Tools for Implementing the Recent IAU Resolutions: USNO Circular 179 and the NOVAS Software Package

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What are Circular 179 & NOVAS?

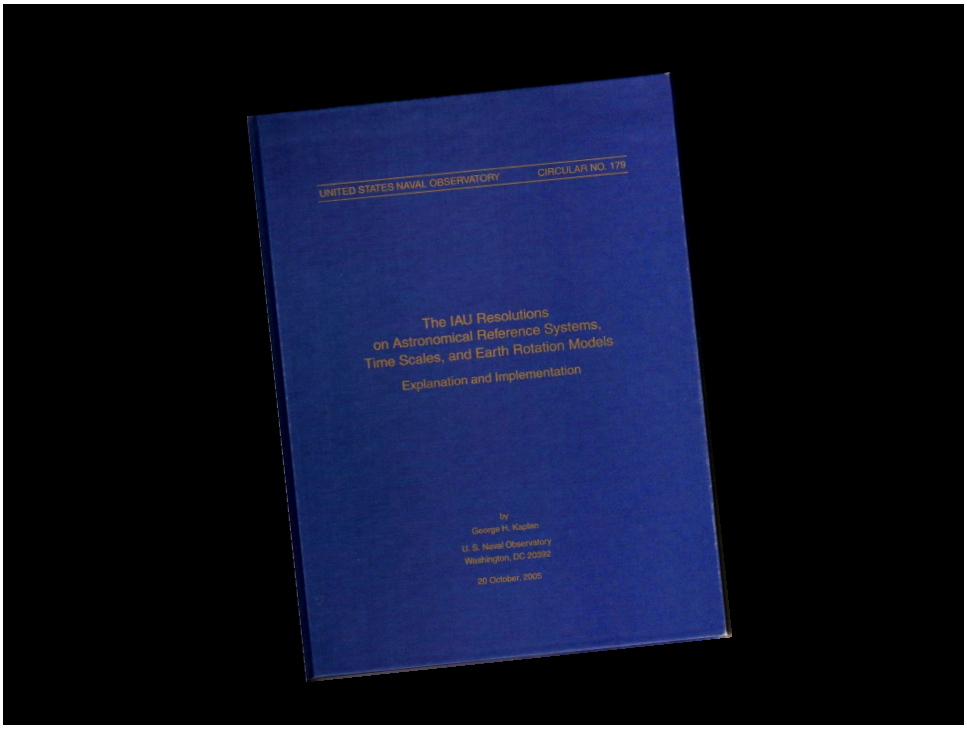
- **USNO Circular 179** (published October 2005) is a 116-page document attempting to explain the 1997 and 2000 IAU resolutions and provide algorithms for their implementation
  - Available as a hardcover book from USNO
  - Available as a free PDF on the web
- **NOVAS** — the Naval Observatory Vector Astrometry Subroutines — is a 25-year old source code package for performing many positional astronomy computations
  - now available in both Fortran and C
  - recently extensively updated for the "new IAU paradigm"

Possible Comparisons

Circular 179 ⟷ IERS Conventions

NOVAS ⟷ SOFA

We will return to these comparisons in a few minutes



USNO Circular 179

- Successor to USNO Circular 163 (of 1981) that summarized the IAU resolutions of 1976, 1979, and 1982
- IAU resolutions of 1997 and 2000 are much more complex, and involve more conceptual shifts

⇒ Circular 179 is a *lot* longer than Circular 163!
(116 pages vs. 32 pages)
… much of which is explanatory narrative

USNO Circular 179 — Overview

- Attempts to *explain* the recent IAU resolutions (especially those of 1997 and 2000)
  - Justification of changes from past practice (Why?)
  - Conceptual overview of new models/geometry (How?)
- Intended audience: People knowledgeable about positional astronomy but not necessarily subject-matter experts
- Six main chapters by subject
  - Not a resolution-by-resolution treatment
- All chapters have a Summary at the beginning
- Four of the six chapters have subsections at the end where the essential equations are given

USNO Circular 179 — Main Chapters

Main Chapter Titles

1. Relativity
2. Time Scales
3. The Fundamental Celestial Reference System
4. Ephemerides of Major Solar System Bodies
5. Precession and Nutation
6. Modeling the Earth's Rotation

USNO Circular 179 — Layout

- Table of Contents
- Introduction
  - History/context , Overview of Resolutions, About this Circular, Other Resources, Acknowledgments
- A Few Words about Constants
- Abbreviations and Symbols Frequently Used
- (6 main chapters — 66 pages)
- Text of IAU Resolutions of 1997
- Text of IAU Resolutions of 2000
- References (includes URLs)
- IAU 2000A Nutation Series (MHB)
- Errata & Updates

USNO Circular 179 — Acknowledgments

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Sergei Kopeikin, Brian Luzum

Thank you!

