IAU 2000 Resolutions for the General User

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Presentation outline

- Important changes even before 2000.
- The IAU 2000 resolutions.
- So what's new?
- What difference will it make to me?
- Future challenges.

Why some astronomers are suspicious

- Sidereal time seems to have gone...
- ...and so have equinox and ecliptic: why?
- The new zero point for right ascension is something elusive called a “non-rotating origin”.

Even before 2000

- B1950 star positions had already died out: everyone was using something they called “FK5 J2000” or “equinox J2000” (or even “epoch J2000”).
- But in fact by then we were all using “ICRS”, realized in the optical by the Hipparcos catalog.
- The successive “equinoxes” had been used formerly so that star catalogs never got too out of step with where the celestial pole and equinox had actually precessed to.
- But ICRS is permanently frozen, close (~23mas) to the J2000 mean equator and equinox. There will never be a change to J2050 (and we no longer have to say “J2000”).

IAU 2000 Resolutions B1

- B1.1 Maintenance and Establishment of Reference Frames and Systems
- B1.2 Hipparcos Celestial Reference Frame
- ✓ **B1.3 Definition of Barycentric Celestial Reference System and Geocentric Celestial Reference System**
- B1.4 Post-Newtonian Potential Coefficients
- B1.5 Extended relativistic framework for time transformations and realization of coordinate times in the solar system
- ✓ **B1.6 IAU 2000 Precession-Nutation Model**
- ✓ **B1.7 Definition of Celestial Intermediate Pole**
- ✓ **B1.8 Definition and use of Celestial and Terrestrial Ephemeris Origins**
- B1.9 Re-definition of Terrestrial Time TT

...in particular

- Two celestial reference systems introduced — BCRS for barycentric uses and GCRS for geocentric uses — and the GR spacetime transformation between them defined. They have (in essence) the same orientation as ICRS, but the BCRS-GCRS transformation includes light deflection and annual aberration as well as annual parallax. (GAIA will use BCRS.)
- Much more accurate precession-nutation models introduced (IAU 2000A).
- A new definition of the celestial pole (CIP).
- New origins for right ascension (CIO*) and zero longitude (TIO*). Ecliptic and equinox no longer involved. Earth rotation angle (ERA) replaced sidereal time.

