Future IERS Products Implementation of the IAU 2000 Resolutions

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1 Introduction

With the implementation of the IAU resolutions adopted at the IAU 24th General Assembly in 2000 not only the software packages that process space geodetic data but also the IERS products combined from the results of the various techniques will have to be consistently modified and updated and even new products will be necessary to report EOP series consistently with the new resolutions.

On one hand, the new resolutions will have an impact on the software packages used by the analysis centers of the various services (IVS, IGS, ILRS, IDS) to compute their EOP series and the definition and conventions concerning the EOP estimates to be reported to the IERS and, on the other hand, there will be an impact on the IERS products themselves. In this paper we will mainly focus on the latter topic.

For completeness it should be mentioned that the new resolutions will also have to be considered by some of the projects within the services, like, e.g., the time transfer project of the IGS, where the time definitions according to resolution B1.9 will be of importance.

In the following we will first give a list of the IERS products that are affected by the new resolutions and then discuss in more detail the various product modifications that will be necessary.

2 IERS Products

A long list of different products are available from the IERS nowadays. Table 1 is not a complete list, but only summarizes the products that are of importance in view of the implementation of the new IAU 2000 resolutions and possible new products discussed at the IERS Workshop 2002 in Paris.

The modifications necessary for the various products given in Table 1 concerning definitions, additions, etc., will be discussed in the next sections. The question of whether leap seconds will also be introduced in future, going hand in hand with the publication of Bulletin C, will not be considered here any further.

3 Maintenance of the ICRS/ICRF

Resolution B1.1 stresses the importance of the maintenance of the ICRF as a continuous and ongoing process. In this context the International VLBI and Astrometry Service (IVS) plays a very prominent role. We will, however, not go into more details here. The coordinates of the primary radio sources, the defining sources, will not be changed in the near future unless a considerable improvement can be achieved compared to the present values. The adoption

Table 1: IERS Products affected by the new IAU 2000 Resolutions

Product(s)	old/ new	Comment	Resolution(s)
ICRS/ICRF	o	Maintenance	B1.1
ITRS/ITRF	o	Scale effect due to change from TT to TCG ($\approx$ 0.7 ppb)	B1.3, B1.5, B1.9
EOP series	o	Clarification of the definitions of x-pole, y-pole, UT1-UTC and celestial pole offsets in the high-frequency domain	B1.6 – B1.8
Series of X, Y, dX, dY	n	Publication of new product files containing these quantities	B1.6 – B1.8
s, s'	n	Make available values of s, s' to be used in the transformation between GCRS and ITRS	B1.7, B1.8
FCN	n	Size of free core nutation corrections	B1.6
Eulerian Angles	n	New product containing full transformation GCRS $\leftrightarrow$ ITRS for easier use (?)	—
Bulletin C	o	Leap seconds (yes or no)	B2
Conventions	o	Modifications according to the new IAU 2000 resolutions	B1.3 – B1.9

of the IAU resolutions B1.3 – B1.5 (relativity issues) will only have a very small effect on the radio source positions. Resolutions B1.6 – B1.8 will also have no significant impact on the radio source positions, because nutation corrections were estimated anyway when deriving the ICRF radio source coordinates (which makes these positions independent of the specific nutation model adopted) and the concepts of the CIP, CEO, and TEO do not change the overall transformation between ICRF and ITRF as determined by the space geodetic techniques.

4 ITRS/ITRF

The present realization ITRF2000 of the ITRS is not really consistent with some of the IAU/IUGG/IAG resolutions — the IAU 2000 resolutions as well as older IUGG/IAG resolutions — (see also contribution by Gerard Petit):

- The permanent solid Earth tides are not treated according to the IAG XVIII General Assembly Resolution 16.
- The scale of ITRF2000 is not consistent with the TCG time scale (IUGG 1991 Resolution 2 and IAU 2000 resolutions B1.3–B1.5). ITRF2000 is given in TT which differs from TCG by the scale factor $L_G \approx 0.7$ ppb.
- Modeling of geocenter motion is presently not performed to realize a center of mass frame at a center of mass frame at all times.

