Proposed terminology for Fundamental Astronomy based on IAU 2000 resolutions

N. Capitaine

and


IAU Division 1 WG on "Nomenclature for Fundamental Astronomy" (NFA)

IAU NFA WG Membership

Nicole CAPITAINE, Observatoire de Paris, France, Chair
Alexandre H. ANDREI, Observatório Nacional, Brazil, Commission 8 Representative
Mark CALABRETTA, ATNF, Australia, Commission 5 Representative
Véronique DEHANT, ROB, Belgique, Commission 19 President
Toshio FUKUSHIMA, NAO, Japan, Division I President
Bernard GUINOT, Observatoire de Paris, France
Catherine HOHENKERK, HMNAO, UK
George KAPLAN, USNO, USA
Sergei KLIONER, Lohrmann Observatory, Germany
Jean KOVALEVSKY, OCA, France
Irina KUMKOVA, St Petersburg State University, Russia
Chopo MA, GSFC, USA
Dennis D. MCCARTHY, USNO, USA
Ken SEIDELMANN, Virginia University, USA
Patrick T. WALLACE, RAL, UK

The WG has also benefited from advice from
Michael SOFFELE, TU Dresden, Germany, Gérard PETIT, BIPM, E. Myles STANDISH, JPL, USA
Resolutions of the 2000 IAU GA on the celestial reference systems

- **IAU Resolution B1.3**  
  **Definition of BCRS and GCRS**  
  Aim: to provide coordinate systems in the framework of GR

- **IAU Resolution B1.5**  
  **Extended Relativistic framework for time transformation**  
  Aim: to give a set of formulas for practical transformations between relativistic time scales

- **IAU Resolution B1.6**  
  **IAU 2000 Precession-Nutation Model**  
  Aim: to provide a model with submilliarcsecond accuracy

- **IAU Resolution B1.7**  
  **Definition of Celestial Intermediate Pole**  
  Aim: to refine the CEP definition and realize the pole in the high frequency domain

- **IAU Resolution B1.8**  
  **Definition and use of the TEO and CEO**  
  Aim: to allow an accurate estimation of UT1, precession-nutation separately

- **IAU Resolution B1.9**  
  **Re-definition of TT**  
  Aim: to clarify the TT/TCG relationship

- **The IERS and SOFA (2003)**  
  have made available the models and procedures to implement these resolutions operationally (including both the new and classical paradigms)

Joint Discussion 16, IAU GA, Prague, 22-23 August 2006

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IAU WG “Nomenclature for Fundamental Astronomy” (NFA)  
http://syrte.obspm.fr/iauWGnfa

NFA IAU Division 1 WG created at the 24th IAU General Assembly (July 2003)

General task of the NFA Working group:  
*to provide proposals for new nomenclature associated with the implementation of the IAU 2000 resolutions and to make related educational efforts for addressing the issue to a large community of scientists.*

<table>
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<th>NFA Recommendations</th>
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<td>IAU Resolution proposals</td>
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<tr>
<td>Explanatory documents including a detailed glossary</td>
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- **The Almanac offices**  
  have begun to implement the resolutions with their 2006 editions

- **USNO Circular 179 (G. Kaplan, 2005)**  
  provides an explanatory and implementation information concerning the IAU resolutions and astronomical reference systems

Joint Discussion 16, IAU GA, Prague, 22-23 August 2006
Nomenclature issues

The IAU2000 precession-nutation and the frame bias

Nutation: IAU2000A: 678 luni-solar terms & 687 planetary terms at 1 μas (IAU 2000 B: shorter version at 1 mas)

Precession: IAU 1976 + corrections to precession rates: \( \Delta \varphi (\text{IAU} 2000) = -0.29965 / \text{cy} \), \( \Delta \epsilon (\text{IAU} 2000) = -0.02524 / \text{cy} \)

