission 31 members especially requesting input from those opposed to the recommendation resulted in three opposing responses. Responses supporting the recommendation were

also received. Based on this and other input from IAU members, the IAU submitted a document to the ITU-R supporting the proposed change. The proposed revision of Recommendation ITU-R.460-6 is to be sent to the Radio Assembly which will meet in Geneva in January 2012. A vote will take place during that meeting, and at least 70% of the votes are required for the approval. The IAU is a recognized international organization in the ITU and is not a Member State. Only Member States have the right to vote.

Commission 52 considered units of measurements for astronomical quantities in a relativistic context leading to the proposed redefinition of the astronomical unit in meters and abandoning the system of astronomical constants based on the Gaussian gravitational constant k. Members also reviewed or developed models for space applications such as Gaia and Lunar Laser Ranging and worked on improving the relativistic formulations and semantics of the 2010 edition of the IERS Conventions.

The Standards of Fundamental Astronomy (SOFA) Center made available its 8th release of software. It includes 18 new routines in the Time Scales section of the Astronomy Library and three new routines in the Operations on Angles section of the Vector Matrix Library for both the Fortran 77 and ANSI C releases. A new cookbook, Time Scale and Calendar Tools, has also been made available in separate versions for Fortran and C users, with common text and appropriately tailored examples. Over 500 people have registered for e-mail updates. An article about SOFA, may be found at http://www.scholarpedia.org/article/Standards_of_Fundamental_Astronomy. SOFA, which stands for Standards of Fundamental Astronomy, is a service operated by IAU Division I to provide authoritative fundamental-astronomy algorithms. To do this SOFA is made up of the SOFA Board, an international panel that reports through Commission 19 (Rotation of the Earth), the software (algorithms) the SOFA Collection and lastly the SOFA Centre, the website that is the public interface to SOFA that makes the software freely available. The SOFA Collection now contains 186 routines provided in Fortran 77 and ANSI C, while the latest Cookbook is tailored so that the content is identical but the examples are pertinent to the particular programming language.The SOFA Centre makes the software and documentation (including all previous releases) available for viewing and downloading. A major upgrade to this website occurred in January 2010, when a new URL (www.iausofa.org) was acquired that is independent of location.

The Working Group (WG) on Numerical Standards for Fundamental Astronomy has expanded its web pages to document ongoing efforts. A report on that work was published in Celestial Mechanics and Dynamical Astronomy summarizing the numerical values for the constants and providing the justification for the values chosen. Members are drafting procedures to adopt new Current Best Estimates and is beginning to test these procedures on a suggested new value for the mass of Mercury. The Working Group members participated in the drafting of a proposed IAU Recommendation on the definition of the astronomical unit.

The Working Group on Astrometry by Small Ground Based Telescopes continues to update and maintain information on astrometric programs and activities carried out by small telescopes through web pages and e-mails and to facilitate the coordination of activities from ground-based telescopes. Its scientific goals are to foster the follow-up of small bodies detected by the large surveys; to set up a dedicated observation network for the follow-up of objects which will be detected by Gaia; to contribute to the observation campaigns of the mutual events of natural satellites, stellar occultations, and binary asteroids and to contribute to some large astrometric studies of stars or other astrophysical objects. The fundamental purpose is to identify and coordinate the

astrometric activities well adapted to telescopes with diameter less than 2 m. In addition to these activities, the WG has the important role to encourage teaching of astrometry and to prepare the next generation for the new astrometry challenges.

The WG on Natural Satellites continued to maintain ephemerides of all planetary satellites at www.imcce.fr/sat and at lnfm1.sai.msu.ru/neb/nss/nssephme.htm. Through an astrometric database and these ephemerides, observed positions of the giant planets may be deduced from satellites observations. Satellites ephemerides are also provided by JPL at ssd.jpl.nasa.gov and by the MPC for the irregular satellites of the giant planets at cfa-www.harvard.edu/iau/NatSats/NaturalSatellites.html The WG on Natural Planetary Satellites encouraged studies on the dynamics of the natural satellites systems. Progress has been made for the theoretical modeling of the motions of the main satellites of Jupiter and Saturn by including tidal effects, introducing constraints on the internal structures. A campaign of observations of the mutual events of the main satellites of Jupiter and Saturn was made in 2009. These photometric observations provide highly accurate astrometric positions.

