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EXPLANATORY SUPPLEMENT
TO IERS BULLETIN A and BULLETIN B/ C04

IERS Bulletins A and Bulletin B/C04 provide values of the Earth's orientation parameters in the IERS Reference System including UT1-UTC, coordinates of the terrestrial pole, and celestial pole offsets. Bulletin A is issued weekly by the IERS Rapid Service/Prediction Center at the U.S. Naval Observatory, Washington, DC. It provides the most recently observed estimates as well as predictions of Earth Orientation Parameters (EOPs). Bulletin B/C04 is issued monthly by the IERS Earth Orientation Centre (EOC) at the Paris Observatory, and provides daily data covering a period from several decades to 30 days previous to the date of publication.. The Earth orientation parameters provided in Bulletins A and B may be used to relate the International Celestial and Terrestrial Reference Systems as realized operationally by the International and Celestial Reference Frames respectively. The rigorous details are outlined in the publications of the International Earth Rotation and Reference Systems Service (IERS), specifically in the *IERS Conventions (2010)* and its updates (see below), which are available electronically at http://tai.bipm.org/iers/conv2010/conv2010.html.*5*. A full description of all of the IERS products is available at the IERS web site [www.iers.org].

THE INTERNATIONAL CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS AND FRAMES

The term "Reference System" refers to a set consisting of an origin, triad of axes and the conventional models used in their definition. The Term "Reference Frame" refers to the set of adopted positions, and motions, or directions that actually define the system in practice. In the case of the celestial frame it refers to the directions to a set of distant radio sources. In the case of the terrestrial frame it refers to an adopted set of geodetic station locations and their motions.

The International Celestial Reference System (ICRS) is the idealized barycentric coordinate system to which celestial positions are referred. It is kinematically non-rotating with respect to distant extragalactic objects and aligned close to previous astronomical reference systems for continuity. Its orientation is independent of epoch, and is realized by a list of adopted coordinates of extragalactic sources called the International Celestial Reference Frame (ICRF). The Geocentric Celestial Reference System (GCRS) is a system of geocentric space-time coordinates defined such that the transformation between ICRS and GCRS spatial coordinates contains no rotation component, so that GCRS is kinematically non-rotating with respect to ICRS. The spatial orientation of the GCRS is derived from that of the ICRS.

The Celestial Intermediate Reference System (CIRS) is a geocentric reference system related to the GCRS by a time-dependent rotation accounting for precession-nutation. It is defined by the intermediate equator of the Celestial Intermediate Pole (CIP) and the Celestial Intermediate Origin (CIO) on the equator of the CIP on a specific date. The CIP is a geocentric equatorial pole defined as being the intermediate pole in the transformation from the GCRS to the ITRS, separating nutation from polar motion. Its GCRS orientation results from the part of precession-nutation with periods greater than 2 days, the retrograde diurnal part of polar motion (including the free core nutation, FCN) and a reference frame bias. The motion of the CIP is realized by the IAU precession-nutation plus small time-dependent corrections called celestial pole offsets. The CIO is the origin for right ascension on the intermediate equator in the CIRS. It is the non-rotating origin in the GCRS originally set close to the GCRS meridian and throughout 1900-2100 stays within 0.1 arc seconds of this alignment. The CIO was located on the CIP equator of J2000.0 at a direction 2.012 milli-arcseconds (mas) from the ICRS prime meridian at right ascension 0h 0m 0s.000 134 16 in the ICRS.

The CIRS is related to the ITRS by rotation matrices that account for polar motion and the Earth's rotation   The polar motion matrix is a function of the pole coordinates x and y, sometimes designated as "PMx" and "PMy" along with the Terrestrial International Origin locater, s′. The Earth's rotation is accounted for by a rotation matrix that is a function of the Earth Rotation Angle, which is linearly related to UT1-UTC. The GCRS is then related to the CIRS by rotation matrices that are functions of frame bias, precession, and nutation. These relationships can be written as

[CIRS] = ***[R(x, y, s', ERA)]*** [ITRS],

[GCRS] = ***[R'(frame bias, precession, nutation)]*** [CIRS].