CIP

\( G X_m Y_m Z_m \): mean celestial frame at epoch

\( G X_m Z_m Y_m \): GCRS

VLBI estimates

\( \varphi_0 (\text{IAU} 2000) = -0.0166170 \)

\( \epsilon_0 (\text{IAU} 2000) = -0.0068192 \)

\( 5.5 \text{ mas} \)

56.8 mas

44.5 mas

41 (CRS) = +23°24′21″.404

14 (CRS) = 148°.404

\( 56.8 \text{ mas} \)

\( 0.9 \text{ mas} \)

\( \Delta a_0 = -14.6 \text{ mas} \)

offset in RA of the J2000 mean dynamical equinox w.r.t. the GCRS

express associated with the IAU 2000 precession-nutation in the GCRS

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The IAU2000 precession-nutation and the Celestial Intermediate Pole

IAU 1980: the CEP definition
IRP-CEP: 8.7 mas at 1s.d.

IAU 2000: the CIP definition
extension of the CEP definition to the high frequency domain
20 μas at 1s.d., 40 μas at 0.5 s.d. in the GCRS
100 μas at 1s.d., 200 μas at 0.5 s.d. in the ITRS

(with frequency ω, such that: $\omega_{\text{GCRS}} = \omega_{\text{ITRS}} + 1$)

<table>
<thead>
<tr>
<th>frequency in the ITRS</th>
<th>polar motion</th>
<th></th>
<th>nutation</th>
<th>polar motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>−3.5</td>
<td>−2.5</td>
<td>−1.5</td>
<td>+0.5</td>
<td>+1.5</td>
</tr>
</tbody>
</table>

celestial motion: IAU 2000 precession-nutation for periods > 2 days + offsets
nutations with periods < 2 days included in model for the pole motion in the ITRS

→ nomenclature associated
  - with the precession-nutation of the CIP (defined by a convention)
  - with the use of the “intermediate” pole and equator

Nomenclature associated with the change of the origin on the intermediate equator

Using the new origin CIO (originally called CEO)
Earth Rotation Angle: $\theta = k \UT1$; $d\theta/dt = \omega_J$

Using the equinox (with implicit use of CIO)
sidereal time: $\GMST (\UT1, \TT) + \text{“equation of the equinoxes”}$
  = $\theta (\UT1) + \text{accumulated precession/nutation in RA}$

→ Give a name to the “intermediary” systems (celestial and terrestrial) between the geocentric celestial system and the terrestrial system, which are realized by using the models, constants and procedures that are conventionally accepted.
The NFA WG Glossary: a few examples of newly proposed terms

Celestial Intermediate Origin (CIO): origin for right ascension on the intermediate equator in the celestial intermediate reference system. It is the non-rotating origin in the GCRS that is recommended by the IAU 2000 Resolution B.1.8, where it was designated the Celestial Ephemeris Origin. The CIO was originally set close to the GCRS meridian and throughout 1900-2100 stays within 0.1 arcseconds of this alignment.

equation of the origins: distance between the CIO and the equinox along the intermediate equator; it is the CIO right ascension of the equinox; alternatively the difference between the Earth rotation angle and Greenwich apparent sidereal time (ERA – GAST).

CIO locator (denoted $s$): the difference between the GCRS right ascension and the intermediate right ascension of the intersection of the GCRS and intermediate equators. The CIO was originally set close to the mean equinox at J2000.0. As a consequence of precession-nutation the CIO moves according to the kinematical property of the non-rotating origin. The CIO is currently located by using the quantity $s$.

TIO locator (denoted $\theta$): the difference between the ITRS longitude and the instantaneous longitude of the intersection of the ITRS and intermediate equators. The TIO was originally set at the ITRF origin of longitude. As a consequence of polar motion the TIO moves according to the kinematical property of the non-rotating origin. The TIO is currently located using the quantity $\theta$, whose rate is of the order of 50 mas/cy which is due to the current polar motion.

