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COMMISSION 4

EPHEMERIDES

ÉPHÉMÉRIDES

TRIENNIAL REPORT 2006–2009

1. Jet Propulsion Laboratory, Caltech, USA

JPL planetary ephemeris development has been very active assimilating measurements from current planetary missions and supporting future missions. The NASA *Mars Science Laboratory* (*MSL*) mission with launch in 2009 requires knowledge of the Earth and Mars ephemerides with 30 m accuracy. By comparison, the accuracy of the Mars ephemeris in the widely used DE405 ephemeris was about 3 km. Meeting the *MSL* needs requires an ongoing program of range and very-long baseline interferometry measurements of Mars orbiting spacecraft. The JPL ephemeris DE421 was released three months before the landing of the Phoenix mission on Mars, and has met the 300 m requirement. Continued measurements are planned to support the *MSL* landing.

Measurements are now routinely made using several NASA and ESA spacecraft in orbit about Mars. VLBI measurements using DSN and ESA tracking stations have been supplemented by use of the Very Long Baseline Array for specific measurement campaigns. Currently the planetary ephemeris is aligned to the ICRF with an accuracy of 0.25 mas based on the VLBI measurements. VLBI and ranging measurements to the ESA Venus Express spacecraft have resulted in a significant improvement in the Venus ephemeris. Measurements of the *Cassini* spacecraft since 2005 have resulted in a significant improvement in the Saturn ephemeris. Measurements from the *MESSENGER* spacecraft encounters with Mercury are expected in the next several years. After a lapse of several years, lunar laser ranging are being included again in the JPL ephemeris development, to support planned lunar missions.

The JPL ephemeris coordinates time is not the TCB time scale recently adopted by the IAU. Instead the time scale is consistent with the earlier JPL coordinate time, and is nominally the same as TDB as it has now been redefined by the IAU as a linear function of TCB. Because of potential harm to NASA spacecraft, there is no plan to change the coordinate time scale for ephemerides to be used with NASA missions.

(*a*) Staff: E. Myles Standish retired in 2007 after 35 yr of leading JPL planetary ephemeris development. William Folkner is currently responsible.

(*b*) JPL planetary ephemerides are made available in ASCII 'export' format and in SPICE binary format via anonymous FTP from <ftp://ssd.jpl.nasa.gov/pub/eph/planets/>

(*c*) The observational data used in fitting the JPL planetary ephemerides is currently being updated, and available at <iau-comm4.jpl.nasa.gov/plan-eph-data/>

(*d*) Documentation on the latest JPL planetary ephemerides is in the form of memoranda available via anonymous FTP from <ftp://ssd.jpl.nasa.gov/pub/eph/planets/ioms>

2. Astronomical Applications Department, US Naval Observatory

This report covers activity in the Nautical Almanac Office (NAO) and its parent organization, the Astronomical Applications Department.

(*a*) Publications.

Publication of *The Astronomical Almanac* and *The Astronomical Almanac Online*, *The Nautical Almanac*, *The* (US) *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 2009, released in January 2008, fully implements the resolutions adopted by the IAU in 2006, both within the tabular data and explanatory text. *The Air Almanac* for 2009, released in June 2008, is now available exclusively as an electronic publication on CD-ROM. U.S. Naval Observatory Circular 179, *The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models: Explanation and Implementation*, was published on-line and in print form in October 2005. Work was underway on a major revision of *The Explanatory Supplement to the Astronomical Almanac*, in collaboration with P.K. Seidelmann (Univ. of Virginia) and numerous contributors.

(*b*) Software.

An update of the *Multiyear Interactive Computer Almanac*, MICA version 2.1, was completed and released in December 2006. The software is available in two editions for computers running Microsoft Windows and Apple Mac OS operating systems. A new version of the Naval Observatory Vector Astrometry Subroutines (NOVAS) that implements relevant IAU resolutions adopted in 1997 through 2006 was essentially completed. The software will be available in both Fortran and C editions. A major redesign of the Astronomical Applications Department web site <aa.usno.navy.mil/>, which included several new data services, was launched in September 2007. Usage of the web site varied from about 0.5 to 1.3 million visits per month.

(*c*) Research.

An active research program in positional and dynamical astronomy is underway within the department. Research topics included new methods of celestial navigation, determination of asteroid masses, and the theory of bodily tides.