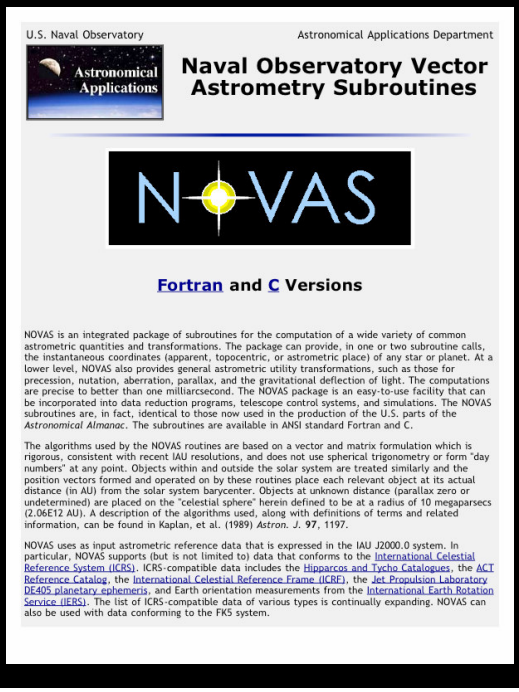
Circular 179 vs. IERS Conventions

Circular 179

- Both paper and online versions
- Intended for knowledgeable non-experts
- Covers mainly changes in positional astronomy concepts and models due to recent IAU resolutions
- Lots of background narrative, explanations of "why"
- Astronomically oriented; very little geophysics
- Written by one person
- Lists entire nutation series!

IERS Conventions

- Both paper and online versions
- Intended for experts
- Collection of models used for one specific type of data analysis, whether related to IAU resolutions or not
- Narratives limited to descriptions of individual models
- Lots of geophysical models
- Many contributors; chapters written by different people



U.S. Naval Observatory — Astronomical Applications Department

Astronomical Applications

Naval Observatory Vector Astrometry Subroutines

NOVAS

Fortran and C Versions

NOVAS is an integrated package of subroutines for the computation of a wide variety of common astrometric quantities and transformations. The package can provide, in one or two subroutine calls, the instantaneous coordinates (apparent, topocentric, or astrometric place) of any star or planet. At a lower level, NOVAS also provides general astrometric utility transformations, such as those for precession, nutation, aberration, parallax, and the gravitational deflection of light. The computations are precise to better than one milliarcsecond. The NOVAS package is an easy-to-use facility that can be incorporated into data reduction programs, telescope control systems, and simulations. The NOVAS subroutines are, in fact, identical to those now used in the production of the U.S. parts of the *Astronomical Almanac*. The subroutines are available in ANSI standard Fortran and C.

The algorithms used by the NOVAS routines are based on a vector and matrix formulation which is rigorous, consistent with recent IAU resolutions, and does not use spherical trigonometry or form "day numbers" at any point. Objects within and outside the solar system are treated similarly and the position vectors formed and operated on by these routines place each relevant object at its actual distance (in AU) from the solar system barycenter. Objects at unknown distance (parallax zero or undetermined) are placed on the "celestial sphere" herein defined to be at a radius of 10 megaparsecs (2.06E12 AU). A description of the algorithms used, along with definitions of terms and related information, can be found in Kaplan, et al. (1989) *Astron. J.* **97**, 1197.

NOVAS uses as input astrometric reference data that is expressed in the IAU J2000.0 system. In particular, NOVAS supports (but is not limited to) data that conforms to the International Celestial Reference System (ICRS). ICRS-compatible data includes the Hipparcos and Tycho Catalogues, the ACT Reference Catalog, the International Celestial Reference Frame (ICRF), the Jet Propulsion Laboratory DE405 planetary ephemeris, and Earth orientation measurements from the International Earth Rotation Service (IERS). The list of ICRS-compatible data of various types is continually expanding. NOVAS can also be used with data conforming to the FK5 system.

NOVAS — History

- Started as a Fortran package in the late 1970s to compute apparent places of stars and planets in according to the IAU resolutions of 1976, 1979, and 1982
  - Used vector/matrix methods instead of spherical trig
  - Treated stars and planets (almost) identically
  - Used C. A. Murray's relativistic developments of aberration and gravitational light-bending
  - Had several options for obtaining basic solar system ephemerides, including from the JPL DE series
- Expanded and revised over the years
  - New functions, such as topocentric places
  - Revisions due to IAU resolutions

continued…

NOVAS — History (cont.)