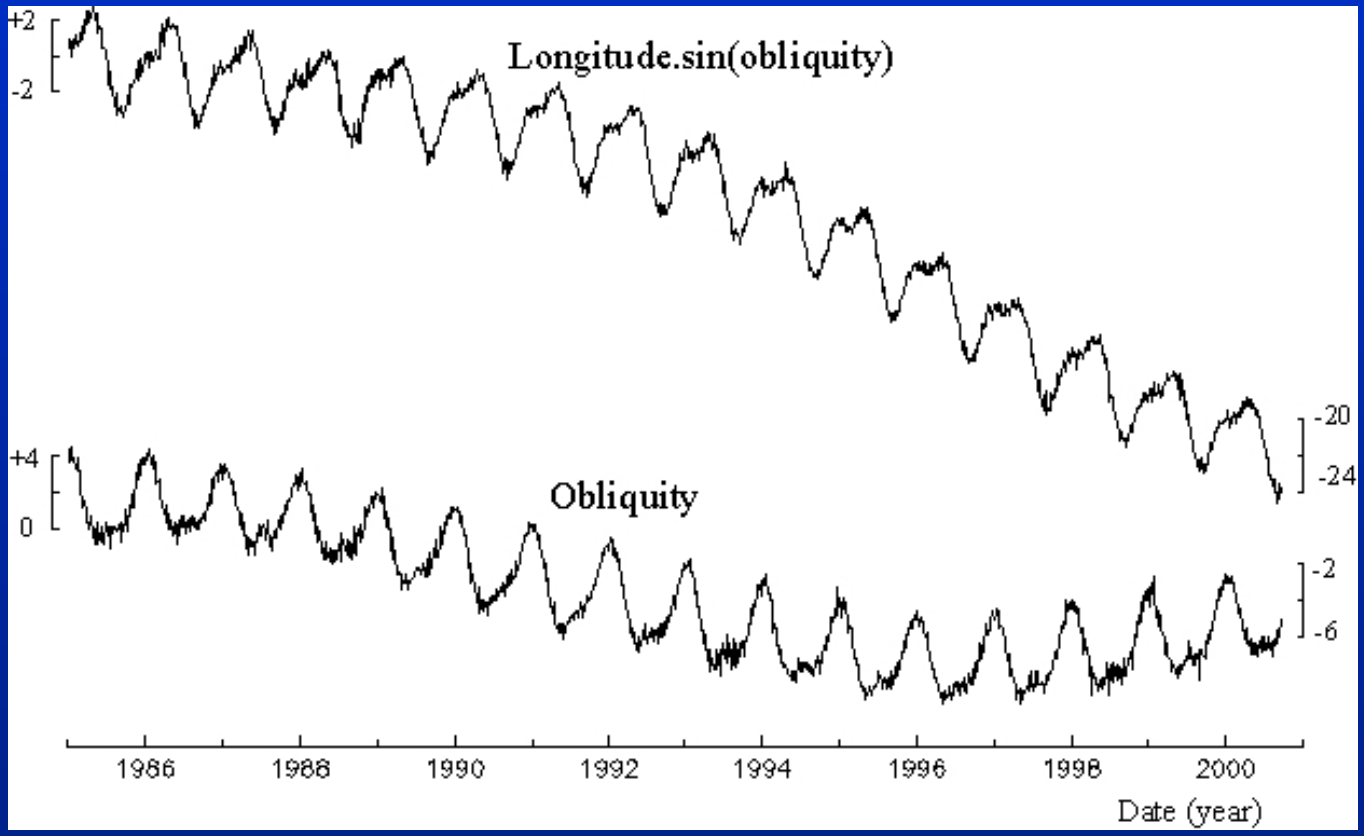
*originally CEO and TEO

Celestial pole and Earth rotation

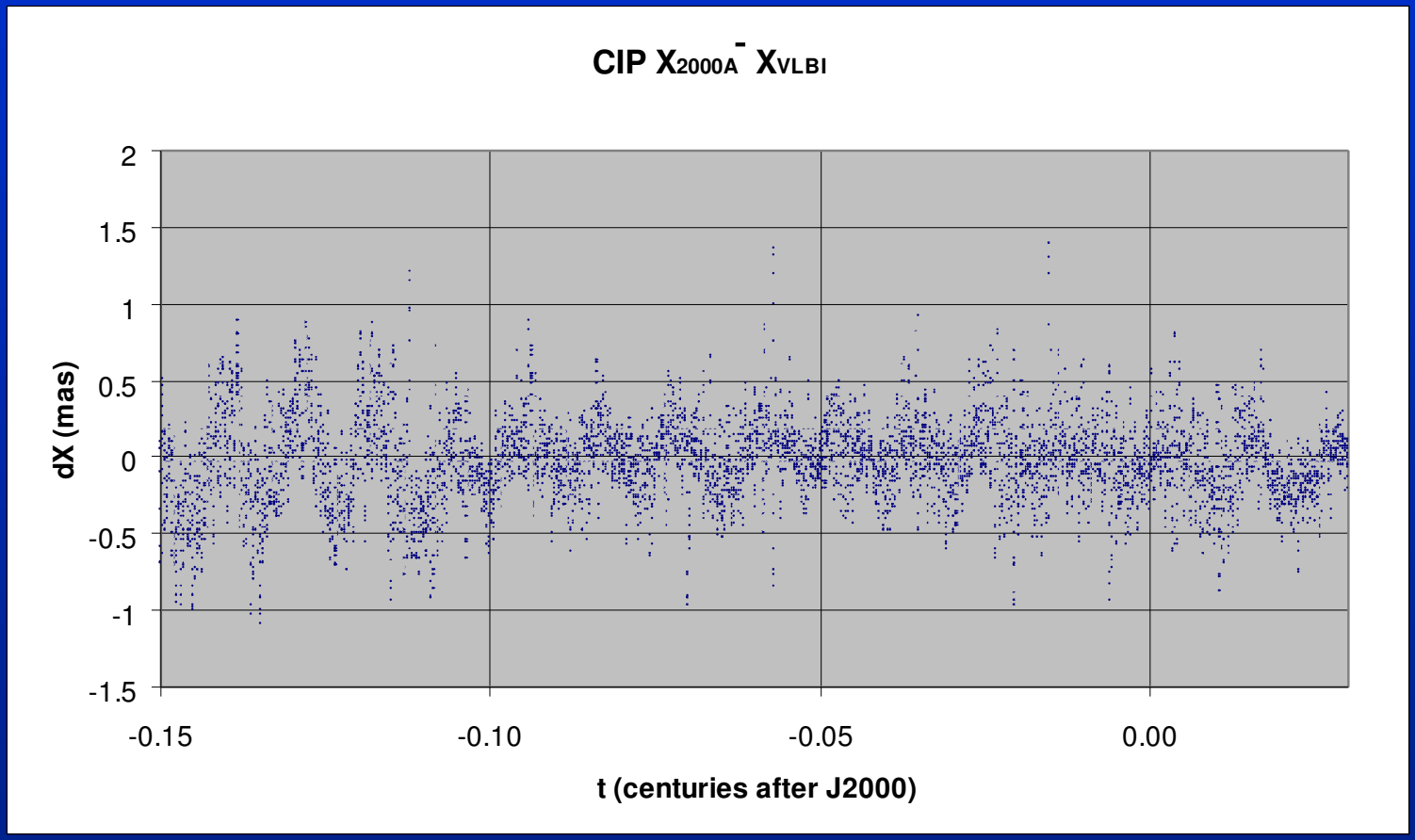
- New precession-nutation model:
  - Quasi-classical, using IAU 1976 precession and IAU 1980 obliquity as a basis
  - New nutation series + frame bias and precession-rate corrections
- New way to express Earth rotation:
  - “Earth rotation angle” proportional to UT1
  - Zero point for the matching RA is a “non-rotating origin”

Why new PN models were needed