3. National Astronomical Observatory and Japan Hydrographic and Oceanographic Department Japan

Annually National Astronomical Observatory of Japan (NAOJ) publishes the 'Calendar and Ephemeris', a basic almanac designed for astronomical observers, teachers, and citizens. From the 2009 edition, NAOJ not only implemented the New Precession Formula adopted by IAU in 2006, but also enhanced its volume, for example, almost doubled its size and its number of pages. This is the first step toward a development of a full-scale ephemeris. In addition, NAOJ has added more tools to its web

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site <www.nao.ac.jp/koyomi/>, such as local prediction of the Solar/Lunar Eclipse and the Transit of Mercury/Venus, and also established a web site for mobile phones.

The Japan Hydrographic and Oceanographic Department (JHOD) will finish publishing 'Japanese Ephemeris' by 2010 edition and plans to publish only Nautical Almanac and Abridged Nautical Almanac. JHOD has also decided to terminate International Lunar Occultation Centre (ILOC) activities, which will be taken over by the International Occultation Timing Association (IOTA) in March, 2009.

4. HM Nautical Almanac Office, UK Hydrographic Office

After having gone through a review by the UK Ministry of Defense (MoD) which established a continuing requirement for the services and publications of HM Nautical Almanac Office, it became part of the UK Hydrographic Office (UKHO), a UK government trading fund and part of the UK MoD, on 1 April 2006. Two staff members are now based at the UKHO in Taunton, Somerset, while one works off site at our previous host, the Rutherford Appleton Laboratory in Oxfordshire. Commercial viability is still important to HMNAO's operation, however, the requirements of both SOLAS (Safety of Life at Sea) and the Royal Navy take precedence.

Joint publications with the US Naval Observatory, The Nautical Almanac (NP 314), The Astronomical Almanac (AsA), its companion the AsA Online and Astronomical Phenomena, have been produced on schedule. Material throughout the AsA, but most noticeably in Section B, has been produced in accordance with all the recommendations and resolutions of the IAU General Assemblies up to and including 2006 including the Celestial Intermediate Reference System, the Earth rotation angle, IAU 2000A nutation and IAU 2006 precession. Effort has also gone into the expansion of web services provided by the office. Our general web site has been revamped, <www.hmnao.com>, and our Crescent MoonWatch, <www.crescentmoonwatch.org>, and Eclipse web sites, <www.eclipse.org.uk>, are under further development. UKHO versions of Rapid Sight Reduction Tables (NP 303), NavPac and Compact Data 2006 - 2010 (DP 330), The UK Air Almanac (AP 1602) and The Star Almanac for Land Surveyors (NP 321) have been published by UKHO and made available through their distributor network.

Despite the formal relocation of HMNAO to UKHO in 2006, the office is still expending significant effort in furthering its integration with its new operating environment.

HMNAO staff have also played an active role in the Division I WG on Nomenclature for Fundamental Astronomy and are involved with the WG on *Numerical Standards in Fundamental Astronomy*. Continued participation on the board of SOFA has been supplemented by HMNAO's provision and maintenance of the SOFA web site, <iau-sofa.hmnao.com>. HMNAO continues to use SOFA software in the production of its publications.

5. Institute of Applied Astronomy, Russia

(*a*) Fundamental ephemerides.

During the years 2005–2008 the regular publication of *The Russian Astronomical Yearbook* is continued. Planetary and lunar ephemerides are based on numerical model EPM-2004 available to outside users via <ftp://quasar.ipa.nw.ru/incoming/EPM2004>. Ephemerides for planetary configurations, eclipses and occultations are updated and located at <quasar.ipa.nw.ru/PAGE/EDITION/RUS/rusnew.htm>. The ephemerides of

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the Moon (as Tchebyshov polynomials) and the mutual phenomena in the system of the Galilean satellites of Jupiter are on the same Web site.

(*b*) Special ephemerides.

The Naval Astronomical Yearbook (annual issues for 2006–2009) and biennial *The Nautical Astronomical Almanac* (issues 2007–2008, 2009–2010) have been published. The basic purpose of producing the Almanac is to increase its applicability without essential increase of its volume and to give the same accuracy as NAY does. The explanation and part of auxiliary tables are given in both Russian and English versions.

(*c*) Software.

Constructing numerical dynamical models, fitting the ephemerides to observations, as well as preparation of the ephemerides for publishing are carried out in the framework of the universal program package ERA (Ephemerides for Research in Astronomy). The unified Windows/Linux as well as the DOS versions of the package ERA which are available via anonymous FTP, `<ftp://quasar.ipa.nw.ru/incoming/ERA>`, are under development. The first electronic version of *The Personal Astronomical Yearbook (PersAY)* has been constructed. It is intended for calculation of the ephemerides published in the Astronomical Yearbook, including the topocentric ephemerides for any observer. The system PersAY is implemented as the Win32 application on the basis of the package ERA. The first version of PersAY for interval 2000–2015 based the fundamental ephemerides DE405/LE405 and EPM2004 is available on `<ftp://quasar.ipa.nw.ru/pub/PERSAY/persay.zip>`. The electronic system the *Navigator* is in progress. It is intended for solution of basic naval astronavigating problems by the mode of remote access.

