The IERS Conventions 2010: Reference Systems and New Models

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IERS Conventions

- Set of constants, models, and algorithms, used in the analysis of Earth orientation and reference systems data
- Assembled and verified by experts
- Strives to be consistent with IERS Products
  - ITRF, ICRF, EOPs
  - self-consistent
- Consistent (when possible) with international standards
- Failure to adhere to conventions results in systematic errors
  - i.e. Non-Gaussian noise
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• Glossary
Ch. 1: General definitions and numerical standards

• Provides definitions
  – e.g. permanent tide, zero tide, mean tide

• Provides numerical values for constants

• Change from Conventions (2003) to (2010)
    • Recommendations of IAU Working Group for Numerical Standards of Fundamental Astronomy
Ch. 2: Conventional celestial reference system and frame

• Provides definitions
  – e.g. equator, origin of right ascension

• Provides realizations
  – ICRF2, HIPPARCOS Catalogue

• Change from Conventions (2003) to (2010)
  – Incorporates IAU (2009) Resolution B3
    • International Celestial Reference Frame (ICRF)2 adopted
Ch. 3: Conventional dynamical realization of the ICRS

• Provides dynamical realizations (i.e. ephemerides)
  – DE421, INPOP08, EPM2008

• Changes from Conventions (2003) to (2010)
  – Updated ephemerides
Ch. 4: Terrestrial reference systems and frames

- Provides basic concepts
- Provides realizations
  - ITRF2008
- Provides software
- Change from Conventions (2003) to (2010)
  - International Terrestrial Reference Frame (ITRF)2008 adopted
Ch. 5: Transformation between the ITRS and the GCRS

• Provides background
  – IAU resolutions
  – Theory
• Provides models
  – e.g. precession/nutation, diurnal/semidiurnal variations
• Provides software
• Changes from Conventions (2003) to (2010)
  – Modified to include new precession theory, libration theory, and to use terminology consistent with IAU recommendations
Ch. 6: Geopotential

• Provides conventional model
• Provides models for effects
  – e.g. solid Earth tide, solid Earth pole tide, treatment of the permanent tide, effect of the ocean tides
• Provide software
• Changes from Conventions (2003) to (2010)
  – Incorporates new geopotential model (EGM2008), new ocean tide model (FES2004), and ocean pole tide
Ch. 7: Displacement of reference points

- Provides models
  - e.g. ocean loading, solid Earth tides, permanent deformation, rotational deformation due to polar motion, atmospheric loading, VLBI Antenna thermal deformation, GNSS antenna phase center offset and variations

- Provides software

- Changes from Conventions (2003) to (2010)
  - new sections on atmospheric pressure loading and non-tidal displacement of reference markers
Ch. 8: Tidal variations in the Earth’s rotation

- Provides model
  - e.g. solid earth tide
- Provides software
- Changes from Conventions (2003) to (2010)
  - Modified solid Earth tide model and software to account for additional geophysical effects
Ch. 9: Models for atmospheric propagation delays

• Provides models
  – e.g. troposphere delay (both radio and optical),
    troposphere horizontal gradients, ionosphere delay

• Provides software

• Changes from Conventions (2003) to (2010)
  – Uses new zenith delay/mapping function and a new section on ionospheric delay
Ch. 10: General relativistic models for space-time coordinates and equations of motion

• Provides theory
  – e.g. time coordinates, equations of motion

• Provides software

• Changes from Conventions (2003) to (2010)
  – New TDB definition, new TCB – TCG transformation, revised to include a new section on the transformation between proper time and coordinate time in the vicinity of Earth
Ch. 11: General relativistic models for propagation

• Provides theory
  – E.g. VLBI time delay, laser ranging theory

• No significant changes from Conventions (2003) to (2010)
Appendices

• App. A: IAU NFA WG Recommendations
• App. B: IAU Resolutions Adopted at the XXVIth General Assembly (2006)
• App. C: IUGG Resolution 2 Adopted at the XXVIth General Assembly (2007)
• App. D: IAU Resolutions Adopted at the XXVIth General Assembly (2009)
• Glossary
General Improvements

• Define classification of models and criteria for choosing models
• Include magnitude of modeled effects
• Better consistency
• Improved software standardization
  – New software template
  – Improved documentation
  – Improved robustness of code
  – Include test cases
• Closer cooperation with the IAU Standards of Fundamental Astronomy (SOFA) software
Future Changes

• Update as needed
  – GPT and other “utility routines”
  – Diurnal and semidiurnal EOP variations
  – Issue of conventional mean pole to be reviewed
  – Ionosphere correction to ray bending
  – Resolve geocenter issues

• Expand
  – Models for the displacement of reference points of instruments
  – Section on ranging techniques

• New topics, following the evolution in the geodetic community
  – Non-tidal loading
  – SINEX format for modeling

• Others?
Introduction

Where conventional choices must be made (Class 2), the Conventions provide a unique set of selections to avoid ambiguities among users. The resolutions of the international scientific unions and historical geodetic practice provide guidance when equally valid choices are available. Class 3 models are included when their use is likely to be sufficiently common, as a guidance to users.

