The History of Time and Leap seconds

P. Kenneth Seidelmann

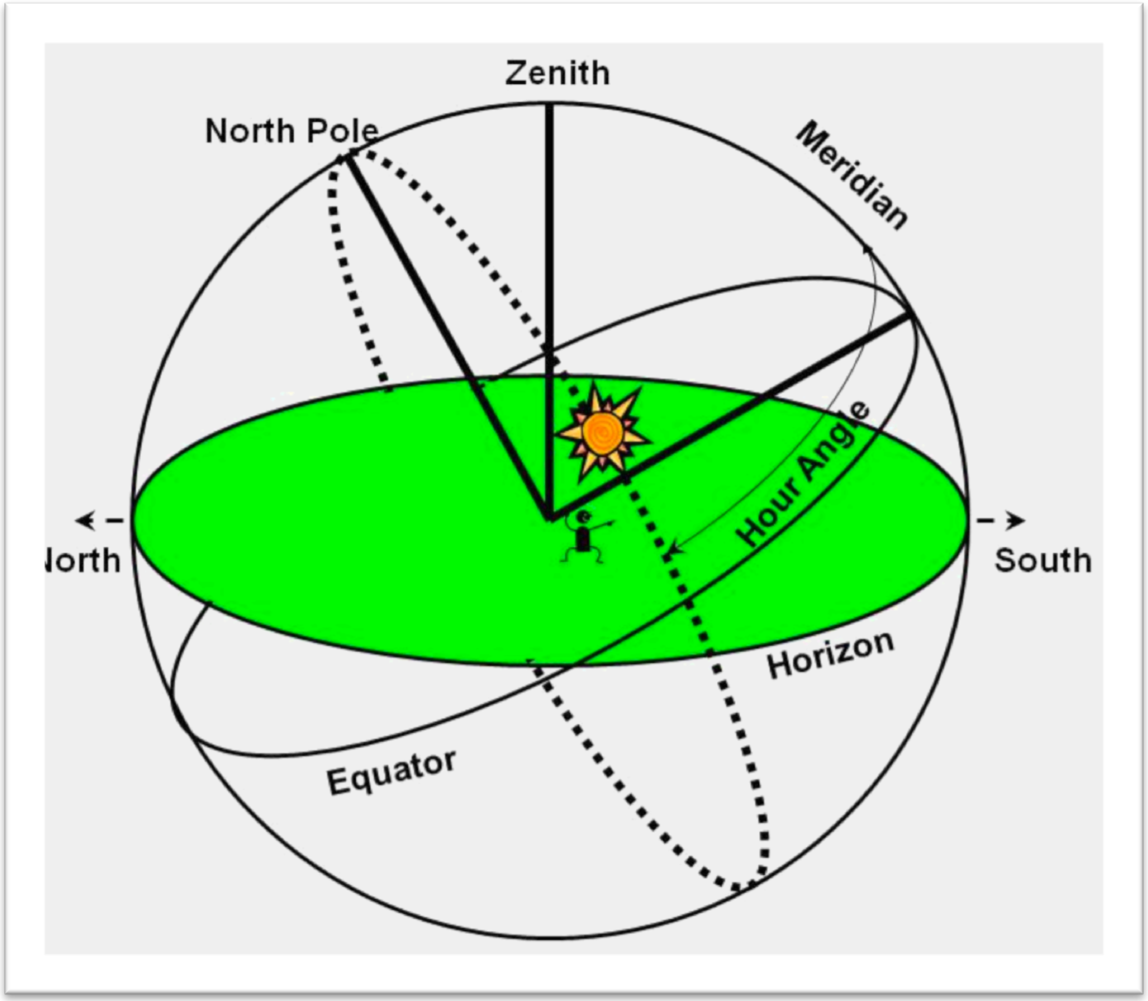
Department of Astronomy
University of Virginia

Some slides thanks to Dennis D. McCarthy

Time Scales

- Apparent Solar Time
- Mean Solar Time
- Greenwich Mean Time (GMT)
- Ephemeris Time (ET)
- Universal Time (UT)
- International Atomic Time (TAI)
- Coordinated Universal Time (UTC)
- Terrestrial Time (TT)
- Barycentric Coordinate Time (TCB)
- Geocentric Coordinate Time (TCG)
- Barycentric Dynamical Time (TDB)

Apparent Solar Time



Could be local or at some special place like Greenwich

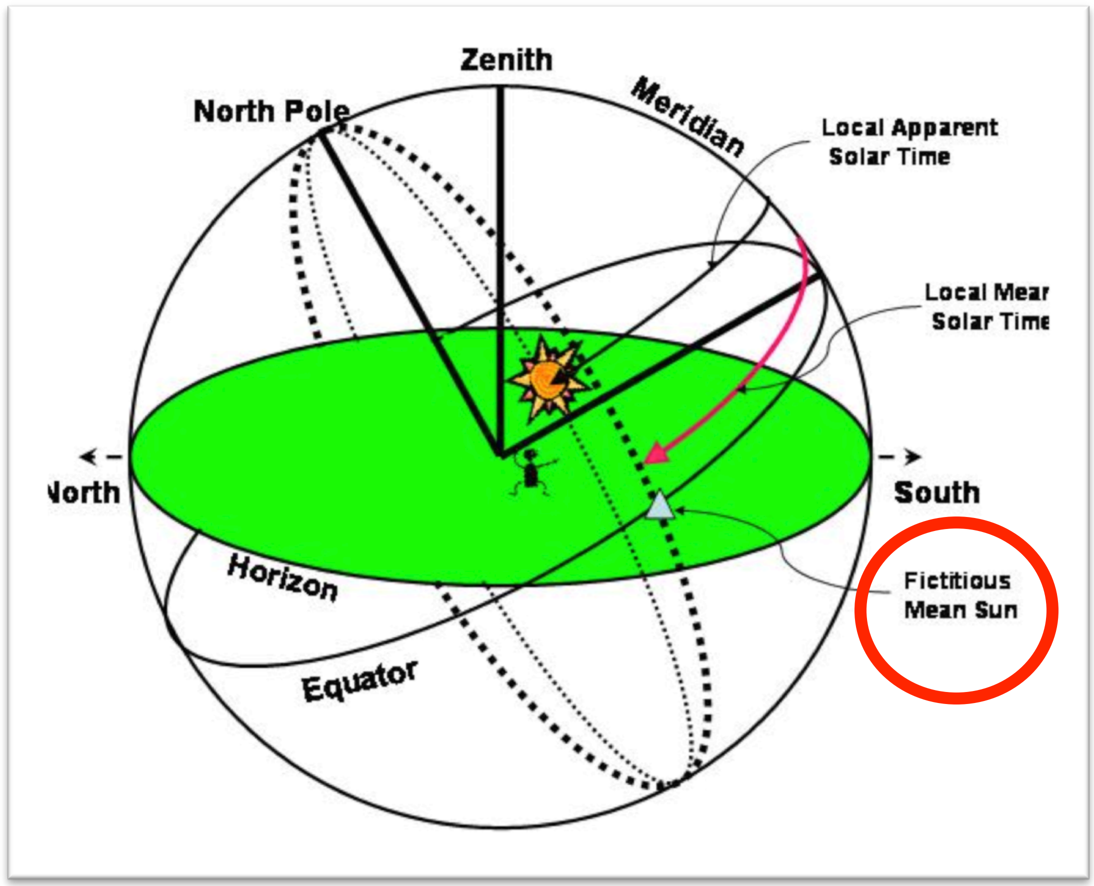
But

Length of the apparent solar day varies during the year because Earth's orbit is inclined and is really an ellipse.