The permanent tide issue and the scale definition have not been changed so far, because a change will introduce a jump in the time series of the station coordinates. Therefore, for consistency with previous ITRF realizations, the IAU/IUGG/IAG resolutions have not been followed in this respect. Further reasons not to change the ITRF coordinate definition are:

- The ITRF coordinates are used now by many national survey institutions to define their national reference frames. We therefore have to ensure consistency from one realization of the ITRS to the next.
- All IGS, IVS, ILRS, and IDS products will change, if the TCG reference frame definition is adopted. All the existing products of the services would have to be recomputed or corrected.
- Major IERS products will also be affected (ITRF directly and the EOP series indirectly).
- Geodynamics and geophysics have to be able to rely on a consistent and very stable reference frame for their research work (e.g., detection of sea level rise, post-glacial rebound, ...).

It makes sense, however, that formulas and procedures are given in the IERS Conventions that allow the transformation of the site coordinates (and velocities) into an ITRS system that is consistent with the IAU/IUGG/IAG resolutions. It is to be expected that in the near future periodic corrections for the geocenter motion will be taken into account by the various space geodetic techniques.

5 Earth Orientation Parameter Series

The most important changes resulting from the IAU resolutions are to be expected in the Earth orientation series published in various forms by the IERS EOP product center and the IERS rapid service and prediction product center. For the users that are not interested in high accuracies the changes in the EOP series resulting from the IAU 2000 resolutions will not be important. Much care is taken to make sure, that the application of the new definitions and concepts will not produce noticeable systematic effects in the EOP products. New products will become available, however, that support the new concepts like, e.g., the celestial coordinates X and Y of the CIP. It should be pointed out here, that the old products will continue to be generated also in the future. But at some point, the high-end users might want to change their software and analysis strategies to comply with the new and more clearly defined EOP concepts.

In the following we will discuss some of the issues to be solved in order to implement the new approaches into the IERS product chain.

5.1 Precession and Nutation

The most important effect of the three IAU 2000 resolutions B1.6, B1.7, and B1.8 will be seen in precession and nutation.

First of all, according to the IAU resolutions, the new IAU 2000A precession/nutation model (and its less precise version IAU 2000B) will replace the older models (IAU 1976 precession and IAU 1980 Theory of Nutation) starting on January 1, 2003. There are in principle two ways to implement this new nutation/precession model:

1. stick to the classical procedure and expressions of the IAU 1976 Precession and IAU 1980 Theory of Nutation but apply corrections for the improved numerical values for the precession rate of the equator and for $\Delta\epsilon$ and $\Delta\psi$ according to the new IAU 2000A (or IAU 2000B) model or
2. switch completely to the new formulation using the celestial coordinates of the CIP, X and Y.

Only this second approach is consistent with the IAU resolutions B1.7 and B1.8 and should therefore be implemented on the long run.

The total nutation values $\Delta\epsilon$ and $\Delta\psi$ themselves were not published by the IERS. They had to be computed using the formulas of the IAU 1980 Theory of Nutation. The corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ from VLBI observations were available in the IERS Bulletins A and C. Because the new precession/nutation model IAU 2000A is accurate to about 0.2–0.4 mas compared to the observed nutation values (assuming that the free core nutation (FCN), which accounts for the bulk of these differences, is not known), some users might not have to care about the corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ any longer when using IAU 2000A. For past times, the FCN effects (available as an option in the IAU2000A subroutine) may be added to the IAU 2000A model, improving the quality of the nutation values to about 0.1 mas.

Starting with the implementation of the new nutation/precession model on January 1, 2003, celestial pole offsets will also have to be given with respect to this new nutation/precession model IAU 2000A. The nutation corrections estimated and reported by the IVS and those distributed by the IERS have to follow a clear convention: at least the a priori model these nutation corrections refer to — it may then be the old IAU 1980 Theory of Nutation or the new IAU 2000A model — always has to be stated. It is clear, that the IERS will have to continue to deliver the celestial offsets in the old way for a very long time. It might be a good idea to give different names to those products that refer to the new IAU precession/nutation model and to those that make use of the new concepts so that the user can easily distinguish between old and new products.

It is also evident that the IERS will have to start distributing the new celestial coordinates X and Y of the CIP and the corrections dX and dY to these coordinates as well as the quantities s and s' to be consistent with the new resolutions. A proposal for concrete new products will be given at the end of Section 5.