- C version added in 1996
- Extensive user base, both civilian and US government
- Used as basis for US sections of *The Astronomical Almanac* and MICA

⇒ Long history and extensive user base means that existing calling sequences are generally maintained, at least for the high-level subroutines/functions

NOVAS — Basis

- Explanatory Supplement to the Astronomical Almanac
- JPL planetary/lunar ephemerides
- Hipparcos documentation
- Klioner (2003) AJ paper on precise astrometry from space
- Lindegren & Dravins (2003) A&A paper on radial velocity
- Kaplan (2003) JD16 paper on computing the CIO position
- Circular 179
- IERS Conventions (2003)
  - specifically including IERS subroutines NU2000A and EECT2000
- Capitaine, Wallace, & Chapront (2003) A&A paper on P03 precession

Note: NOVAS now uses P03 precession

NOVAS — Validation

- C vs. Fortran checks
- vs. HMNAO software, based on SOFA
- vs. VLBI delay algorithm (for aberration and light-bending) — Kaplan (1998) AJ paper
- self-consistency and special-case checks
- vs. other equivalent code (e.g., spherical trig based code)
- Other checks, using JPL Horizons, ARI APFS, etc.

NOVAS — Features

- Many high-level subroutine/functions for easy use by non-experts
  - "normal" defaults — fail safe
- Treats stars and solar system objects similarly so that the same algorithms can be used for both
  - Internally uses position vectors in AU rather than unit vectors
- Often provides more than one way to do a given thing
- Uses a single subroutine/function name for each operation or process (e.g., aberration or precession); allows alternative models to be easily "swapped in"
- Automatically avoids expensive redundant calculations
- C code quasi-independent of Fortran (not "C-tran"); designed to be both efficient and readable

NOVAS — RA Origin

- NOVAS can supply celestial coordinates with respect to either the equinox or CIO
- Position of CIO is computed in one of two ways:

1. Computed from analytical expression for the equation of the origins — the arc along the instantaneous (intermediate) equator between the equinox and the CIO

or

2. Obtained from a pre-computed file of the RA of the CIO as a function of time (in the GCRS) from a numerical integration

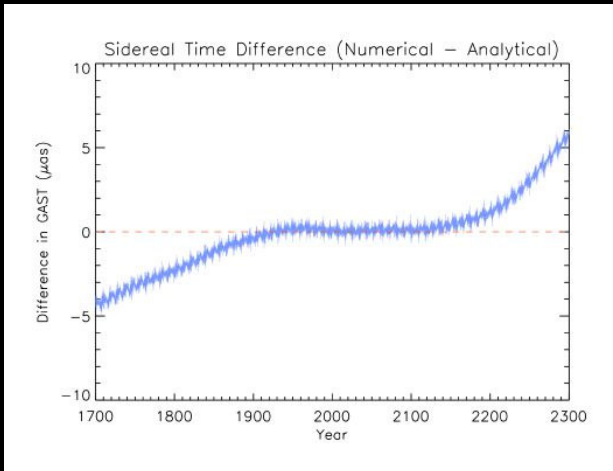
- Note that s is not used anywhere in NOVAS

NOVAS — RA Origin

Effect of numerical vs. analytical position of CIO on sidereal time computation over 6 centuries

P03 + MHB

y-axis runs from –10 to +10 microarcseconds



NOVAS vs. SOFA

NOVAS

- Canonical or equivalent
- Available in both Fortran and C
- No formal independent oversight
- Emphasis on higher-level capabilities; top-down design
- Can be used by non-experts
- Each physical effect has a different subroutine name, but not different models
- Updates and additions constrained by requirement for backwards compatibility

SOFA

- Canonical
- Available in Fortran (C planned)
- Oversight by international SOFA review board
- Emphasis on individual models; a building-block approach
- Requires some expertise
- Each model has a different subroutine name
- Based on a low-level library of vector & matrix functions
- Elegant code! A pleasure to read

Issues

- No list of adopted IAU constants any more
- What do we call P03 + MHB?
- The IAU has defined the BCRS and the GCRS, but no established definition/description (or nomenclature for) a topocentric reference system
- The BCRS/GCRS paradigm is based on SI units, yet all our current models are based on TDB (neither TCG or TCB is explicitly used in NOVAS — no model uses them)
- The "J2000.0 system" — the mean equator and equinox of J2000.0 — was used both as a barycentric and geocentric system, so it can be difficult to figure out (or explain) how some traditional concepts or algorithms apply to the BCRS or GCRS

URLs

USNO Circular 179:

http://aa.usno.navy.mil/publications/docs/Circular_179.html

or

http://arxiv.org/abs/astro-ph/0602086

or simply Google 'Circular 179'

NOVAS:

http://aa.usno.navy.mil/software/novas/new_novas_f