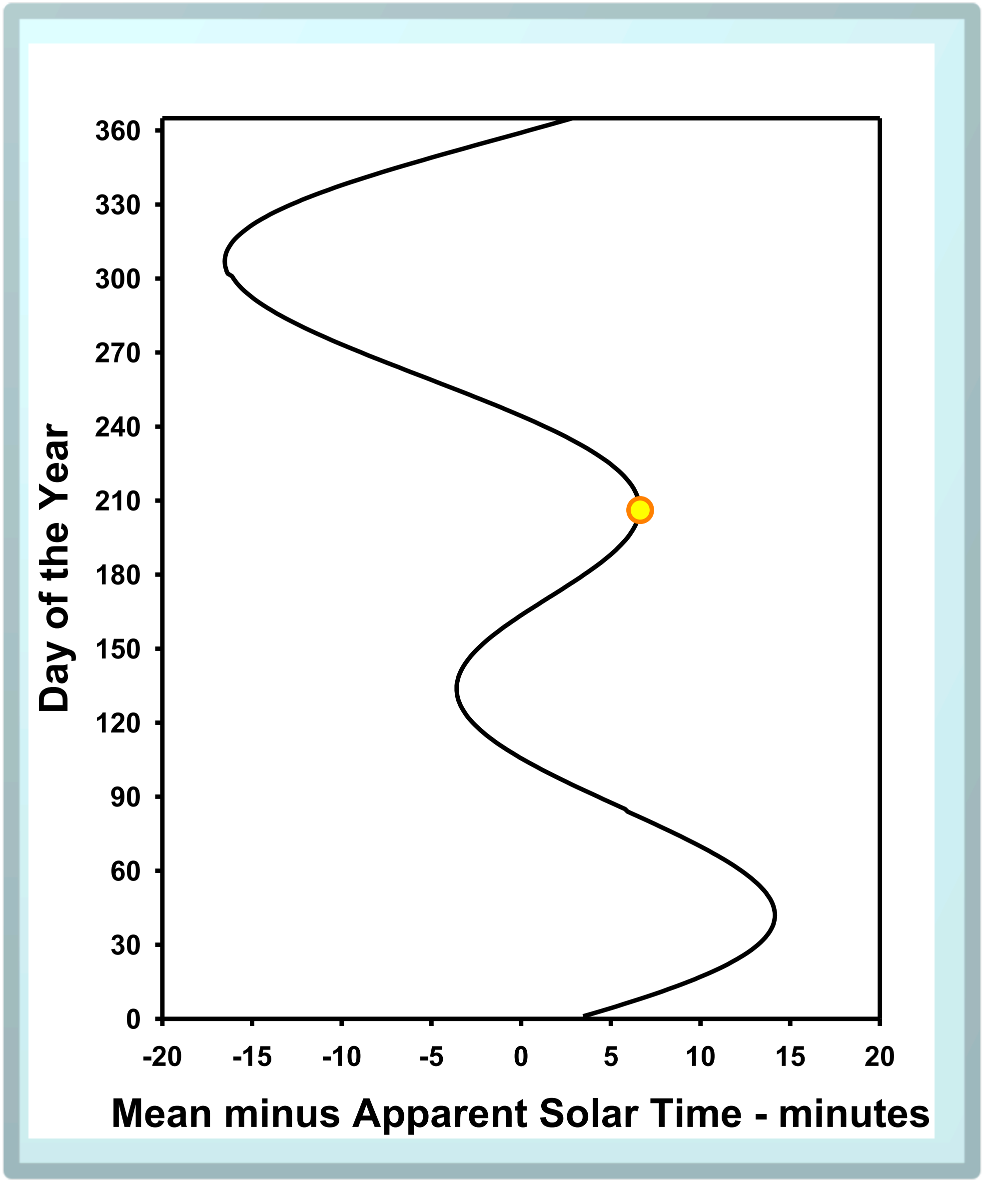
Ptolemy (150 AD) knew this

So…

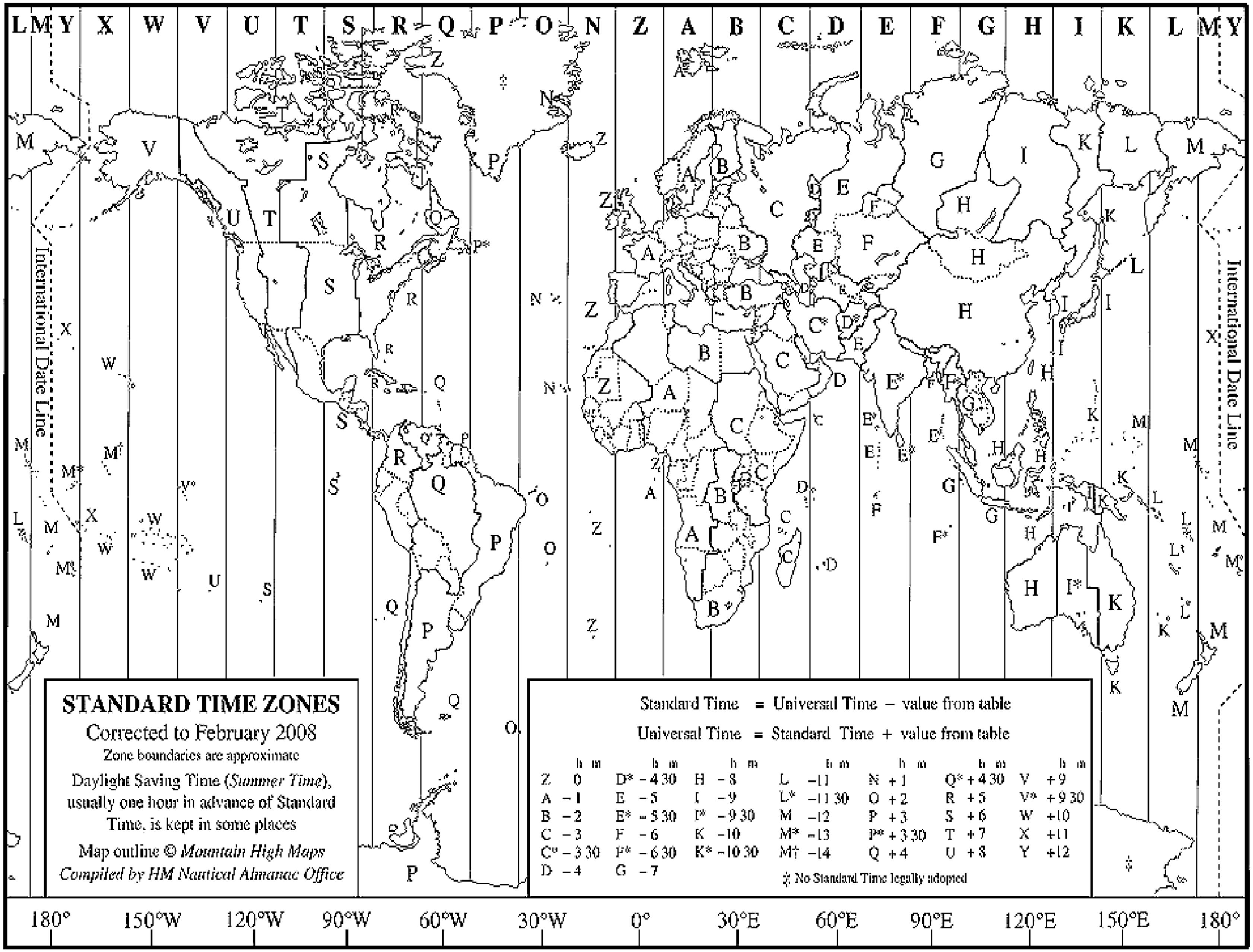
- We need a Sun that behaves



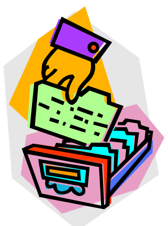
Mean Solar Time



Equation of Time

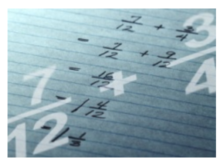

STANDARD TIME ZONES
Corrected to February 2008
Zone boundaries are approximate
Daylight Saving Time (*Summer Time*), usually one hour in advance of Standard Time, is kept in some places
Map outline © *Mountain High Maps*
Compiled by HM Nautical Almanac Office
Standard Time = Universal Time − value from table
Universal Time = Standard Time + value from table
Z 0 | D* −4 30 | H −8 | L −11 | N +1 | Q* +4 30 | V +9
A −1 | E −5 | I −9 | L* −11 30 | O +2 | R +5 | V* +9 30
B −2 | E* −5 30 | I* −9 30 | M −12 | P +3 | S +6 | W +10
C −3 | F −6 | K −10 | M* −13 | P* +3 30 | T +7 | X +11
C* −3 30 | F* −6 30 | K* −10 30 | M† −14 | Q +4 | U +8 | Y +12
D −4 | G −7
‡ No Standard Time legally adopted
International Date Line
180° 150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E 180°
L M Y X W V U T S R Q P O N Z A B C D E F G H I K L M Y

Astronomical Timekeeping



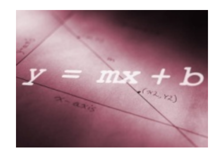
Catalogs of Positions of Celestial Objects