It is to be expected that VLBI groups will probably continue for quite some time to deliver nutation offsets $\delta\Delta\epsilon$ and $\delta\Delta\psi$, because it will take a considerable effort to change the available software packages to estimate the corrections dX and dY to X and Y instead of the nutation offsets $\delta\Delta\epsilon$ and $\delta\Delta\psi$ presently determined by VLBI (or the nutation rates $\delta\Delta\dot{\epsilon}$ and $\delta\Delta\dot{\psi}$ obtained by GPS). It is therefore necessary to have the appropriate formulas and software available to convert celestial pole offsets from the old representation ($\delta\Delta\epsilon$ and $\delta\Delta\psi$) into the new representation (dX and dY). This seems to be reasonably simple, because we only consider very small quantities here and approximate formulas can be used. Eventually, the space geodetic techniques should switch to directly estimating dX and dY and using the CIP coordinates X and Y in their analysis software packages. When most of the IERS components will have switched to the new representation, we will still need the old form to satisfy the users that have no interest to change to the new concepts. It will then become necessary to compute the corrections $\delta\Delta\epsilon$ and $\delta\Delta\psi$ from the new coordinates X and Y and the corresponding corrections dX and dY.

When using the new approach, information has to be available concerning the angles s and s', which are part of the transformation formulas between the GCRS (Geocentric Celestial Reference System, using the TCG time coordinate) and the ITRS. The angle s can be computed according to formulas that are given in the IERS Conventions (2000). Because the angle s' depends primarily on the amplitudes of the Chandler and annual wobbles and because these amplitudes become available only after the observations, its value (although very small) is in principle only known after the determination of polar motion, too. In order to have consistent EOP series over long time periods and to avoid any jumps in the series, predicted values of s' of sufficient accuracy

should be made available for the analysis of the space geodetic data. The publication of appropriate and sufficiently accurate values of s' should therefore be part of the new IERS product that comply with the IAU resolutions. More information about s' may also be found in the poster presentation by S. Lambert and Ch. Bizouard of this IERS Workshop 2002.

Because the free core nutation (FCN) is not taken into account in the new IAU 2000A/B models, it would make sense that the IERS is publishing values for the FCN corrections that can be applied by the users to improve the nutation model. It should be mentioned, that the celestial offsets estimated by the IVS and submitted to the IERS should refer (after a transition period) to the IAU 2000A model and it has to be clearly decided and defined, how the effects of the free core nutation are going to be treated.

5.2 Polar Motion

There will be almost no impact of the new resolutions (B1.6 – B1.8) on the polar motion (PM) values. Because diurnal and semi-diurnal nutation corrections were not taken into account in the IAU 1980 (or IERS 1996) nutation model, they were reported as part of polar motion also in the past. These diurnal and semi-diurnal nutation terms are small — the largest term has an amplitude of 28.5 μas, see "Practical consequences of the resolutions B1.6 – B1.8" by Dennis McCarthy and Nicole Capitaine — compared to the present accuracy of about 0.1 mas for the daily polar motion estimates from the best space geodetic techniques.

It should be mentioned here, that, as a convention, the subdaily ocean tide variations (nearly semi-diurnal and diurnal terms with a size of about 1 mas) are not part of the polar motion values reported to the IERS and distributed by the IERS. This is a convention that is necessary in order to allow for a more precise interpolation of the daily PM values. The subdaily part in PM has to be added after the interpolation according to the model given in the IERS Conventions (2000).

We think that the same procedure should be applied for the high-frequency effects in polar motion and UT1 arising from the high-frequency nutation terms. That means, that these variations should not be included in the reported PM values but should be taken into account using an appropriate model (e.g that by Folgueira et al., 2001, for polar motion; no model exists yet for UT1-UTC). This question of the model to be used should be settled soon because in the near future the space geodetic techniques might reach the accuracy level of these high-frequency nutation terms.

Finally, we would like to point out, that the forced "diurnal polar motion" — nearly diurnal retrograde tidal variations in polar motion also known as Oppolzer terms caused by the luni-solar torque — are not considered part of polar motion but are included in the nutation models (IAU 2000A/B). This was already the case in the previous definition of polar motion using the Celestial Ephemeris Pole (CEP). Because the space geodetic techniques and astrometic observations cannot provide the position of the Instantaneous Pole of Rotation (IRP), it makes sense to use the Celestial Intermediate Pole (CIP) as reference axis. We should not forget, however, that gyroscopes and gravimeters are sensitive to the position of the IRP and not to the CIP.