The International Very Long Baseline Service (IVS) (http://ivscc.bkg.bund.de/) has the operational responsibility for the realization of the ICRS through the observations of extragalactic radio sources using the VLBI technique. The first version, ICRF1 (Ma et al. 1997) was defined by the positions of 212 defining compact radio sources. The latest realization, ICRF2 (IERS Technical Note 35), was adopted by IAU in 2009 and contains positions of 3414 compact radio sources including 295 defining sources. The position uncertainties and the axis stability are respectively about 40 and 10 micro-arc-seconds (μas). Alignment of ICRF2 with the ICRS was made using 138 stable sources. The maintenance of ICRF2 is performed using the set of 295 defining sources selected on the basis of positional stability and the lack of extensive intrinsic source structure.

The International Terrestrial Reference System (ITRS) is a specific Geocentric Terrestrial Reference System defined to have no residual rotation with regard to the Earth's surface. Its center is understood as the center of mass of the whole Earth system, including oceans and atmosphere. It was aligned close to the mean equator of 1900 and the Greenwich meridian, for continuity with previous terrestrial reference systems. The Terrestrial Intermediate Reference System (TIRS) is a geocentric reference system defined by the intermediate equator of the CIP and the Terrestrial Intermediate Origin (TIO), which is the origin of longitude in the ITRS. The TIRS is related to the ITRS by polar motion and the TIO locator. It is related to the Celestial Intermediate Reference System by the Earth Rotation Angle (ERA) around the CIP that realizes the common z-axis of the two systems. The TIO is the non-rotating origin in the ITRS that was originally set at the ITRF origin of longitude and throughout 1900-2100 stays within 0.000 1″ of the ITRF zero meridian. The ITRS orientation with respect to the GCRS is comprised of the part of polar motion which is outside the retrograde diurnal band in the ITRS and the motion in the ITRS corresponding to nutational motions with periods less than 2 days.

The International Terrestrial Reference Frame (ITRF) is a realization of ITRS by a set of instantaneous coordinates (and velocities) of reference points distributed on the topographic surface of the Earth. Its initial orientation is aligned closely to previous terrestrial systems for continuity, and its length unit is the Système International (SI) mètre, consistent with Geocentric Coordinate Time (TCG). The International Terrestrial Reference Frames (ITRF) is provided by the ITRS Product Center (ITRS-PC http://itrf.ensg.ign.fr/). Coordinates and motions are obtained by combining solutions computed by analysis centers using the observations of space geodetic techniques. The current ITRF realization is ITRF2008 (Altamimi *et al.*, 2011). The next version ITRF13 is expected to be available in 2014.

THE IERS CONVENTIONS

The set of models and constants used in defining and relating the reference systems is contained in the IERS Conventions. These are used by the IERS Techniques including the IVS, International GNSS Service (IGS), International Laser Ranging Service (ILRS) and International DORIS Service (IDS) in the analyses of observations and by the IERS Product Centres in the combination of results. The constants and models are, in

general, the best estimates of the specialists in the field. In some cases, they differ from the current IAU and International Association of Geodesy conventional ones. The latest version, Conventions 2010 (IERS technical note 36, Petit and Luzum, 2011), and any updates are available at
http://tai.bipm.org/iers/conv2010/conv2010.html.*5*

EARTH ORIENTATION PARAMETERS

Polar motion

Polar motion refers to the motion of the Celestial Intermediate Pole (CIP) in the International Terrestrial Reference System (ITRS). It is described, in practice, by two angular coordinates with respect to an origin at the pole of the ITRF: x, along the meridian of 0° longitude and y along the meridian of 90° west longitude. The data are derived from astro-geodetic observations using models including high-frequency variations. The motion of the CIP is specified in the Geocentric Celestial Reference System (GCRS) as the motion of the Tisserand mean axis of the Earth with periods greater than two days and is realised operationally by the IAU 2000 A/ 2006 model for Precession and forced Nutation for periods greater than two days plus additional time-dependent corrections called celestial pole offsets (see below). Its direction at the epoch J2000.0 is offset from the direction of the pole of the GCRS in a manner consistent with the precession/nutation model 2000A/ 2006.

The polar motion values published by the IERS at daily intervals do *not* contain small diurnal and sub-diurnal terms due to ocean tides and high-frequency nutation terms. These are represented by a model (IERS Conventions 2010) and should be added after interpolation. The IERS EOC makes available a FORTRAN subroutine for such an interpolation.