Predict Time of an Event, *e.g.* transit



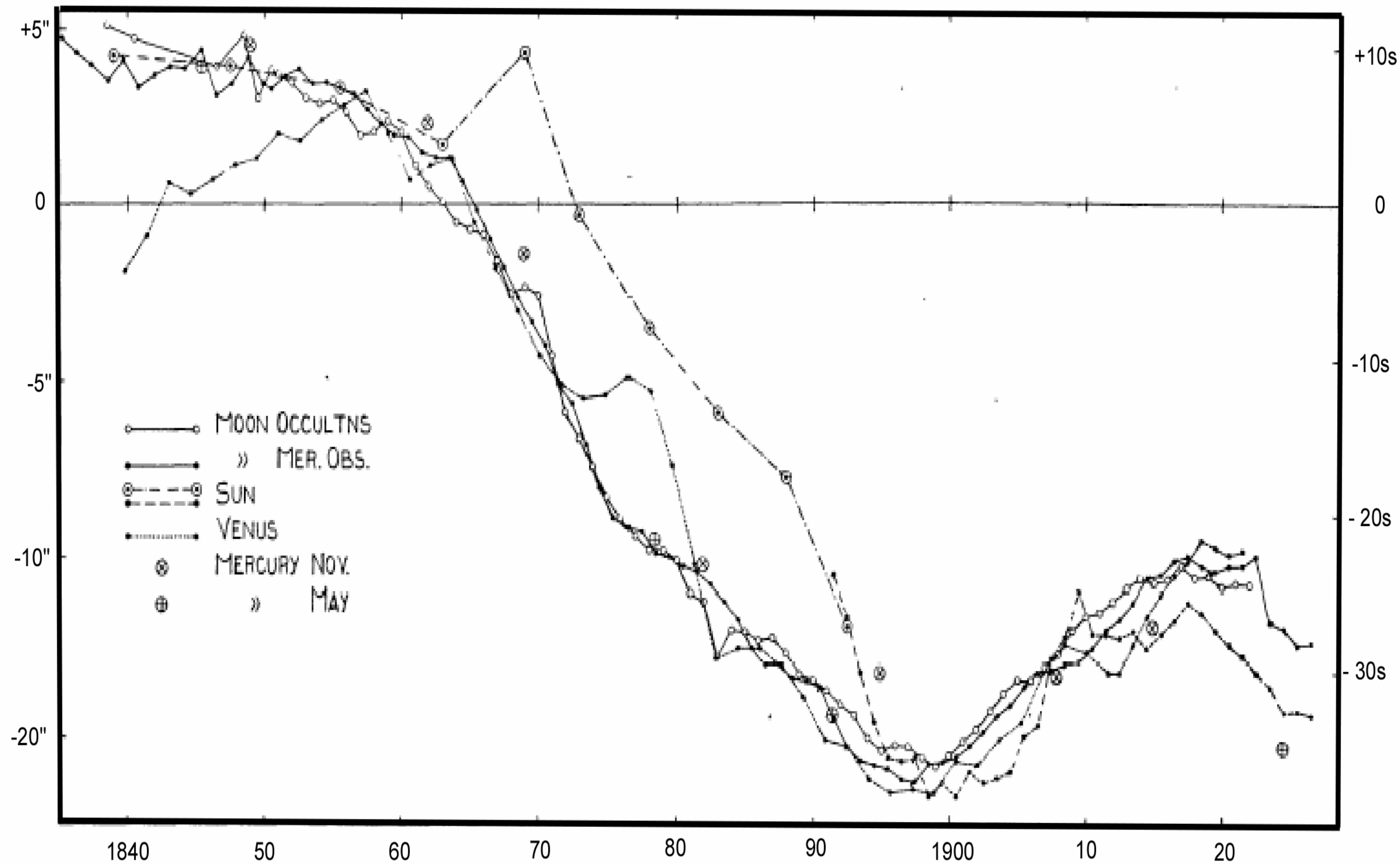
Observations

Determine Clock Corrections



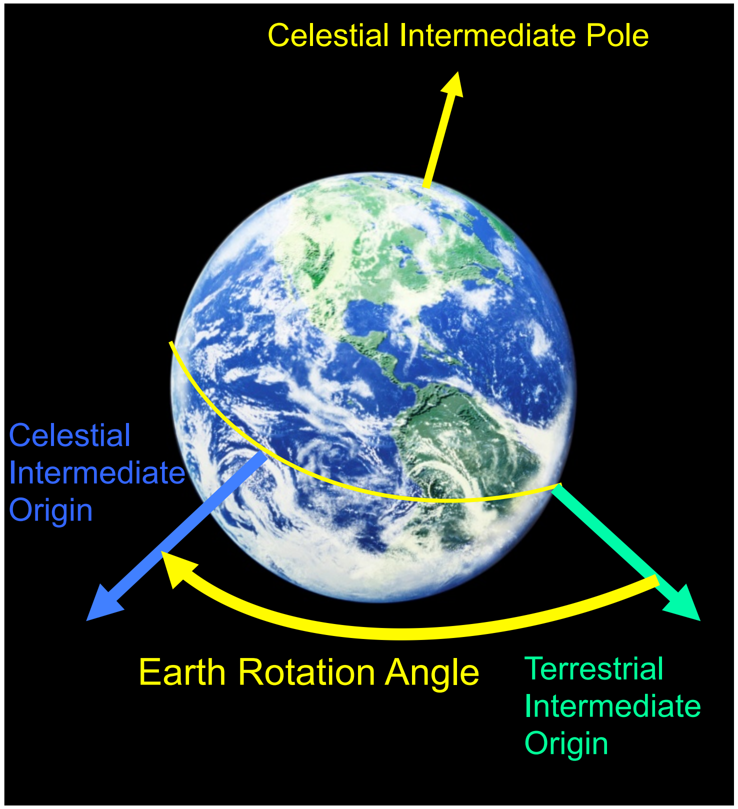
Observational Residuals from de Sitter

Left Scale Moon Longitude; Right Scale Corrections to Time



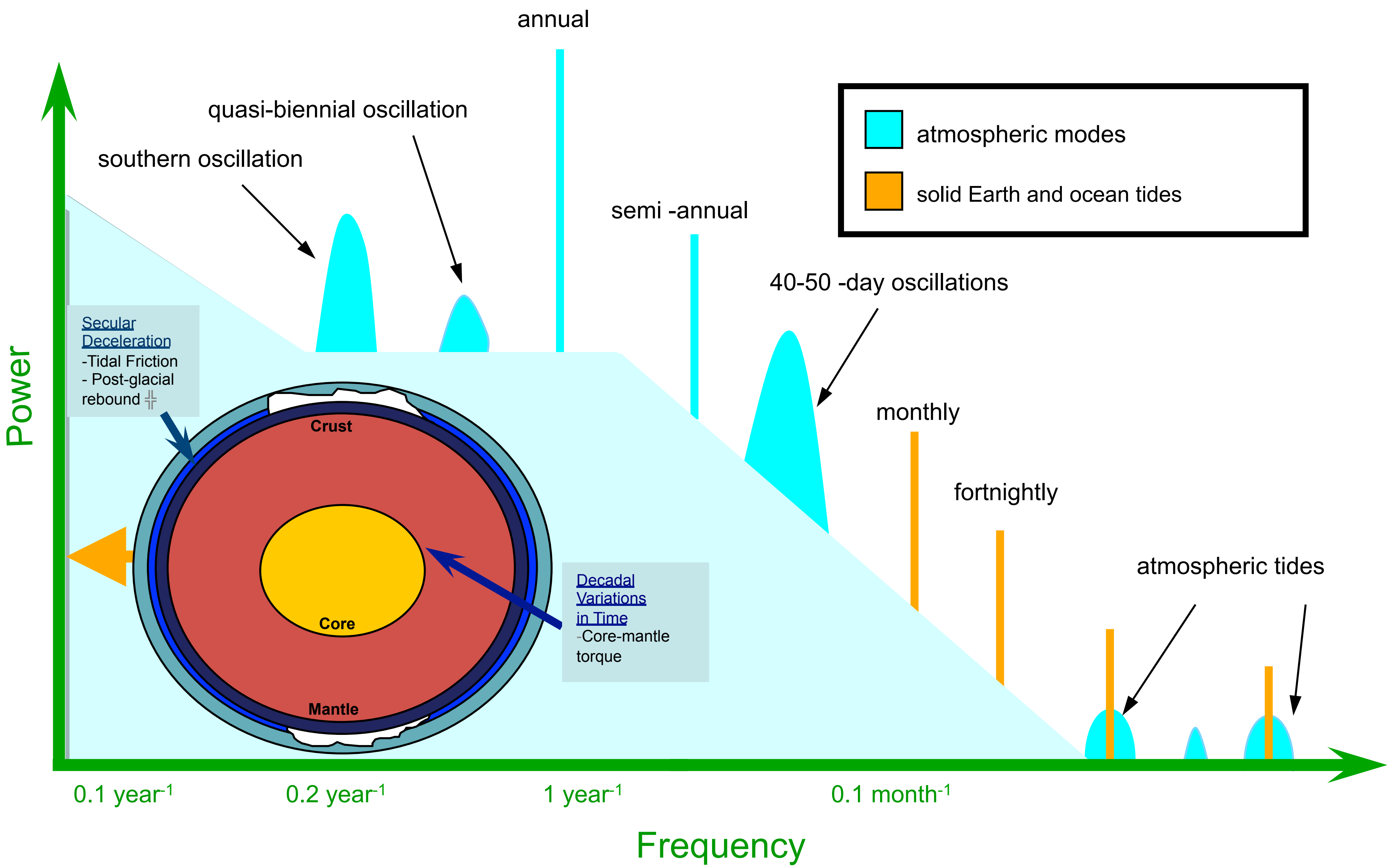
Universal Time (UT)

- Elementary conceptual definition based on the diurnal motion of the Sun
  - Mean solar time reckoned from midnight on the Greenwich meridian
- Traditional definition of the second used in astronomy
  - Mean solar second = 1/86 400 mean solar day