Nomenclature associated with the equatorial coordinates

- nomenclature associated with the use of the new origins,
- nomenclature associated with the ICRS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>RA, right ascension</td>
</tr>
<tr>
<td>$\beta$</td>
<td>RA$_c$, intermediate right ascension, CIO right ascension</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Dec, DEC, declination</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>RA, right ascension</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>ICARS right ascension</td>
</tr>
<tr>
<td>$\theta$</td>
<td>TIO, origin of longitude</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Dec, DEC, declination measured from the ICARS equator</td>
</tr>
</tbody>
</table>

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The NFA WG Glossary: a few examples of newly proposed terms

**Celestial Intermediate Reference System (CIRS):** geocentric reference system related to the GCRS by a time-dependent rotation taking into account precession-nutation. It is defined by the intermediate equator (of the CIP) and CIO on a specific date. It is similar to the system based on the true equator and equinox of date, but the equatorial origin is at the CIO. Since the acronym for this system is close to another acronym (namely ICRS), it is suggested that wherever possible the complete name is used.

**intermediate right ascension and declination:** angular coordinates measured in the celestial intermediate reference system at a specified date. They specify a geocentric direction that differs from the ICRS direction by annual parallax, gravitational light deflection due to the solar system bodies except the Earth, annual aberration, and the time-dependent rotation describing the transformation from the GCRS to the celestial intermediate reference system. They are similar to apparent right ascension and declination when referring to the equinox based system. Note that intermediate declination is identical to apparent declination.

Main NFA WG recommendations related to the pole and origin

- 2. Using “equinox based” and “CIO based” for referring to the classical and new paradigms, respectively.
- 3. Using “intermediate” to describe (i) the moving geocentric celestial reference system defined in the IAU 2000 Resolutions (i.e. containing the CIP and the CIO), and (ii) the moving terrestrial system containing the CIP and the TIO.
- 4. Harmonizing the name of the pole and the origin to “intermediate” and therefore changing CEO/TEO to CIO/TIO.
- 5. Using “system” in a broad sense rather than “frame” in this context of the intermediary system/frame.
- 8. Choosing “equinox right ascension” (or “RA with respect to the equinox”) and “intermediate right ascension” (or “CIO right ascension”, or “RA with respect to the CIO”), for the azimuthal coordinate along the equator in the classical and new paradigms, respectively.
- 9. Giving the name “equation of the origins” to the distance between the CIO and the equinox along the intermediate equator, the sign of this quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the Earth Rotation Angle and Greenwich apparent sidereal time.
Nomenclature associated with the use of the BCRS and GCRS

Definition of BCRS and GCRS

IAU Resolution B1.3 : Clarification of IAU's 1991 definition of the coordinate systems in the framework of GR: distinction between the celestial systems
- a) for Solar System (BCRS) which can be considered to be a global coordinate system that contain all the ‘far away regions’
- b) for the Earth (GCRS) which can only be considered as a local coordinate system

Transformation BCRS/GCRS

$$X^* = X + \frac{1}{2} TCB \left[ TCB \right]_3 \left[ \frac{1}{2} \chi_0 + \omega_x \chi_1 \chi_2 + \chi_4 \chi_3 \right] - \delta \left[ C \right]^T$$

Orientation issue: relationship ICRS/BCRS; orientation of the BCRS axes?

Terrestrial Dynamical Time, TDB

TDB was originally stated to differ from TT by periodic terms only

TDB issue: question on a description of TDB as it is currently understood:
- how literally to take “periodic terms”.
- lack of a rigorous definition of TDB even in principle.
- JPL had independently implemented the TDB “idea” and had called the result $T_{eph}$.
Joint Discussion 16, IAU GA, Prague, 22-23 August 2006

IAU Resolution 3
Re-definition of Barycentric Dynamical Time, TDB

The XXVIth International Astronomical Union General Assembly,

Noting

1. that IAU Recommendation 5 of Commissions 4, 8 and 31 (1976) introduced, as a replacement for Ephemeris Time (ET), a family of dynamical time scales for barycentric ephemerides and a unique time scale for apparent geocentric ephemerides,