UT1-UTC

Coordinated Universal Time (UTC) is the standard atomic based time scale in normal everyday use throughout the world. It is defined by the International Radio Consultative Committee (CCIR) Recommendation 460-4 (CCIR, 1986) to differ from International Atomic Time (TAI) by an integral number of seconds in such a way that UT1-UTC remains smaller than 0.9s in absolute value. TAI is the atomic time scale calculated by the Bureau International des Poids et Mesures (BIPM) from a combination of data from several hundred atomic clocks located at timing laboratories around the world. Its unit interval is exactly one SI second at mean sea level. The origin of TAI is such that UT1-TAI was approximately 0 on 1 January 1958. The instability of TAI is about eight orders of magnitude smaller than that of UT1. On 1 January 2014, TAI-UTC= 35 s. UT1-UTC is used to determine the Earth Rotation Angle (ERA), which is the angle measured along the intermediate equator of the CIP between the Terrestrial Intermediate Origin (TIO) and the Celestial Intermediate Origin (CIO) positively in the retrograde direction. It is computed from:

$$ERA(T_U) = 2\pi(0.779\,057\,273264\,0) + 1.002\,737\,811\,911\,354\,48T_U),$$

where T_U is the Julian UT1 date -2451545.0 and UT1 = UTC+(UT1-UTC).

Greenwich Sidereal Time (GST) is an angle that is the sum of the ERA and the angular distance between the CIO and a conventional equinox along the moving equator. This distance is called the Equation of Origins (EO) which is the CIO based right ascension of the equinox along the moving equator and corresponds to the accumulated precession and nutation in right ascension from the epoch of reference to the current date. This relationship can be written as

$$GST = ERA\ (UT1) - EO,$$

where EO is given by

$$EO = -0.01450600'' - 4612.15653400''t - 1.391581700''t^2 + 0.0000004400''t^3 - \Delta\psi\,\cos\varepsilon_A - P,$$

and t = (Terrestrial Time (TT) – 2451545.0 TT) / 36525, $\Delta\psi \cos\varepsilon_A$ is the classical equation of the equinoxes, and P represents a series of periodic terms given in Table 5.2e of the *IERS Conventions(2010)*. TT is equivalent to TAI +32.184s.

DUT1 is UT1-UTC expressed with a precision of ±0.1s; it is broadcast with time signals and announced in Bulletin D. The difference between the astronomically determined duration of the mean solar day (D) and 86400s of TAI, is called the excess of the length of day (LOD). Its relationship with the angular velocity of the Earth, Omega, is to first order:

Omega = 72 921 151.467064 - 0.843994803 D, where Omega is in picoradians/s and D in ms.

UT1, hence D and Omega are subject to variations due to zonal tides. The model, which describes these variations is a part of the IERS Conventions (Defraigne and Smits, 1999), and includes 62 periodic components with periods ranging from 5.6 days to 18.6 years. UT1R, DR, and OmegaR are the values of UT1, D, and Omega corrected for the short-term part of the model derived from Yoder *et al.* (1981), *i.e.*, the 41 components with periods less than 35 days. In absolute value UT1R-UT1 is smaller than 2.5 ms, and LODR-LOD is smaller than 1 ms. To model the effects of the zonal tides on the solid Earth, the IERS RS/PC uses the subroutine RGZONT2.F, which includes the 62 periodic terms as listed in Table 8.1 of the IERS Conventions (2010) [Petit and Luzum, Technical Note 36]. The UT1R, DR, and OmegaR values computed by the IERS RS/PC are corrected using all 62 periodic terms included in the RGZONT2 model. In addition, IERS Earth orientation data produced at daily intervals are affected by the effects of semidiurnal and diurnal variations due to ocean tides, which are *not* included in the published values. A model by Eanes (see Chapter 8.2 of the IERS Conventions 2010) is available. It should be used when an interpolation between midnight UTC epochs is needed.

