IAU Commission 4 - 2006 Business Meeting
XXVIth IAU General Assembly, August 2006

COMMISSION 4 **EPHEMERIDES**
(EPHEMERIDES)

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PROCEEDINGS BUSINESS SESSIONS, August 24, 2006

1. Introduction

This business meeting was held from 16:00 to 17:30. Toshio Fukushima and George Kaplan were welcomed as the next President and vice-President, respectively.

The following full reports are given by Thuillot (2 pages), Institut de Mécanique Céleste et de Calcul des Éphémérides, Bangert (1 page), of United States Naval Observatory, Krasinsky (3 pages) of Institute of Applied Astronomy and Bell (1 page) HM Nautical Almanac Office.

A summary of these four reports are published in Transactions IAU, Volume XXVIB, edited by K.A. van der Hucht.

2. Institut de Mécanique Céleste et de Calcul des Éphémérides

2.1. *Recent developments and new ephemerides at IMCCE*

The Institut de mécanique céleste et de calcul des éphémérides (IMCCE), formerly "Service des calculs et de mécanique céleste du Bureau des Longitudes", is an institute of the Paris Observatory since 1998. It is in charge of computing the official French ephemerides on behalf of the Bureau des Longitudes. Therefore, besides scientific research in the domains of theoretical celestial mechanics, astrometry and planetology, the teams of IMCCE perform activities in dynamics and applied celestial mechanics with the goal to provide accurate ephemerides.

2.2. *The new dynamical models*

At IMCCE, during the last years, several new dynamical models have been developed. VSOP planetary ephemerides (Variations Séculaires des Orbites Planétaires) initially developed by Bretagnon (Moisson and Bretagnon, 2001) have been improved by Fienga and Simon (2005) who developed a new version VSPO2002b and applied it to a study of the perturbations on inner planets by the asteroids. A new numerical planetary ephemeris named INPOP (Intégration Numérique Planétaire de l'Observatoire de Paris) has also been undertaken (Fienga et al. 2006).

New dynamical models of several planetary satellites systems have been formed. The motion of the Galilean satellites has been modeled by Lainey et al. (2004a, 2004b, 2006). This model is achieved by the recomposition of quasi-periodic Fourier series obtained from a frequency analysis coupled with digital filtering treatments, which has lead to a new ephemeris named L1. The same algorithm labeled NOE (Numerical Orbit and ephemerides) has been also applied to obtain new ephemerides of the Martian satellites (NOE-4-06) and for the Uranian satellites (NOE-7-06). This last model has been used to predict the mutual events of the Uranian satellites (Arlot et al. 2006). A collaboration with the Sternberg State Astronomical Institute of Moscow led to the development of the dynamical modelling of ninety six outer satellites of Jupiter, Saturn, Uranus and Neptune which are progressively used to provide ephemerides (Emelyanov et al 2006).

A new dynamical and physical model of the meteoritic streams (Vaubaillon et al. 2005a, 2005b) has been applied to different specific studies and to the prediction of the meteoritic showers.

2.3. *Ephemerides books*

IMCCE provides yearly ephemerides on behalf of Bureau des Longitudes. Several books related to various Solar System objects and at different levels of accuracy are published.

The ephemerides of high precision titled *Connaissance des temps* has been transformed and revitalized. Since 2003, half of the volume contains scientific texts about constants, timescale, reference systems and transformations of coordinates. The IAU 2000 precession and IAU 2000A nutation models have been considered. Furthermore, IAU recommendations have been taken into account and the values of the variables related to the new reference system concepts are given: Earth rotation angle, equation of the origins, Celestial Intermediate Pole coordinates, angle s. It still gives ephemerides for the Sun, the Moon, the planets, sidereal time, nutations, but the paper ephemerides give only values in tables. Since 2005, the Chebychev coefficients no longer appear in this book but are used by the accompanying software on a CDROM to get accurate positional ephemerides. The positional ephemerides of the main planetary satellites are given through this software, and only the values of differential coordinates at the nearest hour close to the elongations are given in the book, in order to allow for identification of objects. Furthermore the topocentric coordinates, rises and sets are also computable with this software.

A second yearly book is titled *Guide de données astronomiques - Annuaire du Bureau des Longitudes*. These ephemerides provide medium precision data. Data for the Sun, the Moon, the planets are given, but also ephemerides for bright comets and asteroids, stellar occultations by the asteroids and the Moon, phenomena of the Galilean satellites and other various phenomena. Since 2003, a scientific booklet is included in this book. Each year, a new topic is described by some specialists, for example the 2007 edition will treat the new equatorial origin by N. Capitaine and B. Guinot.