Errors in 1976/1980 precession-nutation model (mas) from VLBI



Free core nutation: the “noise floor”



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Accuracies now available

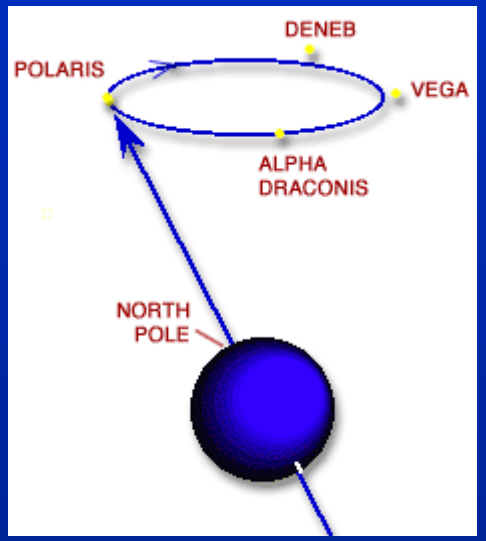
- Earth orientation known to 300 μas RMS, ~ 1 cm
- Smallest terms in nutation model ~ 1 μas
- Size of nutation model = 1365×2×2 coefficients
- Error in former IAU 1976 precession ~ 3 mas/y
- Uncertainty in IAU 2000 precession ~ 30 μas/y
- Nutation-model noise floor ~ 500 μas (from FCN)

n.b.