5.3 UT1-UTC

The effects of the new resolutions on the UT1-UTC values is expected to be very small. They are mainly the result of an improved precession/nutation model, which might help to better separate between nutation and UT1-UTC parameters. The same is true for UT1 itself. Greenwich Sidereal Time (GST),

however, will be replaced by the "Earth Rotation Angle" (ERA) and this ERA will be related to UT1 by a simple linear relationship.

As in the case of polar motion, the effects due to the semi-diurnal and diurnal ocean tide variations should not be part of the UT1-UTC series reported to and distributed by the IERS (see also Section 5.2). The same is true for the high-frequency variations coming from the high-frequency nutation terms, but no model exists yet to take these terms into account.

It is clear that, depending on the outcome of the studies to be performed according to resolution B2, the values of UT1-UTC might not include any leap second jumps any more in the future.

5.4 Old and New IERS EOP Product

The quantities contained in the old and in the new IERS EOP file proposed here and the steps to be performed to compute highly accurate EOP values and the rotation matrix for the transformation between the terrestrial and celestial frame are summarized in Table 2.

Table 2: Old and new procedures to compute with high precision the transformation matrix $\boldsymbol{R}_{tot}$ between terrestrial and celestial reference frame from the IERS EOP products.

Old EOP Representation	**New EOP Representation (preliminary)**
EOP file with: TCG, x'_p, y'_p, UT1-UTC', $\delta\Delta\epsilon$, $\delta\Delta\psi$	EOP file with: TCG, x'_p, y'_p, UT1-UTC', X, Y (and possibly in addition $X_{IAU2000A}$, $Y_{IAU2000A}$, s, s' and FCN)
Compute IAU 1976 precession matrix $\boldsymbol{P}$ and IAU 1980 nutation $\Delta\epsilon_{80}$, $\Delta\psi_{80}$: $\Delta\epsilon = \Delta\epsilon_{80} + \delta\Delta\epsilon$, $\Delta\psi = \Delta\psi_{80} + \delta\Delta\psi$	Compute s and s' with formulas or take them from EOP file
Compute subdaily ocean tide terms: Δx_p, Δy_p, and Δ(UT1-UTC)	Compute subdaily ocean tide terms: Δx_p, Δy_p, and Δ(UT1-UTC) Compute high-frequency nutation terms in PM and UT1-UTC: Δx_p^N, Δy_p^N, and $\Delta(\text{UT1-UTC})^N$
$x_p = x'_p + \Delta x_p$	$x_p = x'_p + \Delta x_p + \Delta x_p^N$
$y_p = y'_p + \Delta y_p$	$y_p = y'_p + \Delta y_p + \Delta y_p^N$
UT1-UTC = UT1-UTC$'$ + Δ(UT1-UTC)	UT1-UTC = UT1-UTC$'$+ Δ(UT1-UTC) + $\Delta(\text{UT1-UTC})^N$
Compute Greenwich Sidereal Time: GST(UT1,$\Delta\psi$)	Compute Earth Rotation Angle: θ(UT1)
$\boldsymbol{R}_{tot} = \boldsymbol{P} \cdot \boldsymbol{N}(\Delta\epsilon, \Delta\psi) \cdot \boldsymbol{R}_3(-GST) \cdot \boldsymbol{R}_1(y_p) \cdot \boldsymbol{R}_2(x_p)$	$\boldsymbol{R}_{tot} = \boldsymbol{PN}(X, Y) \cdot \boldsymbol{R}_3(s) \cdot \boldsymbol{R}_3(-\theta) \cdot \boldsymbol{R}_3(-s') \cdot \boldsymbol{R}_1(y_p) \cdot \boldsymbol{R}_2(x_p)$

The procedure outlined for the new representation should be considered as preliminary, because the details of the content of the new EOP files is under discussion. The following comments should be added here concerning Table 2:

- The quantities x'_p, y'_p, and UT1-UTC' given in the EOP files contain neither the subdaily variations due to the ocean tides nor the variations due to the diurnal and semi-diurnal nutation terms to avoid interpolation problems with the 1-day tabular interval. (In the old representation the latter terms were not considered yet).

- X and Y are the total values of the celestial coordinates of the CIP, i.e., they include the IAU 2000A model and the corrections dX and dY (including the free core nutation contribution) derived from VLBI observations. It might well be that these various contributions to X and Y will be included in the new EOP file in addition to the total values.
- Because the total values of X and Y will be given in the new EOP files, the user will not have to compute the IAU 2000A (or 2000B) model with its 1440 terms.
- Values for s, s', and θ may be computed using simple formulas. Most probably s and s' will be included in the new EOP files so that they do not have to be computed by the user.
- Groups that are estimating nutation parameters from space geodetic data should use the IAU 2000A model only (without FCN contribution) as a priori values for X and Y (or as a priori values for $\Delta\epsilon$ and $\Delta\psi$).