- UT1 is measure of Earth's rotation angle
  - Defined
    - By observed sidereal time using conventional expression
      - GMST= f_1(UT1)
    - by Earth Rotation Angle
      - $\theta = f_2$(UT1)
- UTO is UT1 plus effects of polar motion
- UT2 is UT1 corrected by conventional expression for annual variation in Earth's rotational speed



$$UT2 = UT1 + 0.022s \sin 2\pi t - 0.012s \cos 2\pi t - 0.006s \sin 4\pi t + 0.007s \cos 4\pi t,$$
$$\text{where } t = \text{fraction of Besselian Year}$$

Variations in Length of Day



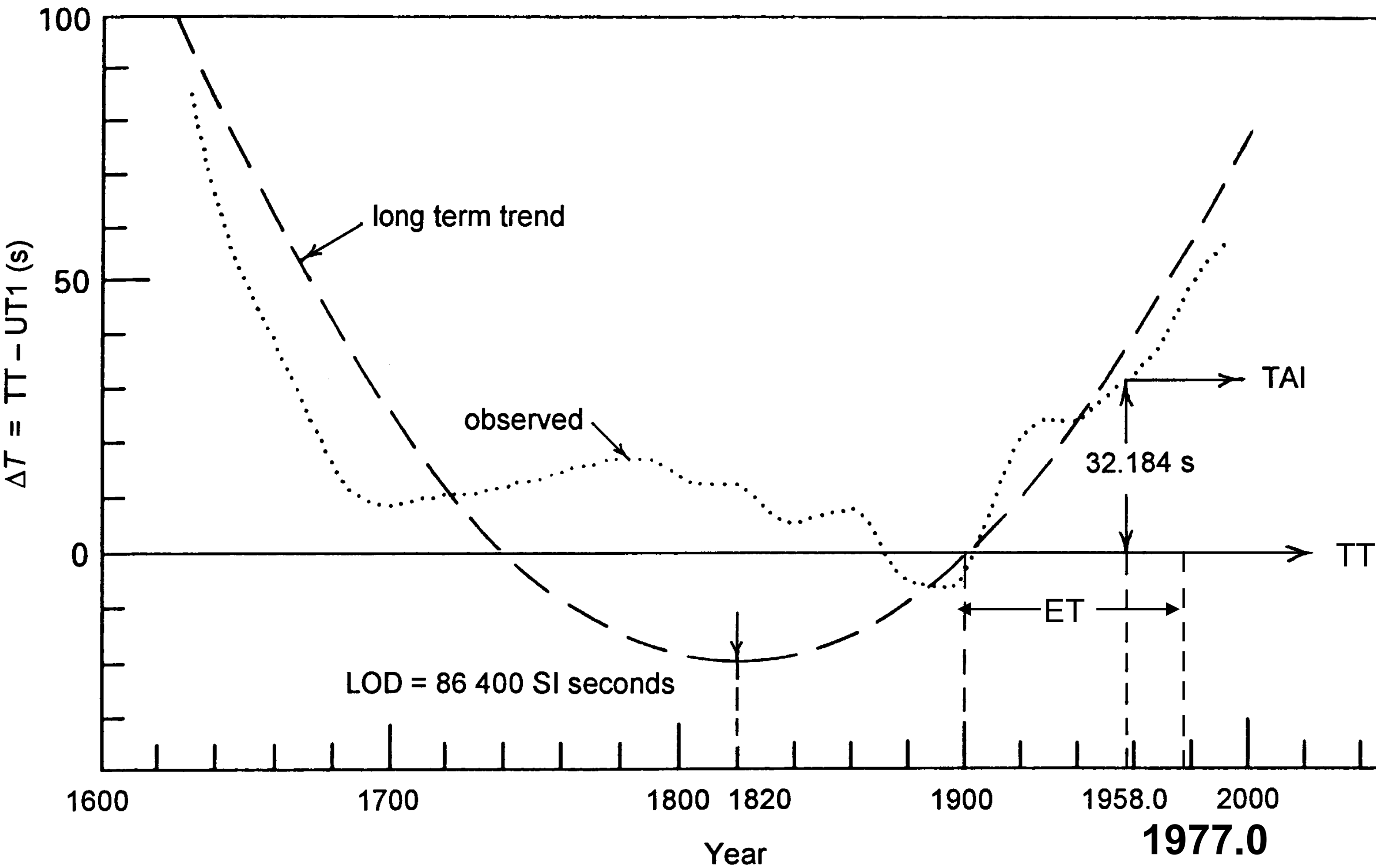
Ephemeris Time (ET)