2. that IAU Resolution 5 of Commissions 4, 19 and 31 (1979) designated these time scales as Barycentric Dynamical Time (TDB) and Terrestrial Dynamical Time (TDT) respectively, the latter subsequently renamed Terrestrial Time (TT), in IAU Resolution A4, 1991,

3. that the difference between TDB and TDT was stipulated to comprise only periodic terms, and

4. that Recommendations II and V of IAU Resolution A4 (1991) (i) introduced the coordinate time scale Barycentric Coordinate Time (TCB) to supersede TDB, (ii) recognized that TDB was a linear transformation of TCB, and (iii) acknowledged that, where discontinuity with previous work was deemed to be undesirable, TDB could be used, and

NFA WG recommendations related to BCRS and TDB

• 13. Fixing the default orientation of the BCRS so that for all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes.

• 14. Re-defining Barycentric Dynamical Time (TDB) so that TDB is a fixed linear function of TCB.
The NFA WG recommendations

NFA WG recommendations and guidelines on terminology

- 1. Using existing terms (e.g. right ascension) in extended ways for the terminology associated with the new paradigm with a clear specification, rather than introducing new names.
- 2. Using “equinox based” and “CIO based” for referring to the classical and new paradigms, respectively.
- 3. Using “intermediate” to describe (i) the moving geocentric celestial reference system defined in the IAU 2000 Resolutions (i.e. containing the CIP and the CIO), and (ii) the moving terrestrial system containing the CIP and the TIO.
- 4. Harmonizing the name of the pole and the origin to “intermediate” and therefore changing CEO/TEO to CIO/TIO.
- 5. Using “system” in a broad sense rather than “frame” in this context of the intermediary system/frame.
- 6. Using special designations for particular realizations of the intermediate celestial system.
- 7. Keeping the classical terminology for “true equator and equinox” (or “true equinox based”) for the classical equatorial system.
- 8. Choosing “equinox right ascension” (or “RA with respect to the equinox”) and “intermediate right ascension” (or “CIO right ascension”, or “RA with respect to the CIO”), for the azimuthal coordinate along the equator in the classical and new paradigms, respectively.
NFA WG recommendations and guidelines on terminology

• 9. Giving the name “equation of the origins” to the distance between the CIO and the equinox along the intermediate equator, the sign of this quantity being such that it represents the CIO right ascension of the equinox, or equivalently, the difference between the Earth Rotation Angle and Greenwich apparent sidereal time.

• 10. Retaining “apparent places” and “mean places” in the equinox based system.

• 11. Not introducing “apparent intermediate places” in the CIO based system, but introducing instead “intermediate places”.

• 12. Using “ITRF zero-meridian” to designate the plane passing through the geocenter, ITRF pole and ITRF x-origin and using, if necessary, “TIO meridian” to designate the moving plane passing through the geocenter, the CIF and the TIO.

• 13. Fixing the default orientation of the BCRS so that for all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes.

• 14. Re-defining Barycentric Dynamical Time (TDB) so that TDB is a fixed linear function of TCB.

The NFA WG Explanatory document
Explanatory document Part B

IAU 2000 Glossary
- updated definitions (BCRS, GCRS, CIO, TIO, TDB, TT)
- new definitions (equinox based/CIO based, intermediate, etc.