For station displacement contributions (Chapter 7), the Conventions clearly distinguish models which are to be used in the generation of the official IERS products from other (Class 3) models. Models in the first category, used to generate the IERS realization of the celestial and terrestrial reference systems and of the transformation between them, are referred to as “conventional displacement contributions.” Conventional displacement contributions include Class 1 models (essential and geophysically based) that cover the complete range of daily and sub-daily variations, including all tidal effects, and other accurately modeled effects (mostly at longer periods). They relate the regularized positions of reference markers on the crust to their conventional instantaneous positions (see Chapter 4) and are described in Section 7.1. In addition, models for technique-specific effects, described in Section 7.3, relate the positions of reference markers to the reference points of instruments.

0.2 Differences between this document and IERS Technical Note 32

The structure of the IERS Conventions (2003) has been retained in this document, but the titles of some chapters have been changed, as indicated. Authors and major contributors of the previous (2003) version of the chapters may be found in the introduction to the Conventions (2003). The most significant changes from the previous version are outlined below for each chapter, along with the major contributors to the changes. These changes are also indicated in two tables that present the realization of reference frames and their accuracy estimates (Table 0.1) and the models along with estimates of the magnitude of the effects (Table 0.2).

The IERS Conventions are one of the products of the IERS Conventions Center. However, this volume would not be possible without the contributions acknowledged below for each chapter. In addition, we would also like to acknowledge the work of the Advisory Board for the IERS Conventions update, that was set up in 2005 under the chairmanship of Jim Ray to advise the Conventions Center in its work of updating the Conventions, with members representing all components of the IERS. Among those, special thanks are due to Ralf Schmid for providing detailed comments and corrections to nearly all chapters in this volume.

Table 0.1: Estimates of accuracy of reference frames

<table>
<thead>
<tr>
<th>Ch.</th>
<th>Reference frame</th>
<th>Conventions 2003</th>
<th>Conventions 2010</th>
<th>Accuracy &amp; difference/improvement between Conventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>celestial reference system &amp; frame</td>
<td>ICRF-Ext.1</td>
<td>ICRF-2</td>
<td>Noise floor ≈ 40 μas (5 times better than ICRF-Ext.1). Axis stability ≈ 10 μas (twice as stable as ICRF-Ext.1). From 717 to 3414 total objects; from 212 to 295 “defining” sources</td>
</tr>
<tr>
<td>3</td>
<td>dynamical realization of ICRS</td>
<td>DE405</td>
<td>DE421</td>
<td>From 1 mas to 0.25 mas for alignment to ICRF</td>
</tr>
<tr>
<td>4</td>
<td>terrestrial reference system &amp; frame</td>
<td>ITRF2000</td>
<td>ITRF2008</td>
<td>Accuracy over 1985-2008: 1 cm in origin, 1.2 ppb in scale. Most important systematic difference vs. ITRF2000: drift in z-direction by 1.8 mm/yr.</td>
</tr>
</tbody>
</table>
## Impact of Specific Changes