- Brings observed positions of solar system objects into accord with ephemerides based on Newtonian theory of gravitation

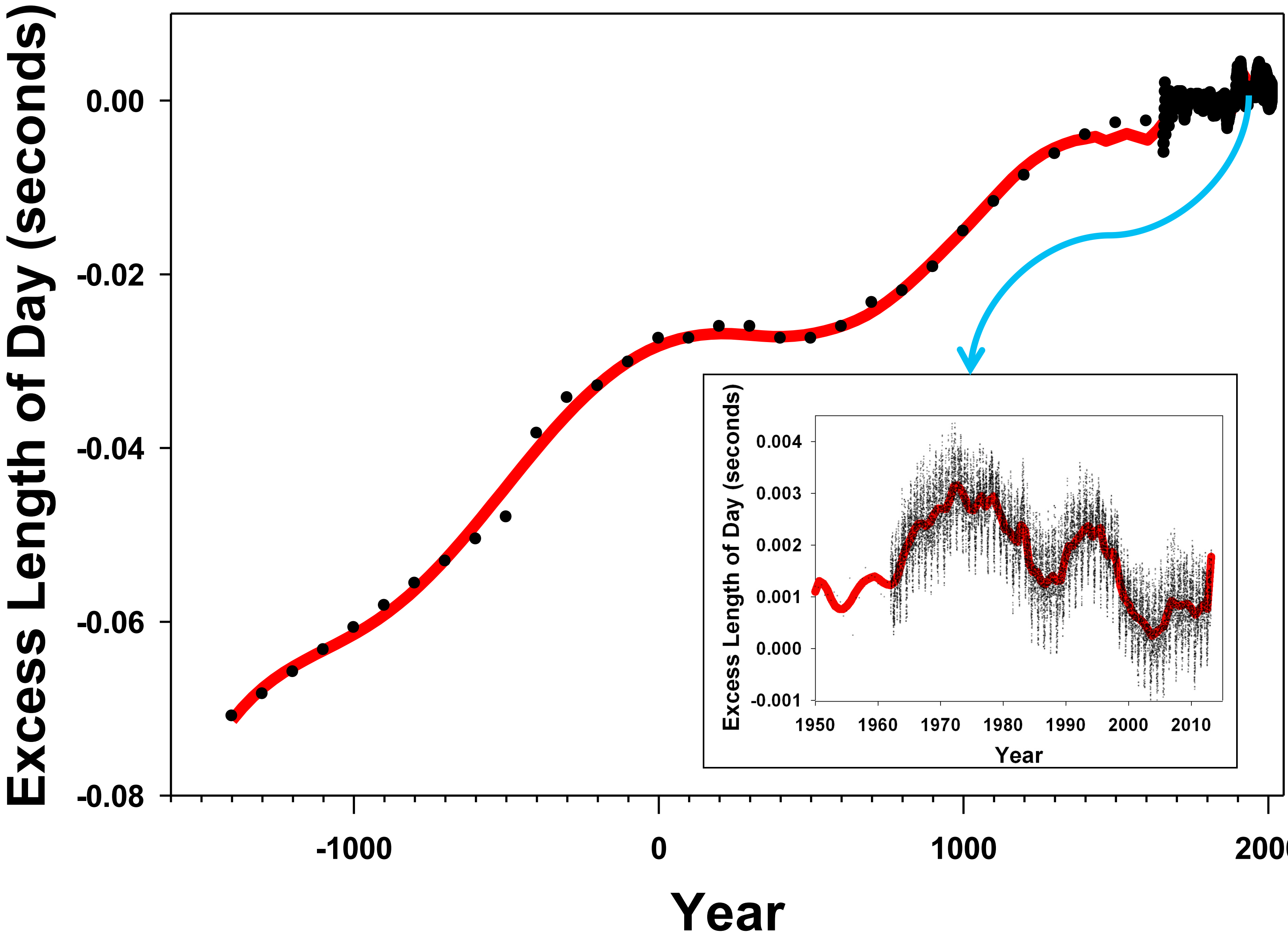
Defined by Newcomb's value for the length of the Tropical Year 1900, but in practice measured by observations of the Moon with respect to the stars

- Since the tropical year of 1900 contains 31 556 925.9747 s the ET second is 1/31 556 925.9747 of the tropical year 1900
- ET replaced UT1 as independent variable of astronomical ephemerides in 1960

ΔT since 1600



After F.R. Stephenson and L.V. Morrison, *Phil. Trans. R. Soc. London* **A351**, 165 – 202 (1995)



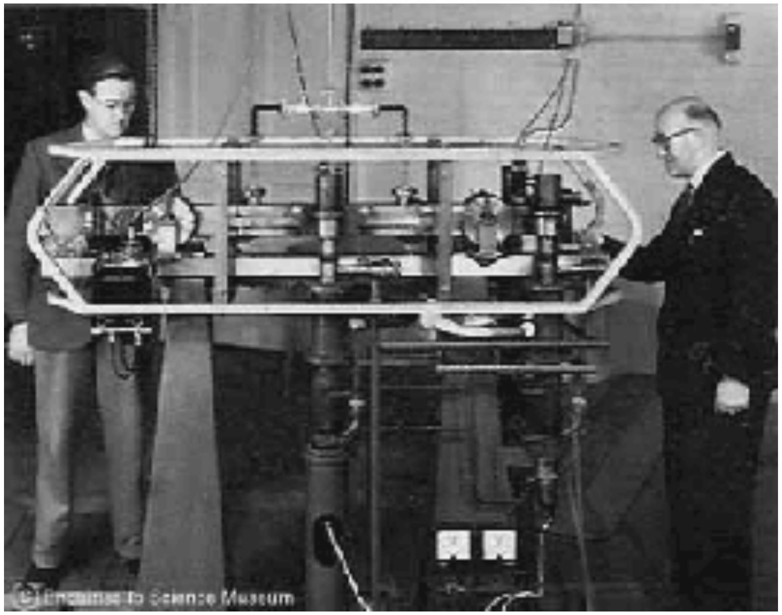
Excess Length of Day (seconds)
0.00
-0.02
-0.04
-0.06
-0.08
-1000
0
1000
2000
Year
Excess Length of Day (seconds)
0.004
0.003
0.002
0.001
0.000
-0.001
1950
1960
1970
1980
1990
2000
2010
Year