Summary of terms and definitions, procedures
Chart

Chart: transformation from ICRS to apparent places of stars in the ITRS

CIO based  equinox based
The NFA WG educational documents

Web page on educational documents at: http://syrte.obspm.fr/iauWGnfa

1) Presentations (PDF files)
- A new definition of Barycentric Dynamical Time (PW)
- Latest proposals of the IAU Working Group on Nomenclature for fundamental astronomy (NC)
- Recent progress in astronomical nomenclature in the relativistic framework (SK & MS)
- The ICRS, BCRS and GCRS, ITRS (SK & MS)
- Progress on the implementation of the new nomenclature in "The Astronomical Almanac" (CH & GK)
- The IAU Recommendations on Reference Systems and their applications (NC & DMC)
- Recent International Recommendations on reference Systems (DMC)
- SOFA software support for IAU 2000 (PW)
- Développements récents des concepts et des modèles en Astronomie fondamentale (NC)
- VLBI contribution to precession (present and future) (NC & PW)
- Effect of the VLBI procedure on the estimated quantities for precession, nutation and UT1 (NC)
- 3D representation of the Non-Rotating Origin (O. de Viron, V. Dehant) (PPT presentation with movies, either on line, or zip file)

2) Examples
- An example transformation (PW): Application of the IAU 2000 resolutions concerning Earth orientation and rotation. The objective is to predict the topocentric apparent direction of a star
The NFA WG resolutions proposed to the XXVIth IAU GA

IAU Resolution 2
Supplement to the IAU Resolutions on reference systems

RECOMMENDATION 1. Harmonizing the name of the pole and origin to "intermediate"
The XXVIIth International Astronomical Union General Assembly,

Noting:
1. the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000,
2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFIA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Officers have begun to implement them beginning with their 2006 editions, and
3. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XVIIa, 2005), and

Recognizing:
1. that using the designations "intermediate" in refer to both the pole and the origin of the new systems linked to the Celestial Intermediate Pole and the Celestial or Terrestrial Ephemeris origins, defined in Resolutions B1.7 and B1.8, respectively would improve the consistency of the nomenclature, and
2. that the more "Conventional International Origin" with the potentially conflicting acronym "CIO" is no longer commonly used to refer to the reference pole for measuring polar motion as it was in the past by the International Latitude Service,

Recommends:
1. that the designation "intermediate" be used to describe the moving celestial and terrestrial reference systems defined in the 2000 IAU Resolutions and the various related systems, and
2. that the terminology "Celestial Intermediate Origin" (CIO) and "Terrestrial Intermediate Origin" (TIO) be used in place of the previously introduced "Celestial Ephemeris Origin" (CEO) and "Terrestrial Ephemeris Origin" (TEO), and
3. that authors carefully define axioms used to designate entities of astronomical reference systems to avoid possible confusion.
**IAU Resolution 2**

**Supplement to the IAU Resolutions on reference systems**

**RECOMMENDATION 2. Default orientation of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS)**

The XXVIIth International Astronomical Union General Assembly,

Noting

1. the adoption of resolutions IAU B1.1 through B1.8 by the IAU General Assembly of 2000,
2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFAR) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Office have begun to implement them beginning with their 2006 editions,
3. that, in particular, the systems of space-time coordinates defined by IAU 2000 Resolution B1.3 for the solar system (called the Barycentric Celestial Reference System, BCRS) and B1.5 for the Earth (called the Geocentric Celestial Reference System, GCRS) have begun to come into use,
4. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIa, 2005), and
5. a recommendation from the IAU Working Group on "Relativity in Celestial Mechanics, Astronomy and Metrology".

Recommending

1. that the BCRS definition does not determine the orientation of the spatial coordinates,
2. that the natural choice of orientation for typical applications is that of the ICRS, and
3. that the GCRS is defined such that its spatial coordinates are kinematically non-rotating with respect to those of the BCRS,

Recommends

that the BCRS definition is completed with the following: "For all practical applications, unless otherwise stated, the BCRS is assumed to be orientated according to the ICRS axes. The orientation of the GCRS is derived from the IERS-oriented BCRS."