<table>
<thead>
<tr>
<th>Sec. Cl.</th>
<th>Phenomenon</th>
<th>Amplitude of effect</th>
<th>Conventions 2003</th>
<th>Conventions 2010</th>
<th>Accuracy &amp; difference/improvement between Conventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 1</td>
<td>Transformation between the ITRS and GCRS</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5.5.1 1</td>
<td>libration in polar motion</td>
<td>tens of μas</td>
<td>No specific routine</td>
<td>Brzezinski PMSDNUT2 model</td>
<td>Specific routine</td>
</tr>
<tr>
<td>5.5.3 1</td>
<td>libration in the axial component of rotation</td>
<td>several μs in UT1</td>
<td>Not available</td>
<td>Brzezinski &amp; Capitaine (2003) UTLIBR model</td>
<td>New model</td>
</tr>
<tr>
<td>5.5.4 1</td>
<td>precession-nutation of the CIP</td>
<td>tens of as/yr and tens of as for the periodic part in X and Y</td>
<td>IAU2000 PN</td>
<td>IAU2006/2000 PN</td>
<td>100 μas/c. + 7 mas/c.² in X; 500 μas/c. in Y</td>
</tr>
<tr>
<td>5.5.5 3</td>
<td>FCN</td>
<td>Few hundred μas</td>
<td>not available</td>
<td>Lambert model</td>
<td>Accuracy: 50 μas rms, 100 μas at one year extrapolation</td>
</tr>
<tr>
<td>5.5.6 1</td>
<td>space motion of the CIO</td>
<td>mas/c.</td>
<td>IAU2000 PN</td>
<td>IAU2006/2000 PN</td>
<td>no change larger than 1 μas after one century</td>
</tr>
<tr>
<td>6 1</td>
<td>Geopotential</td>
<td></td>
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<tr>
<td>6.1 1</td>
<td>Global geopotential model</td>
<td>$10^{-3}$ of central potential</td>
<td>EGM96</td>
<td>EGM2008; C20 and rates of low degree coefs from other sources</td>
<td>EGM96: degree and order 360; EGM2008: complete to degree and order 2159; rate terms for low degree coefs.</td>
</tr>
<tr>
<td>6.2 1</td>
<td>Solid Earth tides</td>
<td>$10^{-8}$ on $C_{2m}$, $10^{-12}$ on $C_{3m}$, $C_{4m}$</td>
<td>Eanes et al., 1983; Mathews et al., 2002</td>
<td>Unchanged</td>
<td>No change</td>
</tr>
<tr>
<td>6.3 1</td>
<td>Ocean tides</td>
<td>For LEO orbit integration: decimetric over 1 day</td>
<td>CSR 3.0</td>
<td>FES2004; Treatment of secondary waves specified</td>
<td>Effect of new model for LEO / MEO: few mm over several days integration; Treatment of secondary waves for LEO: 20% of total effect</td>
</tr>
</tbody>
</table>

*continued on next page*
## Impact of Specific Changes

### 6.4 Solid Earth pole tide
- $10^{-9}$ on $C_{21}, S_{21}$
- Centrifugal effect vs. conventional mean pole (2003)
- Centrifugal effect vs. conventional mean pole (2010)
- Change of conventional mean pole: effect may reach 1 mm

### 6.5 Ocean pole tide
- Few $10^{-11}$ on low degree coeffs
- Not available
- Desai (2002)
- New model

### 7 Displacement of reference points

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Unit</th>
<th>Reference</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1.1</td>
<td>Solid Earth tides</td>
<td>decimetric</td>
<td>Conventional routine from Dehant &amp; Mathews</td>
<td>Unchanged</td>
</tr>
<tr>
<td>7.1.2</td>
<td>Ocean loading</td>
<td>centimetric</td>
<td>Loading response from Scherneck (several tide models); no conventional implementation.</td>
<td>Loading response from Scherneck (several tide models); Implementation by Agnew software (342 constituent tides)</td>
</tr>
<tr>
<td>7.1.3</td>
<td>S1-S2 Atmospheric pressure loading</td>
<td>millimetric</td>
<td>not available</td>
<td>Implementation of Ray &amp; Ponte (2004) by vanDam</td>
</tr>
<tr>
<td>7.1.4</td>
<td>Conventional mean pole</td>
<td>Hundreds of mas</td>
<td>linear model</td>
<td>cubic model from 1976.0 until 2010.0; linear model after 2010.0</td>
</tr>
<tr>
<td>7.1.5</td>
<td>Pole tide</td>
<td>2 cm radial, few mm tangential</td>
<td>Centrifugal effect vs. conventional mean pole (2003)</td>
<td>Centrifugal effect vs. conventional mean pole (2010)</td>
</tr>
<tr>
<td>7.1.6</td>
<td>Ocean pole tide loading</td>
<td>2 mm radial, &lt; 1 mm tangential</td>
<td>Not available</td>
<td>Desai (2002)</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Reference points of instruments: effect of temperature and pressure</td>
<td>~ 1 mm</td>
<td>Not specified</td>
<td>Reference temperature and pressure: GPT model, Boehm et al. (2007)</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Thermal deformation of VLBI antenna</td>
<td>&gt; 10 ps on VLBI delay, several mm variation in coordinates</td>
<td>Notingham et al. (1995)</td>
<td>Notingham (2009)</td>
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### Impact of Specific Changes