Atomic Time

- First Caesium-133 atomic clock established at National Physical Laboratory in UK in 1955
- Frequency of transition measured in terms of the second of ET

  9 192 631 770 ± 20 Hz
- Definition of the Système international d'unités (SI) second adopted in 1967
- Atomic time = ET second corresponding to Earth rotation second of mid-nineteenth century

Second = duration of 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the Caesium-133 atom

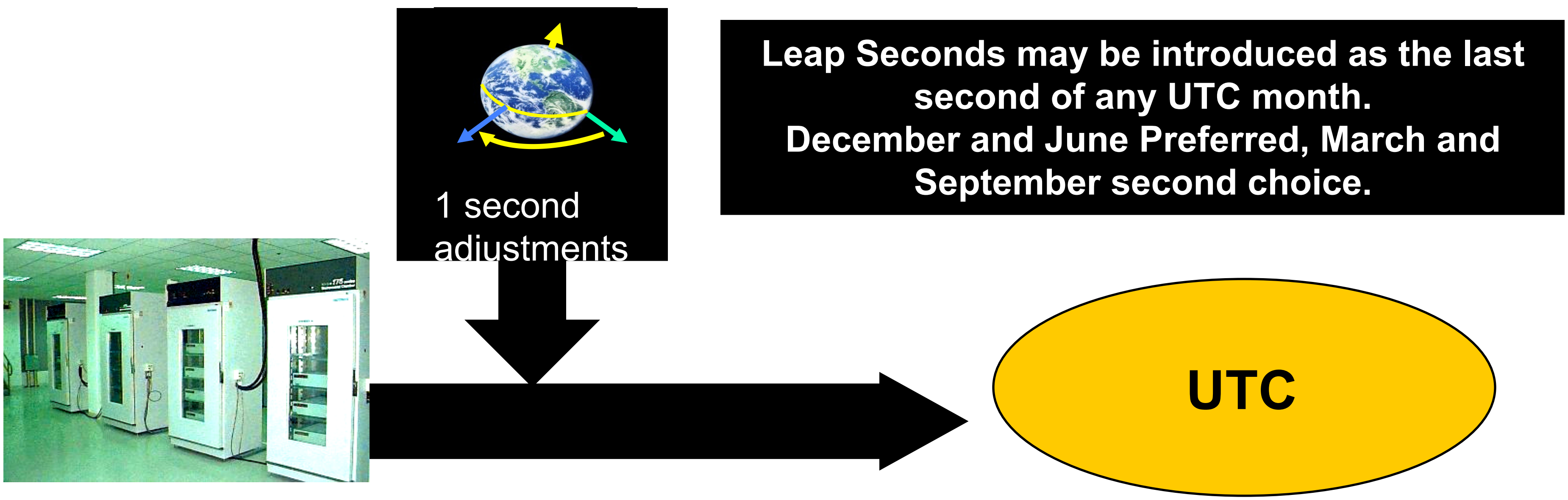


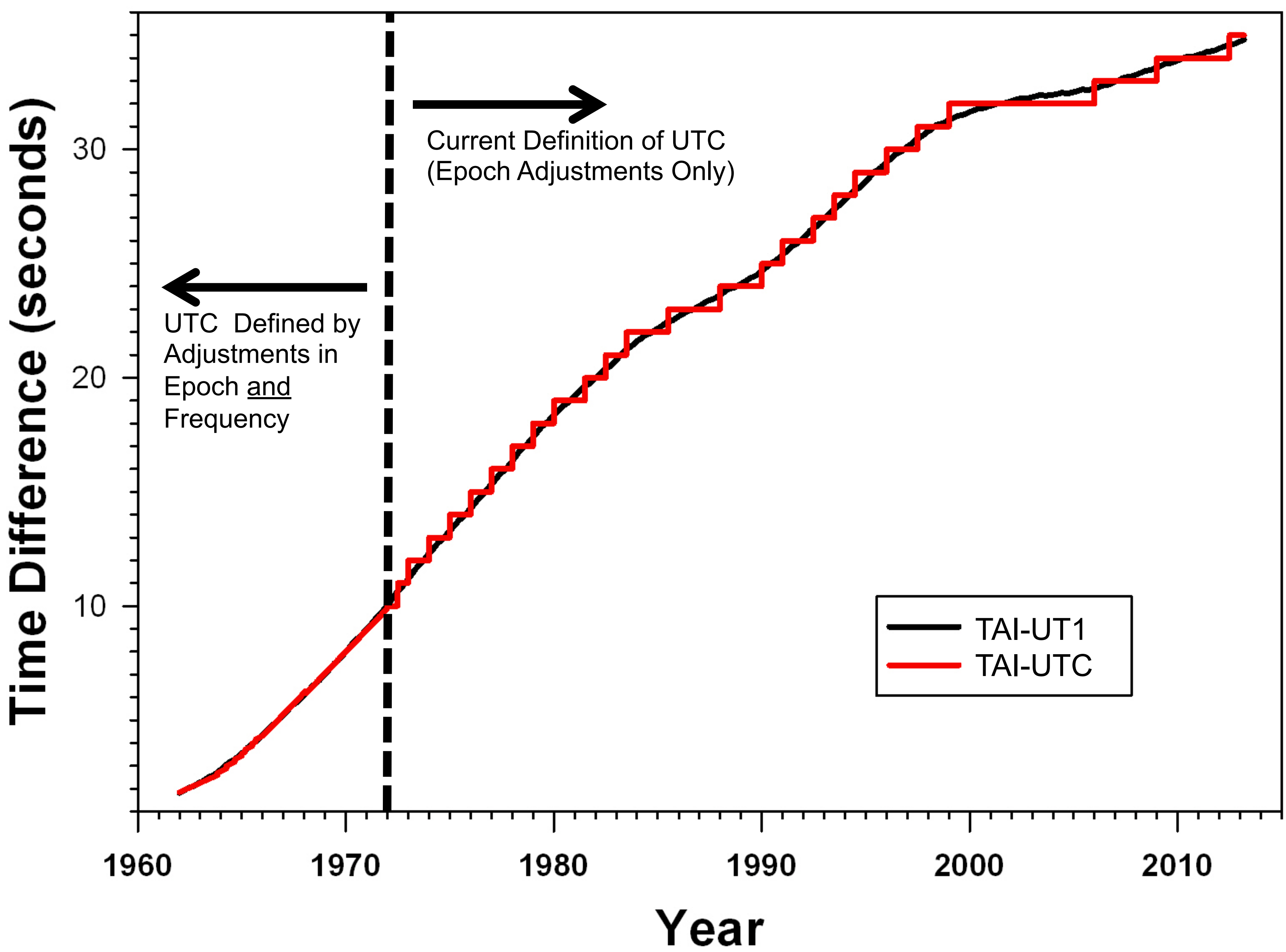
International Atomic Time (TAI)

- Coordinate time scale
  - in a geocentric reference frame
  - SI second realized on the rotating geoid is the scale unit
- Continuous atomic time scale determined by
  - Bureau International de l’Heure (BIH) beginning in 1958
  - Now maintained by Bureau International des Poids et Mesures (BIPM)
- TAI = UT2 on January 1, 1958 0 h
- Became AT (or TA) in 1969, TAI in 1971

Coordinated Universal Time (UTC)

- Name adopted officially in 1967
- From 1961 to 1972 UTC used frequency offsets and steps (less than 1 s) to maintain agreement with UT2 within about 0.1 s
- In 1970 formalized by International Radio Consultative Committee (CCIR), predecessor of International Telecommunication Union (ITU), to correspond exactly in rate with TAI but differ by integral number of seconds, adjusted by insertion or deletion of seconds to ensure agreement within 0.9s of UT1 to permit navigation at sea via radio time signals