- 1 mas (~Hipparcos) is the aberration you get from walking pace
- 1 μas is about 30 μm at Earth's surface

Precession-nutation and Earth rotation

- Astronomers have traditionally talked of the "precession of the equinoxes" and also have distinguished between luni-solar precession, planetary precession and general precession.
- But to the layman precession is simply about what the Earth's rotation axis does.
- This is also the IAU 2000 picture: precession-nutation describes the motion of the pole with respect to the stars. The ecliptic has only a "behind the scenes" role.
- In the IAU 2000 "new paradigm", the clean separation between the formulations for the pole's motion and Earth rotation respectively makes things simpler still by eliminating crosstalk from the former to the latter, as can be seen by comparing GST and ERA.



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The change from GST to ERA

That familiar pre-2000 expression for sidereal time:

$$GST_{1982}\,(0h) = 24110.54841 + 8640184.812866\,t_{UT} + 0.093104\,t_{UT}^{2} - 6.2e\text{-}6\,t_{UT}^{3} + \Delta\psi\cos\varepsilon + \text{small correction terms (2)}$$

The even more complicated IAU 2000 expression:

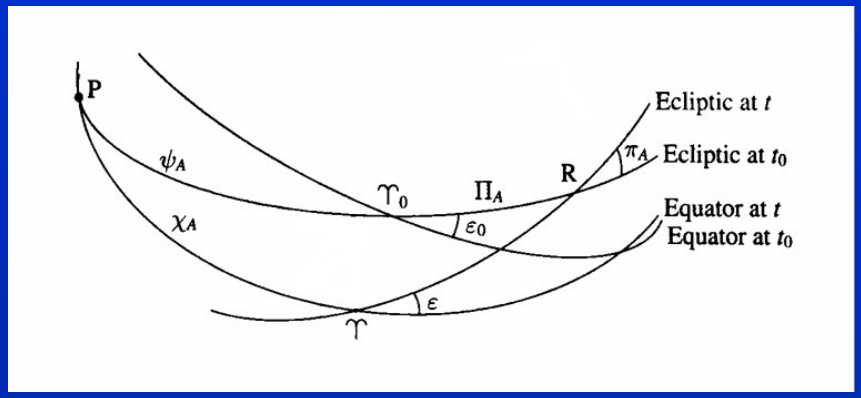
$$GST_{2000}\,(0h) = 24110.5493771 + 8639877.317376\,t_{UT} + 307.4771600\,t_{TT} + 0.0931118\,t_{TT}^{2} - 0.0000062\,t_{TT}^{3} + 0.0000013\,t_{TT}^{4} + \Delta\psi\cos\varepsilon + \text{small correction terms (34)}$$

The much more straightforward Earth rotation angle formula:

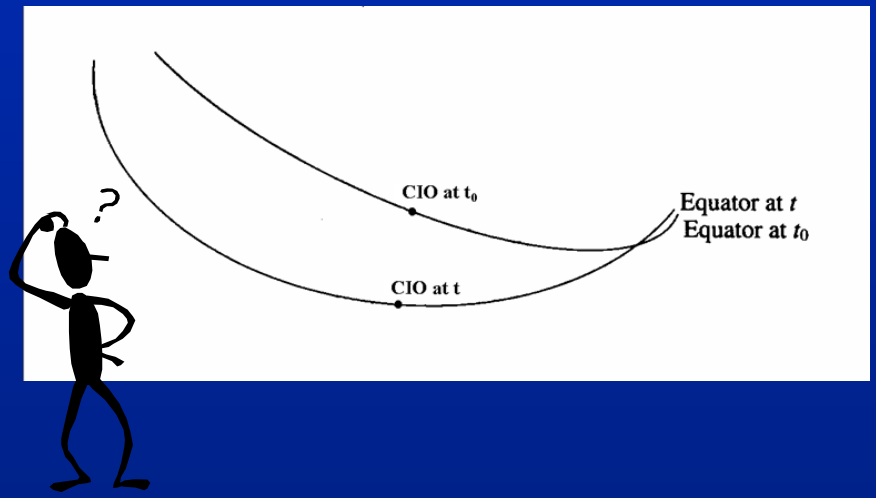
$$ERA\,(0h) = 24110.54841 + 8639877.317376\,t_{UT}$$

CIO: the new zero point of right ascension

- Classical: zero point defined geometrically, by intersection with ecliptic. Messy (intersection of *two* moving planes) but familiar.