Celestial pole offsets

Precession-Nutation is referred to the CIP and exhibits, by definition, only motions with periods greater than two days with respect to an inertial observer in space. The IERS determines observational residuals with respect to the precession and nutation models, called celestial pole offsets. The celestial pole offsets values can be represented in two forms. The first, δX_{2000} and δY_{2000} refers to use with the model IAU 2006/2000A (Capitaine *et al.*, 2009). The second refers to use with the classical nutation angles in longitude and obliquity ($\delta\Delta\psi_{2000}$, $\delta\Delta\varepsilon_{2000}$). The latter can be derived from the former using equations 5.25 page 57, in Chapter 5 of the IERS Conventions 2010 or using the relative FORTRAN subroutine dXdY_dpsideps included in the package, uai2000.package. They are also available from the IAU SOFA Collection (SOFA: http://www.iausofa.org). δX and δY are smaller than 1 mas peak to peak, reflecting mostly the effect of the Free Core Nutation (FCN) that is not predictable and therefore not modeled. In parallel with these values, the values of the 'classical' celestial pole offsets $\delta\Delta\psi_{1980}$ and $\delta\Delta\varepsilon_{1980}$ referred to the old IAU 1980 Nutation model and the IERS 1996 Precession/Nutation theory are also being published in Bulletin A and Bulletin B as long as they are required by users.

DATA ANALYSES

The data analyses used to produce the values of the EOP published in Bulletin A and Bulletin B/ C04 includes several steps that are summarized below. Details of the procedures can be found in Gambis and Luzum (2011).

1. The Technique Centres (IVS, ILRS, IGS, and IDS) coordinate observations made by the VLBI, Satellite Laser Ranging (SLR), GPS, and DORIS networks, respectively. Both the IERS EOC and the IERS RS/PC then obtain the combined solutions from the Analysis Centres of the Technique Centres,
.

2. The IERS RS/PC obtains additional inputs and performs additional data processing to produce near real-time combined observations as well as short and long term predictions of EOP. Some of the additional data sets providing rapid turn-around from observation to EOP estimates, include the VLBI intensive (one –hour) solutions, a GPS derived UT1-like quantity (called UTGPS), the IGS ultra-rapid observations, and the atmospheric angular momentum (AAM) analysis and forecast data from the National Oceanographic and Atmospheric Administration (NOAA) and the U.S. Navy Global Environmental Model (NAVGEM). .

3. The IERS RS/PC applies systematic corrections to all input data to remove any offset and bias relative to the C04 solution. The combined solution is slightly smoothed to remove high-frequency noise using a statistical weighing of the inputs based on estimated accuracies. Final results are updated at around 17:15 UTC each day and contain EOP results spaced at one-day intervals. The accuracies of both the combined and predicted solutions are given in Table 1.

The results are published in Bulletin A at approximately 18:00 UTC on Thursdays and in the finals.daily solution at about 17:20 UTC each day. The latency between the last UT1 observation (from VLBI or UTGPS) and the updated finals.daily solution varies, but is typically between 12 and 22 hours. The latency between the last IGS polar motion observation and the updated daily solution is generally 17 hours; the latency of the celestial pole offsets is generally greater than 7 days. The details of the procedure are outlined in McCarthy and Luzum (1991) and in several Journées “Systèmes de référence spatio-temporels” papers written by Stamatakos and Luzum between 2009 and 2012.

4. Determination of EOP by the IERS EOC is in the form of slightly smoothed combined solutions derived from combined series issued by technique centers. In the procedure systematic corrections and statistical weighting are applied. The accuracy of the solution is given in Table 1. The results are published in Bulletin B/C04 with a sliding delay of thirty days between the date of publication and the last date of the solution (Gambis, 2004).

5. The EOP predictions provided in Bulletin A (and the finals.daily rapid-turnaround solutions) produced by the IERS RS/PC are computed using seasonal filtering algorithms and auto-regressive processing for x, y, UT1, and an approximate modeled correction for the celestial pole offsets. Table 1 shows the resulting precisions and accuracies

Solutions		Terrestrial Pole μas	UT1 μs	Celestial Pole μas
Bulletin A daily		30	8	60
Prediction	1d	0.4	800	
	4d	1.7	2400	
	10d	3.7	7000	
	40d	10.2	55000	
08C04 daily		30	8	60

Table 1*: Precision of the current solutions. The accuracy, which includes the uncertainty of the tie to the IERS System can be estimated by adding quadratically 30 microarcseconds in terrestrial pole, 5 microseconds in UT1, and 0.0002" in celestial pole to the tabular values.*

CONTENTS OF BULLETINS A AND B.