Time Difference (seconds)
30
20
10
1960
1970
1980
1990
2000
2010
Year
Current Definition of UTC
(Epoch Adjustments Only)
UTC Defined by
Adjustments in
Epoch and
Frequency
TAI-UT1
TAI-UTC

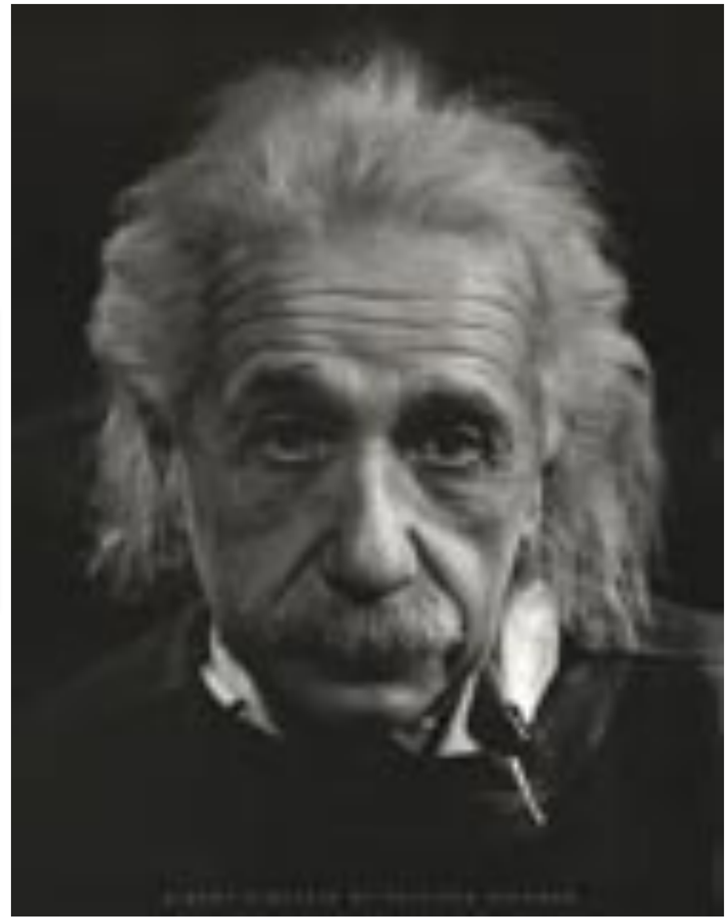
Relativistic Time Scales

- Ephemeris Time (ET)
  - Based on the Newtonian gravitation
  - No distinction between proper time and coordinate time

❖Proper time: Reading of an ideal clock in its own rest frame

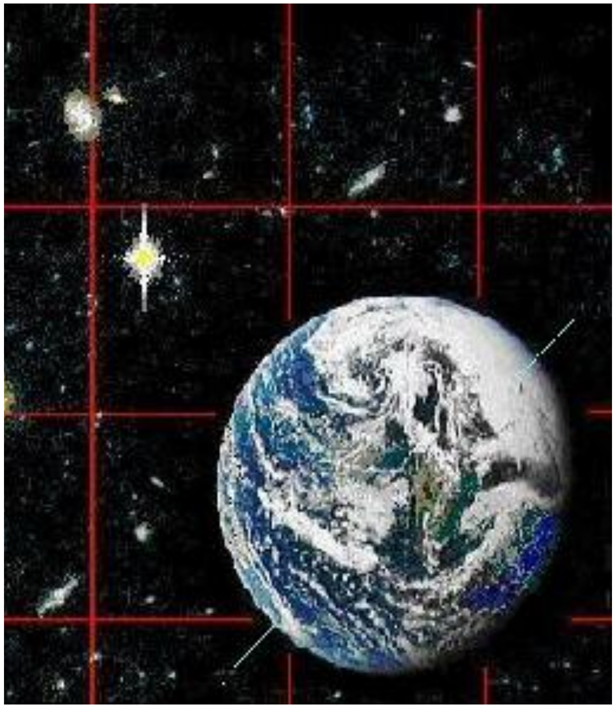
❖Coordinate time: Time coordinate in given space-time coordinate system

- Between 1976 and 2000, the IAU adopted relativistic time scales
  - Consistent with the general theory of relativity
  - Unit is the SI second



Terrestrial Time (TT)

- In 1991 IAU renamed TDT - Terrestrial Time (TT)
  - Unit is the SI second on the geoid
  - Defined by atomic clocks on the surface of the Earth
  - Origin of January 1, 1977 0 h
  - TT = TAI + 32.184 s
  - Maintains continuity with Ephemeris Time (ET)
  - Theoretical equivalence of time measured by quantum mechanical atomic interaction and time measured by gravitational planetary interaction
  - Time reference for apparent geocentric ephemerides.
- Any difference between TAI and TT is a consequence of the physical defects of atomic time standards
  - probably remained within the limits of ± 10μs
  - may increase slowly as time standards improve
  - In most cases, and particularly for the publication of ephemerides, this deviation is negligible.

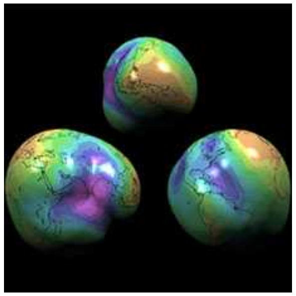


Coordinate Time

Geocentric Coordinate Time (TCG)

$$\mathrm{TCG} - \mathrm{TT} = \mathrm{L}_G \times (JD - 2443144.5) \times 86400$$

- Time with respect to center of Earth
- Defining value of L_G, chosen to provide continuity with the definition of TT so that its measurement unit agrees with the SI second on the geoid



Barycentric Coordinate Time (TCB)

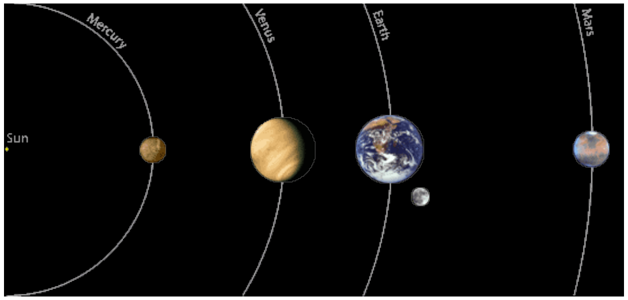
$$\mathrm{TCB} - \mathrm{TT} = \frac{1}{c^2}\int\left(U_{E\,ext}(\mathbf{r}_E) + \frac{1}{2}v_E^2\right)dt + L_G\,\Delta D + \frac{1}{c^2}\mathbf{v}_E\cdot(\mathbf{r}-\mathbf{r}_E)$$
$$= L_C\,\Delta D + P + L_G\,\Delta D + \frac{1}{c^2}\mathbf{v}_E\cdot(\mathbf{r}-\mathbf{r}_E)$$

$L_C \approx$ 1.28 ms/d, P represents periodic terms with largest having amplitude 1.7 ms, and last term has amplitude 2.1 μs