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**IAU Resolution 3**

**Re-definition of Barycentric Dynamical Time, TDB**

The XXVIIth International Astronomical Union General Assembly,

Noting

1. that IAU Recommendation 5 of Commissions 4, 8 and 31 (1976) introduced, as a replacement for Ephemeris Time (ET), a family of dynamical time scales for barycentric ephemerides and a unique time scale for apparent geocentric ephemerides,
2. that IAU Resolution 5 of Commissions 4, 19 and 31 (1979) designated these scales as Barycentric Dynamical Time (TDB) and Terrestrial Dynamical Time (TDT) respectively, the latter subsequently renamed Terrestrial Time (TT), in IAU Resolution A4, 1991,
3. that the difference between TDB and TDT was stipulated to comprise only periodic terms, and
4. that Recommendations III and V of IAU Resolution A4 (1991) (i) introduced the coordinate time scale Barycentric Coordinate Time (TCB) to supersede TDB, (ii) recognized that TDB was a linear transformation of TCB, and (iii) acknowledged that, where discontinuity with previous work was deemed to be undesirable, TDB could be used, and
Recognizing

1. that TCB is the coordinate time scale for use in the Barycentric Celestial Reference System,
2. the possibility of multiple realizations of TDB as defined currently,
3. the practical utility of an unambiguously defined coordinate time scale that has a linear relationship with TCB chosen so that at the geocenter the difference between this coordinate time scale and Terrestrial Time (TT) remains small for an extended time span,
4. the desirability for consistency with the Toph time scales used in the Jet Propulsion Laboratory (JPL) solar-system ephemerides and existing TDB implementations such as that of Fairhead & Bézagnon (A&A 229, 240, 1990), and
5. the 2006 recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVII, 2006),

Recommends

that, in situations calling for the use of a coordinate time scale that is linearly related to Barycentric Coordinate Time (TCB) and, at the geocenter, remains close to Terrestrial Time (TT) for an extended time span, TDB be defined as the following linear transformation of TCB:

\[ TDB = TCB - L_\phi \times (JD_{TCB} - T_0) \times 86400 + TDB_0, \]

where \( T_0 = 2443144.5003725 \),
and \( L_\phi = 1.5585197086 \times 10^{-5} \) and \( TDB_0 = -6.55 \times 10^{-5} \) are defining constants.

(slight revisions in the wording, 21 August 2006: in red)

Joint Discussion 16, IAU GA, Prague, 22-23 August 2006

Notes

1. \( JD_{TCB} \) is the TCB Julian date. Its value is \( T_0 = 2443144.5003725 \) for the event 1977 January 1 0h0m0s TAI at the geocenter, and it increases by one for each 86400s of TCB.
2. The fixed value that this definition assigns to \( L_\phi \) is a current estimate of \( L_\phi = L_0 \times \left( 1 - \frac{TDB}{TT} \right) \)
where \( L_0 \) is given in IAU Resolution B1.9 (2000) and \( L_\phi \) has been determined (Irwin & Fukushina, 1999, A&A, 348, 642) using the JPL ephemerides DE405. When using the JPL Planetary Ephemeris DE405, the defining \( L_\phi \) value effectively eliminates a linear drift between TDB and TT, evaluated at the geocenter. When realizing TCB using other ephemerides, the difference between TDB and TT, evaluated at the geocenter, may include some linear drift, not expected to exceed 1 ns per year.
3. The difference between TDB and TT, evaluated at the surface of the Earth, remains under 2 ns for several millennia around the present epoch.
4. The independent time argument of the JPL ephemeris DE405, which is called Toph (Standish, A&A, 336, 381, 1998), is for practical purposes the same as TDB defined in this Resolution.
5. The constant term \( TDB_0 \) is chosen to provide reasonable consistency with the widely used TDB - TT formula of Fairhead & Bézagnon (1990).
   n.b. The presence of \( TDB_0 \) means that TDB is not synchronized with TT, TCG and TCB at 1977 Jan 1.0 TAI at the geocenter.
6. For solar system ephemerides development the use of TCB is encouraged.

(slight revisions in the wording, 21 August 2006: in red)

Joint Discussion 16, IAU GA, Prague, 22-23 August 2006