- New: zero point defined kinematically. Tidy but unfamiliar.



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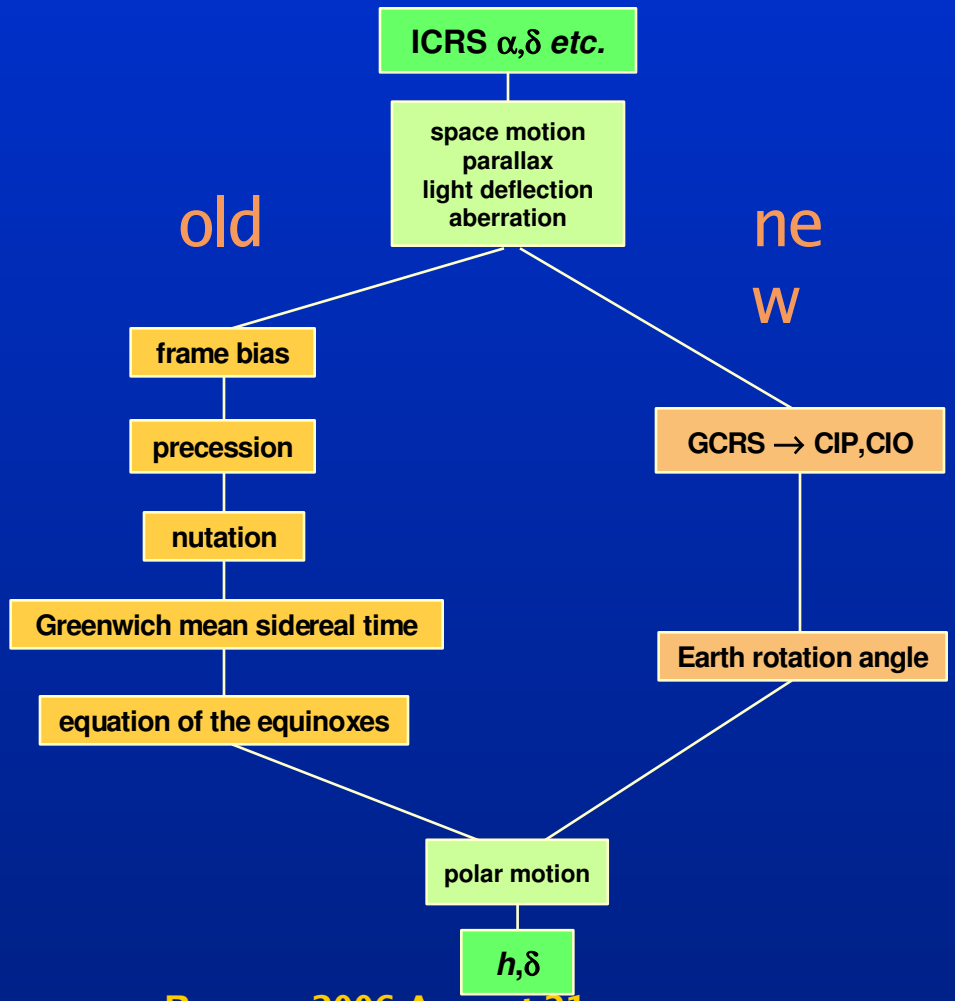
Where is the CIO?