The IAU Working Group on Cartographic Coordinates and Rotational Elements published its triennial (2009) report containing current recommendations for models for solar system bodies. It introduced improved values for the pole and rotation rate of Mercury, returned the rotation rate of Jupiter to a previous value, introduced improved values for the rotation of five satellites of Saturn, and added the equatorial radius of the Sun for comparison purposes. It also adds or updates size and shape information for the Earth, Mars satellites, the four Galilean satellites of Jupiter, and 22 satellites of Saturn. Pole, rotation, and size information has been added for various solar system objects. The high precision realization for the pole and rotation rate of the Moon is also updated. The WG adopted the IAU Working Group for Planetary System Nomenclature (WGPSN) and the IAU Committee on Small Body Nomenclature (CSBN) definition of dwarf planets. As a result, Pluto and Charon now use the positive right handed coordinate system adopted for dwarf planets, minor planets, their satellites, and comets. The Working Group is considering providing limited updates to its recommendations on its web site(http://astrogeology.usgs.gov/Projects/WGCCRE). This will not remove the need for triennial reports, and in the next report the usefulness of these interim procedures will be considered.

The WG also provided general recommendations regarding urgent needs relating to the development of planetary cartographic products. These include planning and funding geodetically controlled cartographic products, updating the Mars orientation model, and resolving various determinations for the rotation of Jupiter and Saturn. In its next report, to be completed at the Working Group meeting at the IAU General Assembly in Beijing in 2012, the WG anticipates using an improved lunar ephemeris to define the Moon's orientation, and updates due to new results from on-going space Missions and Earth-based observations. The Working Group is also looking into establishing or reestablishing links to organizations, such as the International Association of Geodesy and the International Society for Photogrammetry and Remote Sensing.

The International VLBI Service for Geodesy and Astrometry (IVS) continued to provide products for the densification and maintenance of the celestial reference frame as well as for monitoring Earth orientation parameters (EOP). It held two General Meetings, one in Hobart, Tasmania, Australia in February 2010 and the other in Madrid, Spain in March 2012. Further, two Technical Operations Workshops were held at MIT Haystack Observatory in Westford, MA in April 2009 and May 2011, respectively. Another important

meeting was the VLBI2010 Workshop on Technical Specifications in Bad Ktzting, Germany in March 2012.

As an activity for the International Year of Astronomy 2009, the IVS organized a very large astrometry session. On 18/19 November 2009, thirty-four VLBI antennas observed the largest astrometry session ever scheduled. The previous record was 23 stations in a single session. The scientific goals of this session were to strengthen the ICRF2 by observing as many ICRF2 defining sources as possible in one single session and to provide the arc lengths between all sources without relying on source overlaps. The session was accompanied by press releases through the IYA09 (IAU), IVS, and other organizations and open doors at the participating stations. It resulted in news coverage in regional and national media. Further, the Bordeaux group created a dynamic Web page which allowed interested people to watch the progress of the session via the Internet in real time. The response to the Web page was very positive with about 1000 users during the session; hence, it was decided to extend this service to the entire IVS observing program. More information on IYA09 is available at http://ivscc.gsfc.nasa.gov/program/iya09/.

In September 2011, a 15-day continuous VLBI observation campaign called CONT11 was observed. The network consisted of thirteen IVS stations, nine in the northern hemisphere and four in the southern hemisphere, giving the best geographical distribution and coverage in the series of CONT campaigns.