Additional information on conventions implied in the new products will be given in the new set of IERS Conventions.

5.5 Eulerian Angles

Due to the continuously increasing precision and accuracy as well as time resolution of the Earth orientation parameter series obtained from the various space geodetic techniques, ever complexer and more elaborate models and correction terms have to be considered by the IERS user in order to get the most accurate EOP values. In view of this complexity (precession/nutation models with almost 1400 terms, polar motion and UT1-UTC corrections from IERS Bulletins, knowledge of the parameters s and s', subdaily nutation model in polar motions, subdaily ocean tide corrections for polar motion and UT1-UTC with about 70 terms, effect of the Free Core Nutation (FCN), ...), it might make sense to publish a file with Eulerian angles containing all effects down to a certain accuracy level. For users that are only interested in the transformation between GCRS and ITRS and not in the mechanism and subtleties of Earth rotation itself, tables with Eulerian angles given with a high enough sampling rate to allow for linear (or quadratic) interpolation might be an attractive alternative to the present procedure. Before such a product is envisaged, it would be necessary, however, to estimate the frequency, at which the Eulerian angles would have to be specified, and what amount of data would be needed for, e.g., a table containing the EOP information of one year. Such a study will be performed in the near future and, if the outcome is positive, a new IERS product containing the Eulerian angles will be established.

6 IERS Conventions (2000)

The IERS Conventions (2000) should also be considered a product of the IERS. This product is extremely important, because it has to give the guidelines and formulas to be used in analysis software packages in order to be consistent with the IAU resolutions. The IERS Conventions (2000) should therefore have the following characteristics:

- All chapters should be **consistent with the IAU resolutions** to the extent possible.
- All chapters should also be **consistent with each other** (models, numerical values, and notation) to the extent possible.
- The chapters should give a **complete** description of the models, algorithms, processing strategies and parameterizations to be used.

In addition to the information given in the IERS Conventions, it would also make sense to describe (as part of the IERS Conventions or separately) the exact characteristics of the products that the space geodetic services (IGS, IVS, ILRA, IDS, ...) should deliver to the IERS and the IERS delivers to its users. In the case of EOP time series for instance the analysis centers have to know, that the subdaily variations due to the ocean tides are not to be included in the reported ERP values. Similar conventions are needed for the subdaily nutation effects etc. (see Section 5.1).

7 Software Changes for Analysis Centers

Although the changes necessary by the analysis centers of the different services (IGS, IVS, ILRS, IDS) to comply with the new IAU resolutions are not part of the topic here, we would like to mention a few of the issues there. It is quite evident, that the software changes required to fully implement all IAU resolutions are not to be underestimated and are certainly much more problematic than the changes required for the IERS products.

The implementation of the exact relativistic formulas according to IAU resolutions B1.3 – B1.5 is cumbersome and difficult to test, because of the rather small effect these modifications will have compared to the relativistic corrections already used now.

It will be quite a heavy task to switch from the classical EOP representation to the new concepts (CIP, CEO, TEO, ...) in the various geodetic software packages. It includes:

- Implementation of the new models (IAU 2000A precession/nutation, model for diurnal and semi-diurnal nutation terms in PM, X and Y, formulas for s and s', ...).
- New parameterization with dX and dY instead of $\delta\Delta\epsilon$ and $\delta\Delta\psi$ and computation of the new partials.
- New data structures and formats for the new quantities (e.g., X, Y, dX, dY, s, s', ...).
- Modifications of the IERS EOP format and the SINEX format.
- All results obtained using the new representation will have to be carefully tested and validated to ensure compatibility with the classical results.

It is no question that the new IAU 2000A precession/nutation model will be implemented very soon in all major space geodetic software packages. It is also clear that the implementation of the new approach with CEO, TEO and ERA will take much more time to realize. The use of the new concepts only makes sense, if they are fully implemented into all major space geodetic software packages, too. It will certainly take quite some time to reach this status, especially in view of the fact that the new EOP representation "per se" will not change the quality of the transformation between ICRF and ITRF. However, clear and more concise EOP concepts will be beneficial to all EOP series in the long run.