(*d*) Research work.

The updated Ephemerides of Planets and the Moon – EPM2008 – have been constructed by the simultaneous numerical integration of the equations of motion of the major planets, the Moon, the Sun, 301 biggest asteroids, 21 trans-Neptunian objects and the lunar physical libration accounting for the perturbations due to the solar oblateness and the massive ring of small asteroids. The parameters of EPM2008 have been fitted to lunar laser ranging measurements 1970–2008 as well as to planet and spacecraft observations 1900– 2007 of different types. The numerical ephemerides of the main satellites of the outer planets have been constructed and fitted to modern photographic and CCD observations. These ephemerides are used for improving the ephemerides of their parent planets, in which connection the ephemerides of the Galilean satellites are used for publication in the Russian Astronomical Yearbook.

6. Institut de Mécanique Céleste et de Calcul des Éphémérides, Observatoire de Paris, France

During the last three years, various works on ephemerides have been pursued at the Institut de mécanique céleste et de calcul des éphémérides (IMCCE). IMCCE, as institute of the Paris Observatory, is in charge to compute the official French ephemerides on behalf of the Bureau des longitudes. Therefore, besides scientific researches in the domains of theoretical celestial mechanics, astrometry and planetology, the research teams of IMCCE perform activities in dynamics and applied celestial mechanics with the goal to provide accurate ephemerides. Besides, the Ephemerides Service of IMCCE works for the improvement of the ephemerides books, softwares, web server and facilities.

(*a*) The new dynamical models.

Several new dynamical models have been developed for the planets and the natural satellites. The development of the new numerical planetary ephemerides named INPOP (Intégration Numérique Planétaire de l'Observatoire de Paris) has been carried on. A

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new version named INPOP06 has been published (Fienga *et al.* 2007; Fienga *et al.* 2008). The motion of the eight planets, Pluto and the Moon are modelized and fitted on the most accurate observations including tracking data from *Mars Global Surveyor* and *Mars Odyssey*. The accuracy is comparable to the accuracy of recent versions of the JPL DE414 ephemerides and of the EPM2004 ephemerides. With the goal to provide accurate ephemerides for the study of insolation quantities and paleoclimates, planetary dynamical models on very long term are also investigated by (Laskar 2007). Dynamical models of several planetary satellites systems have been developed or improved. The model of satellite motion named NOE (Numerical Orbit and ephemerides) takes into account various gravitational effects down to the small ones. Ephemerides are obtained by recomposition of quasi-periodic Fourier series issued from a frequency analysis of a numerical model coupled with digital filtering treatments. The motion of the Galilean satellites L1 has been modelized by (Lainey *et al.* 2006) and has been used to predict the next season of mutual events of the Galilean satellites by (Arlot 2008). Similarly, different models have been used by (Arlot & Thuillot 2008) to predict the next season of mutual events of the Saturnian satellites and of the eclipses by Saturn itself. NOE has also been applied to the development of new ephemerides of the Uranian satellites named LA06/NOE-7-06. An improved version, LA07/NOE-7-07 is now available on the ftp server of IMCCE <ftp://ftp.imcce.fr/pub/ephem/satel/la06/>. New ephemerides of the Martian satellites Phobos and Deimos (NOE-4-07) that are fitted to observations from 1877 to 2005 and include recent spacecraft observations by *Mars Global Surveyor* and *Mars Express* have been published by (Lainey *et al.* 2007). In an other work based on the use of the onboard camera (Super Resolution Camera) of the *Mars Express* space probe, an accurate dynamical model of the Martian satellites has been developed in a fruitful collaboration with the Royal Observatory of Belgium (Rosenblatt *et al.* 2008). This work combines observations of the moons positions from a spacecraft and from the Earth and this allows to assess the real accuracy of the spacecraft orbit. A collaboration with the Sternberg State Astronomical Institute of Moscow led to the development of the dynamical modeling of different satellites and the providing of ephemerides. Thus, ephemerides of Phoebe has been provided by (Emelyanov 2007). The problem of the propagation of errors in the dynamical model related to the fit of observations, and the sampling of these observations, is investigated by (Desmars *et al.* 2007). They showed some different statistical methods, re-sampling of observations, which allow a better estimation of the extrapolated accuracy in the future. During the last years, the model of the meteoroid streams developed by Vaubaillon has been successfully applied in international collaborations to the analysis of various observations and to the prediction of the date of the Earth encounter and their activity (Jenniskens *et al.* 2008).