IVS Live is a generalized version of the IYA09 dynamic Web site, developed to provide easy access to the entire IVS observing plan. It has grown into a new tool that can be used to follow the observing sessions organized by the IVS, navigate through past or coming sessions, or search and display specific information related to sessions, sources (especially the most recent VLBI images) and stations. The IVS Live user interface and all its functionalities are accessible at the URL: http://ivslive.obs.u-bordeaux1.fr/.

The current VLBI system (S/X system, legacy system) was conceived and constructed in the 1960s and 1970s. Aging antennas, increasing radio frequency interference (RFI) problems, obsolete electronics, and high operating costs make it increasingly difficult to sustain the current level of accuracy, reliability, and timeliness. Recognizing these shortcomings, the IVS has been developing the next generation VLBI system, commonly known as the VLBI2010 system. It is envisaged that the VLBI2010 system will replace the current S/X system in the next several years. In 2009, a progress report outlined recommendations for the next generation system in terms of systems, analysis, operations, and network configuration. Currently two complete VLBI2010 signal paths have been completed and data are being produced. A VLBI2010 Project Executive Group (V2PEG) has been created to provide strategic leadership. A number of VLBI2010 projects are underway; several antennas have been erected and construction of about ten antennas is at various stages of completion. The next generation IVS network is growing, with an operational core of stations becoming available within the next few years, plus further growth continuing into the foreseeable future.

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 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 IERS web site www.iers.org and about 15 individual web sites of IERS components were updated. The following workshops were held, partially co-organized with GGOS: IERS Workshop on EOP Combination and Prediction, Warsaw, Poland, October 2009; Second GGOS Unified Analysis Workshop, San Francisco, CA, USA, December 2009; Third GGOS Unified Analysis Workshop, Zurich, Switzerland, September 2011. Abstracts and presentations of all these workshops are available at the IERS web site.

2.2. *Organization*

All Division I Commissions have reviewed and updated their terms of reference.

Patrick Wallace (RAL, UK), the Chair of SOFA for over 15 years, has stepped down, but remains a member of the Board. Division I acknowledges his leadership over SOFA's first fifteen years, and the huge contribution that he has made and is still making to SOFA and to the wider astronomical community. Catherine Hohenkerk (HMNAO, UK) was elected by the Board as Chair in 2010.

The subcommittee on Division I structure discussed the possible creation of Working Groups on Extrasolar Planets and Near-Earth Objects. As a proposal is currently in circulation regarding possible changes in divisional structure including the formation of a Commission on Extrasolar Planets and since it appears that this will be discussed at length in the near future the subcommittee made no recommendations pending the outcome of the IAU Executive Committee meeting. Potential changes in the names of commissions 19, 31 and 52 were also discussed but no action was recommended by the subcommittee.

The co-affiliation of Commission 7 with Division III while retaining its affiliation with Division I was proposed and officially supported by the Division I Organizing Committee. Consent by Division III is expected.

IAU Division I is proposing that the IAU consider modifying existing statutes, bye-laws and working rules to allow Divisions to create two new organizational elements within the current Divisional structure. These would be designated "Services" and "Standing Committees." A Service would be a quasi-permanent organization created to provide well-defined products, such as data or software, to the astronomical community. A Standing Committee would be organized to provide specific specialized information, such as adopted values of astronomical quantities, to the astronomical community. It would be composed of a limited number of subject-matter experts and instituted by the Division Organizing Committee. Specifically, IAU Division I proposes that the IAU Executive Committee create a committee to draft the appropriate changes to the existing IAU statutes, bye-laws and working rules to permit the existence of these organizational elements within Divisions for consideration at the next General Assembly. If the Division I proposal to change the IAU rules is not accepted by the IAU Executive Committee. IAU Division I would propose to change the name of Commission 4 to "Ephemerides and Astronomical Constants." Also, an initiative for the Asteroid Dynamic Site (AstDyS) to become a permanent IAU service was proposed in response to this broader initiative.

Dennis D. McCarthy
president of the Division