- The CIO is merely a point on the moving celestial equator that stays as still as it can.
- Obviously, it has to move north-south in the sky as the equator precesses…
- …but the CIO doesn't move *along* the equator: from moment to moment it moves only *at right-angles to the equator*.
- In fact it does creep along a bit, but *very* slowly.
- The CIO's present α_{ICRS} is about $00^h\ 00^m\ 00^s.0001$; by the end of the century it will have drifted only as far as $\alpha_{ICRS} = 0^h\ 00^m\ 00^s.0046$.
- Best introduced to students as "a point on the celestial equator close to $\alpha_{ICRS} = 0$"; the correct kinematical definition can come later.

So what happened to the ecliptic?

- The ecliptic remains important in a qualitative and descriptive sense…
- …and is part of constructing a precession model…
- …but is no longer needed to define the zero point of right ascension.
- The ecliptic is in any case a slippery concept:
  - Is it defined by the Earth-Moon barycenter's path, or the orbital angular momentum vector? *n.b.* Difference ~0.1".
  - Does the ecliptic plane go through the Sun? The solar-system barycenter? The Earth-Moon-Sun barycenter?
  - What about long-period nutation terms?

Old and new ways of calculating h, δ



Predicting h, δ , old and new: example

2004 May 31, 22^h UTC
$\lambda = -104.9950$, $\varphi = +39.7427$
fictitious star
polar motion omitted

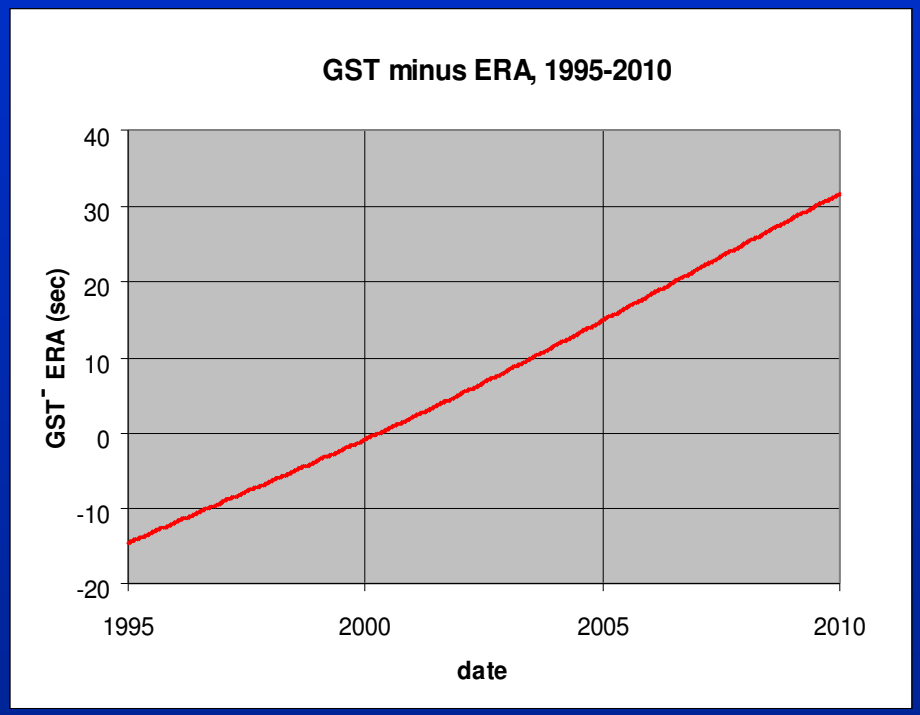
Old-style prediction using sidereal time