(*b*) 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. Several changes have been done in these books during the last years. The yearly book of ephemerides of high precision titled 'Connaissance des temps' has been recently transformed and revitalized by the introduction tables (instead of Chebychev coefficients) and many scientific texts upon constants, timescale, reference systems and transformations of coordinates. An ephemerides software allowing the computation of topocentric coordinates, rises and sets, is provided on a CD accompanying the book. On these last years we have introduced in this book the new planetary model INPOP06 and the new satellites models: L1 for the Galilean satellites and NOE for the Martian and the Uranian satellites. 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 eight first satellites of Saturn. The third one gives positional ephemerides of several faint satellites of Jupiter and Saturn. A second yearly book titled 'Guide de données astronomiques - Annuaire du Bureau des longitudes' gives 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. A scientific booklet is included in this book. Each year, a new topic is stated by some specialists. For the navigation, IMCCE publishes every year a nautical almanac, titles 'Ephémérides nautiques' and ephemerides for air navigation in the 'Ephémérides aéronautiques'.

(*c*) Electronic ephemerides.

Ephemerides on-line are available at the address `<www.imcce.fr/>`, the web site of IMCCE. The main improvement for these electronic ephemerides concerns the setting up of web services with the objectives to provide 'self-defined' data and interoperable services. Several ephemerides are now being transformed in order to become interoprable. This work is fully installed in the Virtual Observatory framework (Thuillot *et al.* 2006). The software labeled SkyBoT (Sky Bodies Tracker), has been developed in collaboration with the Centre de données de Strasbourg in France (CDS) and has been recently improved. It deals with a large and regularly updated database of ephemerides of the small Solar System Bodies to facilitate their identification on a 60 yr period. At the present time all the asteroids, the planets and 33 satellites are available. This software is well adapted to the data mining and has been implemented in other softwares thanks to the information which can be accessed at `<www.imcce.fr/webservices/skybot/>`. SkyBoT is also available through the Aladin sky atlas of the CDS (Berthier *et al.* 2006). The next improvement will be to introduce more satellites and the comets on the basis of the orbital elements (Rocher 2008) already available in the VizieR catalog of the CDS accessible at `<webviz.u-strasbg.fr/viz-bin/VizieR?-source=B/comets>`.

7. Real Observatorio de la Armada, Spain

The Real Observatorio de la Armada (ROA) is responsible for the publication of 'Efemérides Astron ómicas', a national Almanac with a similar layout to *The Astronomical Almanac*, which in a near future will incorporate the IAU recommendations regarding the ICRF. The ephemerides are computed from JPL DE405/LE405 fundamental ephemerides and USNO/AE98. The publication also incorporates ephemerides of the satellites of Jupiter, Uranus, and Neptune that are kindly provided by NAO (USNO). In addition, the publication includes information of apparent places of 194 stars, and prediction of lunar occultations for six Spanish sites.

Besides, ROA regularly issues a nautical almanac, in printed and electronic format, a booklet with the more relevant astronomical phenomena for the Sun, Moon and planets, and maintains a web site with interactive ephemerides computation and other astronomical information `<www.roa.es/>`.

8. Astronomical Institute, Czech Republic

The Institute, in close cooperation with the Observatory and Planetarium of Prague, issues every year an astronomical yearbook of about 250 pages for amateur astronomers 'Hvězdářská ročenka' (in Czech), with a limited precision. The yearbook is based on the VSOP82 ephemerides and it contains the ephemerides of the Sun, Moon, planets and

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their satellites, asteroids, comets, meteoric streams and variable stars. Many phenomena (such as eclipses, occultations, conjunctions and oppositions, etc., . . .) are also included. All calculations are made at the Astronomical Institute, still in the 'old' system (i.e., using equinox, IAU1976 precession and IAU1980 nutation). We suppose to follow other 'big' ephemeris books such as The Nautical Almanac, The Astronomical Almanac, Connaissance des Temps, Astronomicheskii Ezhegodnik, etc., . . . , when they decide on the new format of published data. In addition, the prediction of lunar occultations is provided also for four Romanian observatories and published in Romanian astronomical yearbook.

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president of the Commission

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