#### 7.3.3 GNSS antenna phase center offsets and variations

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<tr>
<td>1</td>
<td>GNSS antenna phase center offsets and variations</td>
<td>decimetric</td>
<td>Not specified</td>
<td>Schmid <em>et al.</em> (2007)</td>
<td>$10^{-9}$ on scale: tropospheric zenith delay and GPS orbit consistency improved</td>
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#### 8 Tidal variations in the Earth’s rotation

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<tr>
<td>3</td>
<td>Zonal tides on UT1</td>
<td>785 µs at $M_f$</td>
<td>Combination of Yoder <em>et al.</em> (1981) elastic body tide, Wahr and Bergen (1986) inelastic body tide, and Kantha <em>et al.</em> (1998) ocean tide models</td>
<td>6 µs at $M_f$</td>
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#### 9 Models for atmospheric propagation delays

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<tr>
<td>1</td>
<td>Troposphere; optical</td>
<td>~ 2.2 m at zenith to ~ 14 m at 10° above horizon</td>
<td>Marini and Murray (1973)</td>
<td>Mendes and Pavlis (2004) zenith delay; Mendes and Pavlis (2003) &quot;Fcul&quot; mapping function (MF)</td>
<td>more accurate delays below 20° elevation and all the way to 3° above horizon; accurate to ~ 7 mm (Total error due to ZTD and MF)</td>
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#### 9.2 Troposphere; radio

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<td>1</td>
<td>Hydrostatic zenith delays ~ 2.3 m Wet zenith delays typically ~ 10–150 mm</td>
<td>Several MF <em>e.g.</em> Neill (1996) or Lanyi (1984)</td>
<td>MF: VMF1 based on 6-hour ECMWF data, GMF based only on latitude, site height, time of year (Boehm <em>et al.</em>, 2006)</td>
<td>Both VMF1 and GMF remove latitude-dependent mapping function bias (average ~ 4 mm in site height). VMF1 reduces short-term vertical scatter (average ~ 4–5 mm)</td>
<td></td>
</tr>
</tbody>
</table>
## Impact of Specific Changes

<table>
<thead>
<tr>
<th>9.2</th>
<th>1</th>
<th>Troposphere; horizontal gradients</th>
<th>can lead to systematic errors in the scale of estimated TRF at level of $\sim 1$ ppb</th>
<th>Not available</th>
<th>J. Boehm APG a priori model</th>
<th>New model</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>1</td>
<td>Ionosphere; radio: First order term</td>
<td>can reach 100 ns for GPS</td>
<td>Not available</td>
<td>Sources for Vertical TEC + conventional mapping function</td>
<td>New model</td>
</tr>
<tr>
<td>9.4</td>
<td>1</td>
<td>Ionosphere; radio: Higher order terms for dual-frequency</td>
<td>can reach 100 ps for GPS; a few ps for wide-band VLBI</td>
<td>Not available</td>
<td>Conventional model based on Slant TEC + Magnetic field model</td>
<td>New model</td>
</tr>
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</table>

### 10 General relativistic models for spacetime coordinates and equations of motion

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<tbody>
<tr>
<td>10.1</td>
<td>1</td>
<td>TCB-TCG transform</td>
<td>1.5 ms annual; 2 $\mu$s diurnal on Earth</td>
<td>FB2001; TE405; HF2002</td>
<td>HF2002_IERS</td>
<td>HF2002_IERS vs. HF2002: $1.15 \times 10^{-16}$ in rate;</td>
</tr>
</tbody>
</table>

| 10.2 | 1 | transformation between proper time and coordinate time near Earth | GNSS: frequency shift of $\sim 4.5 \times 10^{-10} + \text{periodic term of several tens of ns}$ | Not specified | Conventional GNSS model specified; Information on next most significant term. | New model |

### 11 General relativistic models for propagation

<table>
<thead>
<tr>
<th>11.1</th>
<th>1</th>
<th>VLBI delay</th>
<th>tens of ms</th>
<th>conventional 'consensus' model</th>
<th>no change</th>
<th>Uncertainty of model: 1 ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>1</td>
<td>time of propagation for ranging techniques</td>
<td>up to a few s</td>
<td>conventional model</td>
<td>no change</td>
<td>Uncertainty of model: 3 ps</td>
</tr>
</tbody>
</table>
Electronic Conventions


• Copy also available at http://maia.usno.navy.mil/conv2010/conventions.html

• Updates to IERS Conventions 2010 available at http://tai.bipm.org/iers/convupdt/convupdt.html
Backups