BULLETIN A (weekly and daily)

1. General information including key definitions and the most recently adopted values of DUT1 and TAI-UTC.
2. Quick-look daily (finals.daily) and weekly (finals.all and finals.data) estimates of the EOP determined by combining the most recently available observed and modeled data along with their uncertainties. The UT1-UTC estimates are determined mostly from VLBI 24-hour and intensive, GPS, and AAM inputs; polar motion from IGS, SLR, and VLBI 24-hour inputs; and celestial pole offsets exclusively from 24-hour VLBI inputs. The SLR data type is updated daily.
3. Predictions of EOP with a delay of about 18-hours between the time of publication and the last available date with estimated EOP.

    a. Daily bulletins contain predictions of polar motion (x and y) and UT1-UTC up to 90 days following the last day of input data
    b. Weekly solutions contain predictions of polar motion (x and y) and UT1-UTC daily up to 360 days following the last day of input data and smoothed daily values of celestial pole offsets.

4. Additional files (finals2000A.daily and finals2000A.data) containing dX and dY with respect to IAU 2000A Precession/Nutation theory.

BULLETIN B / C04

Section 1: Daily final values and corresponding uncertainties at 0:00 UT of pole components, UT1-UTC as well as dX and dY based on a combination of the series and their uncertainties for time span up to one month before the date of publication. Data published in previous bulletins are held fixed.

Section 2: Daily values at 0:00 UT of celestial pole offsets $\delta\Delta\psi$ and $\delta\Delta\varepsilon$ relative to IAU 1980 and their uncertainties.

Section 3: Daily estimates of LOD and Omega with their uncertainties.

Section 4: Information on time scales and announcement of future leap seconds.

Section 5: Formal precision of the individual and combined series and their agreement with the combination in term of WRMS over the time span given in Section 1.

DISTRIBUTION OF PUBLICATIONS

IERS Rapid Service/Prediction Centre, at U.S. Naval Observatory:
Bulletin A

By 0h UTC of Friday of each week via e-mail and other distribution methods:

- e-mail subscription (contact: ser7@maia.usno.navy.mil)
- World Wide Web (http://maia.usno.navy.mil/)
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IERS Earth Orientation Centre, at Paris Observatory:
Bulletin B / C04

- e-mail (contact: services.iers@obspm.fr)
- World Wide Web (http://hpiers.obspm.fr/eop-pc/)
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GLOSSARY

BIPM	Bureau International des Poids et Mesures
CCIR	International Radio Consultative Committee
CIO	Celestial Intermediate Origin
CIP	Celestial Intermediate Pole
CIRS	Celestial Intermediate Reference System
DORIS	Doppler Orbit determination and Radio positioning Integrate on Satellite
EO	Equation of Origins
EOC	IERS Earth Orientation Centre
EOP	Earth Orientation Parameters
ERA	Earth Rotation Angle
GCRS	Geocentric Celestial Reference System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GST	Greenwich Sidereal Time
IAU	International Astronomical Union
IERS	International Earth Rotation and Reference Systems Service
ICRF	IERS Celestial Reference Frame
ICRS	International Celestial Reference System
IDS	International DORIS Service
IGS	International GNSS Service
ILRS	International Laser Ranging Service
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IVS	International VLBI Service
LLR	Lunar Laser Ranging
LOD	Length of day
LODR	Length of day corrected from zonal tides effects
MJD	Modified Julian Day
NAVGEM	U.S. Navy Global Environmental Model
NOAA	National Oceanic and Atmospheric Administration
Omega	Earth Angular Velocity
SLR	Satellite Laser Ranging
SI	Système International
TAI	Temps Atomique International
TCG	Geocentric Coordinate Time
TIO	Terrestrial Intermediate Origin
TIRS	Terrestrial Intermediate Reference System
TT	Terrestrial Time
USNO	United States Naval Observatory
UT1	Universal time
UT1R	Universal time corrected for the effect of zonal tides
UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry

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