Three booklets are published to supplement the main ephemerides *Connaissance des temps* and are guides for observers. They are titled *Suppléments à la Connaissance des temps* and concern the natural satellites. The first one gives graphic configurations and dates of the phenomena of the Galilean satellites. The second one gives the graphic configurations of the first eight satellites of Saturn. The third one gives positional ephemerides of several faint satellites of Jupiter and Saturn.

For navigation, IMCCE publishes every year a nautical almanac, titles *Ephémérides nautiques* and ephemerides for air navigation in the *Ephémérides aéronautiques*.

2.4. *Electronic ephemerides*

Ephemerides on-line are available on the web site of IMCCE at the address http://www.imcce.fr. Several improvements in the data provided and their arrangement have been made since 2003. But the main work done concerns the introduction of web services with the objective to provide "self-defined" data and to make these services interoperable. Therefore the service of ephemerides of IMCCE has been supplemented with a working group dedicated to the development of software and databases in the Virtual Observatory framework.

The first product of this working group (Berthier et al. 2005) has been developed in collaboration with the Centre de données de Strasbourg in France (CDS). This software labeled SkyBoT (Sky bodies Tracker) deals with dynamical models of all the known asteroids and of the main natural satellites. It provides weekly updated ephemerides on the 1949-2009 time span, well adapted to the identification of Solar System Objects in star fields and to data mining. Two ways are possible for using this software: firstly the access to http://www.imcce.fr/webservices/skybot/ allows the use of query forms by a user or the implementation in other software, secondly the use of the CDS's Star Atlas Aladin at the address http://aladin.u-strasbg.fr/aladin.gml gives the graphic identification of Solar System objects in any archives, thanks to the interoperability feature between the CDS and the IMCCE servers.

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3. Report of United States Naval Observatory

This report covers activity in the Astronomical Applications (AA) Department since the XXVth General Assembly in Sydney. The AA Department employs 14 scientists in three divisions: The Nautical Almanac Office (NAO), the Software Products Division (SPD), and the Science Support Division (SSD). The SSD was established in January 2004 as the department's research arm. S. Urban was appointed Chief of the NAO in June 2004. M. Efroimsky joined the staff on a permanent basis in March 2005. G. Kaplan, who was Chief of the SSD, retired in October 2005, and was rehired into a part-time position the following month. A. Fredericks joined the SPD staff in Decemeber 2005. R. Miller retired from the NAO in January 2006, and was replaced by E. Barron. The same month, J. Hilton moved from the SSD to the NAO.

Hilton served as chair of the Division I Working Group on Precession and the Ecliptic and as a member of the Inter-Division Working Group on Cartographic Coordinates and Rotational Elements. Urban chaired the Commission 8 Working Group on the Densification of the Optical Reference Frame. Kaplan served as a member of the Division I Working Group on Nomenclature for Fundamental Astronomy. J. Bangert served as a member of the Standards of Fundamental Astronomy (SOFA) reviewing board.

Publication of *The Astronomical Almanac* and *The Astronomical Almanac Online*, *The Nautical Almanac*, *The* (U.S.) *Air Almanac*, and *Astronomical Phenomena* continued as a joint activity between Her Majesty's Nautical Almanac Office of the United Kingdom and the NAO. *The Astronomical Almanac* for 2006, released in January 2005, was the first edition to incorporate fully the resolutions on reference frames, Earth rotation models, and time scales adopted by the IAU in 1997 and 2000.

U.S. Naval Observatory Circular 179, *The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models: Explanation and Implementation*, was published in October 2005. It is available in print form, and as a PDF file at *http://aa.usno.navy.mil/publications/docs/Circular_179.html*.

A major upgrade of the *Multiyear Interactive Computer Almanac*, MICA version 2.0, was completed and released in July 2005. The software is available in two editions for computers running Microsoft Windows and Apple Mac OS operating systems.

Use of the Astronomical Applications Department Web site (*http://aa.usno.navy.mil/*) continued to grow during the reporting period, hosting as many as 45000 user sessions per day. The site now contains approximately 1200 pages and numerous interactive calculators.

A new version of the Naval Observatory Vector Astrometry Subroutines (NOVAS) that implements the 1997 and 2000 IAU resolutions is under development, with release anticipated in late 2006 or early 2007.

An active research program is underway within the department. Research topics include gauge functions in celestial mechanics, solid-body tides in orbit theory, asteroid ephemerides and determination of asteroid masses, determination of orbital parameters of one satellite from observations taken from another, and development of instruments to fully automate celestial navigation and surveying.

Other projects underway at USNO, and of interest to Commission 4, include the USNO CCD Astrograph Catalog (UCAC; *http://ad.usno.navy.mil/ucac/*) and observations of solar system bodies made with the Flagstaff Astrometric Scanning Transit Telescope (FASTT; *http://www.nofs.navy.mil/about_NOFS/telescopes/fastt.html*).