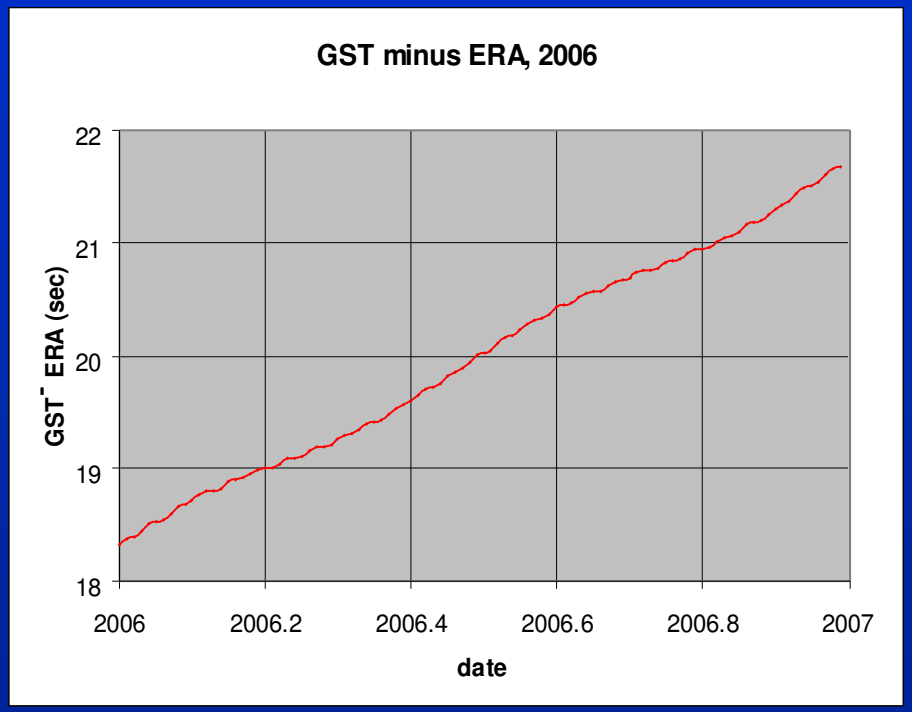
ICRS	23 32 55.171	+52 16 38.29
Apparent RA,Dec	23 33 06.176	+52 17 43.50
Local HA,Dec	+ 8 05 50.276	+52 17 43.66

New-style prediction using Earth rotation angle

ICRS	23 32 55.171	+52 16 38.29
Intermediate RA,Dec	23 32 53.329	+52 17 43.50
Local HA,Dec	+ 8 05 50.276	+52 17 43.66

GST and ERA compared





Apart from a ~3^{s} per year slope (precession) and some ~1^{s} wiggles (nutation), they are very similar...