4. Ephemeris Astronomy in Institute of Applied Astronomy

4.1. *ALMANACS*

Apart from Ephemerides of Minor Planets (which are not described here), IAA publishes on a regular basis the almanacs of the following three types:

(*a*) *The Astronomical Yearbook* of Russia for different scientific and practical applications (published since 1921.) It includes geocentric apparent places of the Sun, Moon, major planets, 779 bright stars and some information on current astronomical phenomena, such as solar and lunar eclipses, planet configurations and so on (686 pages in the edition for the year 2007).
(*b*) *The Nautical Astronomical Yearbook* (published since 1930). It contains daily tables of Greenwich hour angles and declinations of the Sun, the Moon, Venus, Mars, Jupiter, Saturn and 160 stars.
(*c*) *The Nautical Astronomical Almanac* (biennial, for ships on long voyages).

The Astronomical Yearbook follows the recommendations of IAU whenever it is possible to do so. The detailed *Explanatory Supplement to Astronomical Yearbook* (in Russian) has recently been published (Brumberg et al., 2004). Apart from the examples on how to calculate the various ephemerides of stars, the Moon and the major planets, it describes, in brief, the modern trends in ephemeris astronomy and gives a review of new theories of the major planets, relativistic time scales, precession-nutation models, relativistic theory of reference systems and the new concept of the CIO. The extensive bibliography (over 500 references) is also given.

In the navigation almanacs, IAU 2000 resolutions concerning CIO are deliberately not implemented in order that the navigators might continue to use their old software without any danger of confusion that might lead to a disaster.

4.2. *SCIENTIFIC WORK*

The work of preparing the publications and updating the algorithms in accordance with IAU recommendations is carried out at the Laboratory of the *Astronomical Yearbook*. The research work to support published ephemerides at the required level of accuracy is the duty of Laboratory of Ephemeris Astronomy. It is also involved in other research studies which are not directly connected with the fundamental ephemerides (minor planets and comet ephemerides, Earth's rotation, SLR and VLBI campaigns) which are considered to be necessary for updating, testing and improving the software in use. As attaining the highest accuracy is the main objective, the recommendations and standards of the IAU or IERS are not always rigorously followed.

In the recent years, when reforming the almanacs, a new dynamical base for the published ephemerides was adopted. It was decided to publish ephemerides after fitting their dynamical models to available high-accuracy observations. The current stage of realization of this approach is given in brief as follows:

A. THE MAJOR PLANETS AND THE MOON The ephemerides EPM of the major planets for *The Astronomical Yearbook for the Year 2007* have been fitted to the all observations given in the site of Commission 4 *http://ssd.jpl.nasa.gov/iau-comm4* which is the observational basis of the last version DE ephemerides (Pitjeva, 2005). The current version EPM2006 (Ephemerides of Planets and Moon, version of the year 2006) accounts for the gravitational interaction of the 9 major planets, the Sun, the Moon, 301 biggest asteroids, the perturbations from the asteroid ring of smaller asteroids, and for the perturbations from the solar oblateness. The planetary part of EPM2006 ephemerides has resulted from a least squares adjustment to observational data totaling 437883 observations (for years 1913–2005) of different types, including radiometric observations of the planets and spacecraft, and astrometric observations of the outer planets and their satellites.

The lunar ephemerides are obtained by integrating the equations of lunar orbital and rotational motion simultaneously with the equations of planet motion described above. Parameters

of the lunar ephemerides are estimated from the analysis of LLR observations of 1970–2004 (15599 time delays.) About 60 parameters were adjusted, including the lunar Love numbers k_2, h_2, l_2, the tidal lag of the lunar body tides, and harmonics of the lunar potential from C_{20} to S_{33}. The earlier stage of the work is described in (Krasinsky, 2002).

As the data are published with 1 mas truncation errors, the published planetary ephemerides coincide with those based on DE405, while for the lunar ephemerides, the differences exceed the truncation error.

The EPM ephemerides are available in the form of Chebyshev's polynomials from the FTP server *ftp://quasar.ipa.nw.ru/incoming/EPM2004*.

B. NATURAL SATELLITES OF THE MAJOR PLANETS It is planned, in the near future, to expand the contents of the *Astronomical Yearbook* by including the ephemerides of the main satellites of the major planets. For that, the numerical ephemerides of these satellites will be used. As a rule, the equations of motion of the satellite systems are to be integrated simultaneously, accounting for the mutual perturbations of the satellites. At present, such work is carried out in the cases of four Galilean satellites, eight satellites of Saturn, and five satellites of Uranus. The resulting theory of the Galilean satellites is fitted to astrometric and radiometric data; for other satellites (including Phobos and Deimos), such work is in progress.