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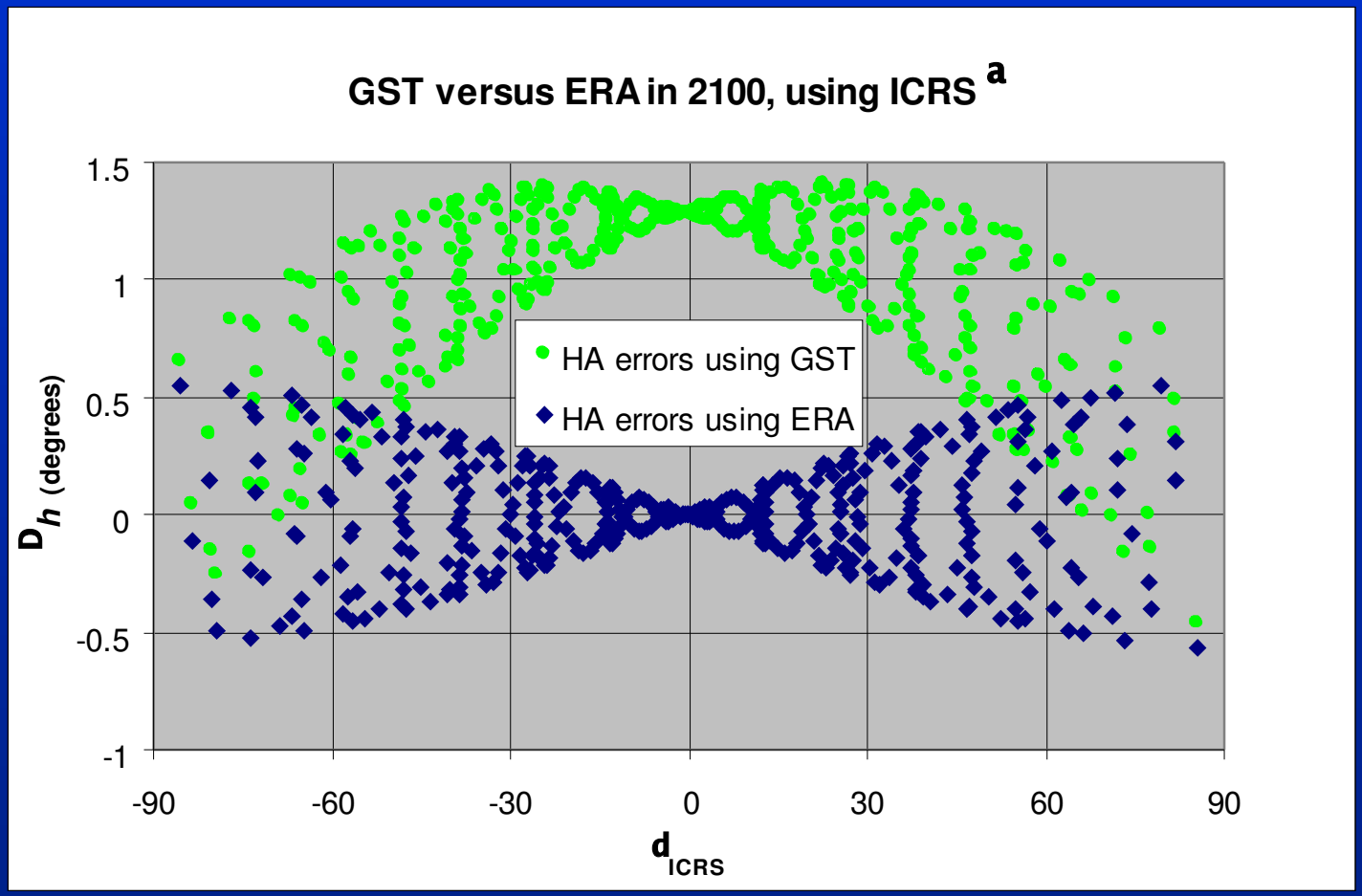
...so set your sidereal clock to ERA!



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Why none of this matters much

- When did you last compute an apparent place? Telescopes nowadays are always pointed by a computer.
- Star positions are always ICRS now.
- Planet positions can be astrometric places.
- “Intermediate places” (the new apparent places) are an internal detail only.

The real challenges

- The new ways are easier, not harder...
  - the celestial sphere is ICRS for ever
  - precession-nutation simply describes where the CIP is
  - the CIO (zero point of α) stays as still as possible
  - $h - \alpha$ = Earth rotation angle = $a + b \cdot \mathrm{UT}$
- ...so the challenge is to persuade people to unlearn the old ways:
  - mean places and the precession of the equinoxes
  - equinox of date, and apparent places
  - mean and apparent sidereal time, and the equation of the equinoxes
- ...and then to educate the next generation.

Further reading

- IAU Resolutions and implementation:
  - IERS Conventions (2003)
  - Kaplan (2005) USNO Circular 179
  - NFA WG explanatory documents
  - Kovalevsky & Seidelmann (2004), *Fundamentals of Astrometry*
- GCRS/BCRS:
  - Soffel et al. (2003) AJ, 126, 2687–2706
- IAU 2000 precession-nutation:
  - Herring et al. (2002) , JGR, 107, B4, Issue B4, ETG 4-1
- CIP/CIO:
  - Capitaine et al. (2003) A&A, 400, 1145–1154
  - Capitaine & Wallace (2006) A&A, 450, 855–872
- UT1/GST:
  - Capitaine et al. (2000) A&A, 355, 398–405
  - Capitaine et al. (2003) A&A, 406, 1135–1149