C. ROTATION OF THE EARTH AND THE MAJOR PLANETS For all these bodies, the theories of their rotation are to be constructed by numerical integration, with the resulting dynamical theories presented in the form of Chebyshev's polynomials. A numerical theory of rotation of the deformable Earth with a fluid core was constructed and fitted to the VLBI observed position of Celestial Pole and Universal Time UT1 (the series of Goddard Space Flight Center of 1984–2004.) It appeared that the numerical theory provides somewhat better fitting than the adopted theory of precession-nutational motion IAU 2000. The theory and its applications are described in detail in papers (Krasinsky, 2006; Krasinsky and Vasyliev, 2006). For the case of Mars, constructing the analogous numerical theory, based on the observations of Martian landers, is in progress.

4.3. *SOFTWARE*

The practical preparation of the almanacs, as well as its ephemeris support is carried out by a technology which is under development at IAA since 1982, when general specifications of the software for ephemeris and dynamical astronomy were formulated, and the first version of the software, based on these specifications, was accomplished. The approach is based on using a high-level problem-oriented language SLON designed specially for ephemeris and dynamical astronomy (Krasinsky et al., 1985). The corresponding programming system ERA is still in use. The current version ERA-7 (Krasinsky and Vasyliev, 2006) is much more advanced both in the functional diversity of applications built-in to the applied program package and in the descriptive power of the language SLON. The system has been thoroughly tested by a number of practical tasks and has proved its efficiency. In particular, it provides the user with:

(a) a unified method of constructing numerical dynamical theories of any of the Solar system bodies (both of orbital and rotational motion) presenting them in the form of Chebyshev's polynomials,
(b) easy processing of any types of observables for improving the parameters of the dynamical theories,
(c) a toolkit for updating the constructed numerical ephemerides by processing relevant observations by the standard Least Squares Method or by Kalman filtering.

The 16-bit version of ERA-7 is available by anonymous FTP from the FTP server: *ftp://quasar.ipa.nw.ru/incoming/era/*

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5. HM Nautical Almanac Office, Rutherford Appleton Laboratory

This is the report of HM Nautical Almanac Office (HMNAO) covering the period since the XXVth General Assembly in Sydney. After seven and a half years operating under commercial conditions within CCLRC at the Rutherford Appleton Laboratory (RAL), HMNAO has been transferred to the UK Hydrographic Office (UKHO), an agency of the UK Ministry of Defence (MoD).

HMNAO consists of three staff who are funded by the royalties generated by the sales of the almanacs produced by the office and jointly with the US Naval Observatory and also from the sales of its services. These funds were insufficient to take on and train new staff. As RAL were also unable to provide any support, financial assistance was sought from the Royal Navy/UK MoD. Having satisfied themselves HMNAO's services were needed, the UK MoD requested UKHO to access the viability of taking on the office. Having generated a satisfactory business plan, HMNAO was handed over to UKHO on April 1st 2006. This entire process took the better part of 4 years requiring considerable staff input.

Joint publications with the US Naval Observatory, in particular, *The Nautical Almanac* and *The Astronomical Almanac* have been produced on schedule. A fully navigable pdf version of *The Nautical Almanac* has been produced and extensive changes have been made to *The Astronomical Almanac* to implement the resolutions relating to reference frames, times scales and earth orientation from the previous two IAU's. Improvements have also been made to the calculation and provision of satellite data and phenomena in Section F, to Section K and the provision of lunar eclipse diagrams in Section A.

A new edition of *Navpac and Compact Data 2006-2010* has been produced including some new features. To emphasise its use by the Royal Navy, a joint launch of this product with the Admiralty Manual of Navigation (BR45) was arranged.

Catherine Hohenkerk has served on the IAU Working Group on Nomenclature for Fundamental Astronomy and has given talks at the Journées meetings in Paris (2004) and Warsaw (2005) on the application of this topic to *The Astronomical Almanac*. She has taken an active role on the Software for Fundamental Astronomy (SOFA) board. HMNAO now hosts the SOFA Center web site. She has taken a leading role in the major changes to Section B in the 2006 edition and has also received the USNO Superintendent's Award 2005 for her services to *The Nautical Almanac*. Steve Bell attended the IAU Colloquium 196 on New Views of the Solar System and Galaxy.

Significant effort has gone into the generation of new web site material. Transit information was provided for the 2004 transit of Venus and a new eclipse web site http://www.eclipse.org.uk has been generated giving solar and lunar eclipse information for the period 1500 CE to 2100 CE. A mass participation project for Einstein Year was launched in collaboration with the Institute of Physics to observe the first sighting of new crescent moon involving a web site http://crescentmoonwatch.org. This received significant media coverage. Steve Bell has given several talks around the UK on this subject.

Don Taylor has been involved in work relating to the astronomical application of map projections and the compilation of time zone and daylight saving time rules for web services. He has also continued his worked on solar perturbations for the satellites of Uranus and integration software for cometary ephemerides.