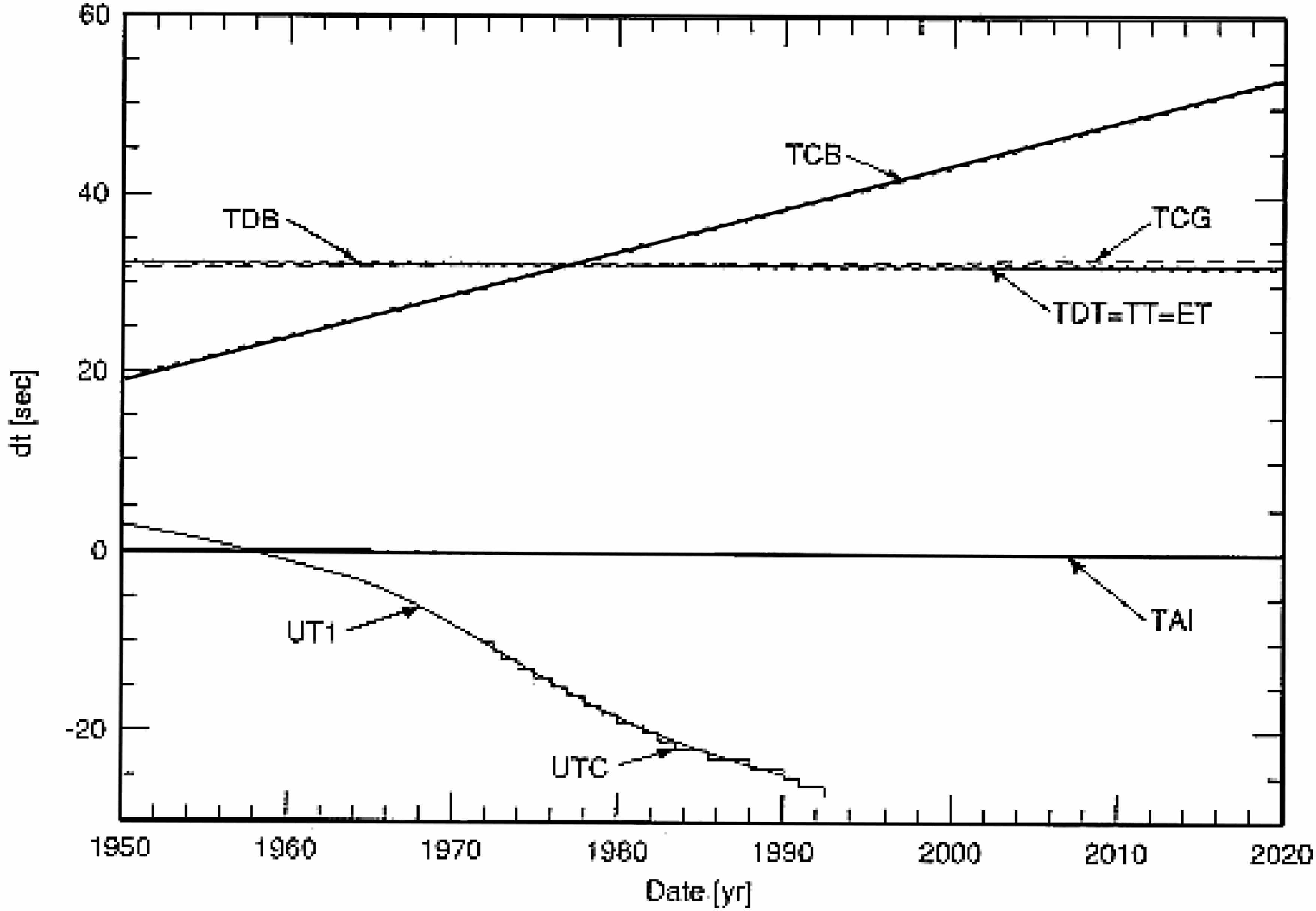
- TCB and TDB differ in rate

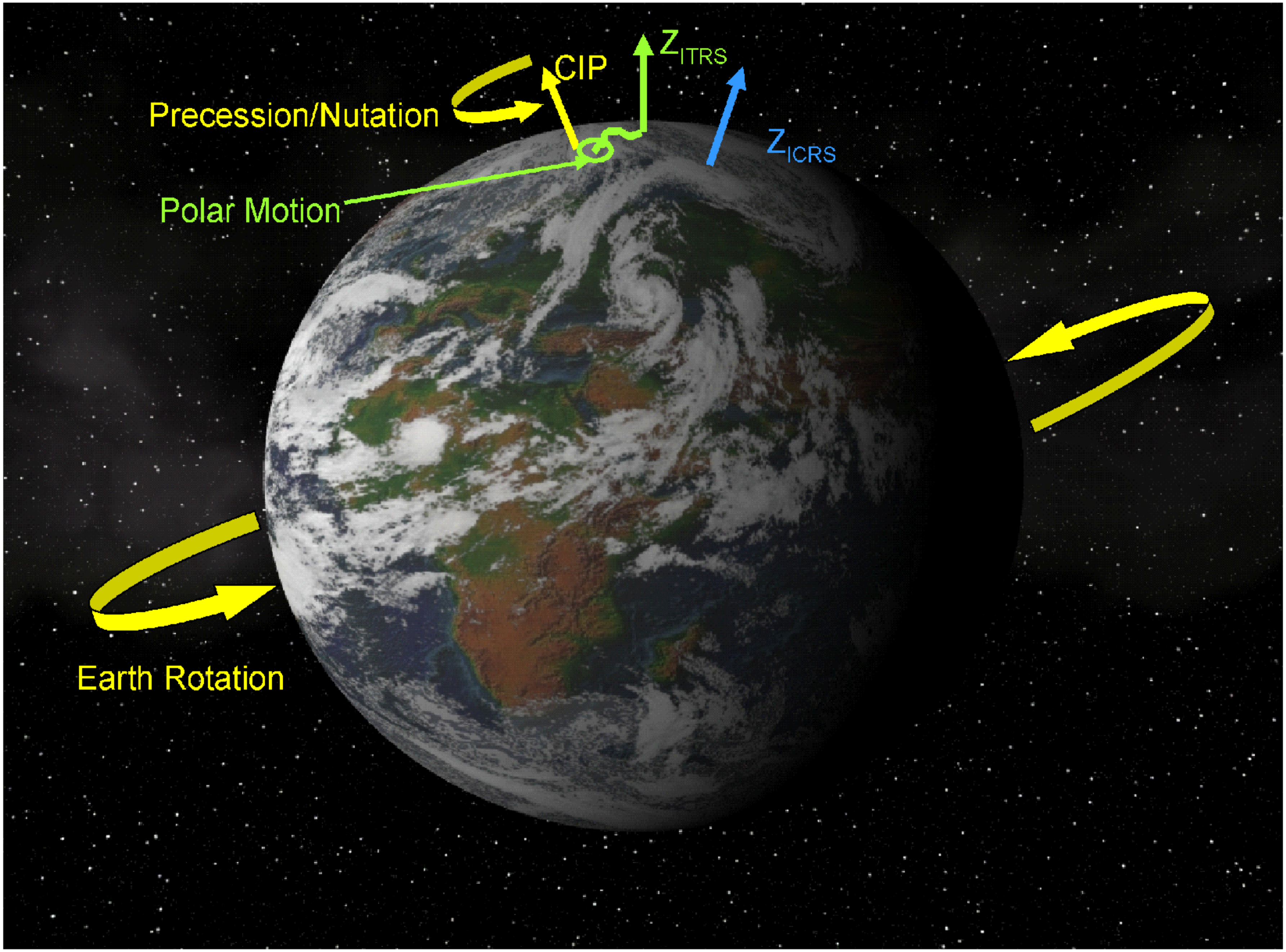
$$\text{TCB-TDB}=\mathrm{L}_B \times (JD - 2433144.5) \times 86400 + P_0$$

P_0 represents the periodic terms of order 10^{-4} seconds.



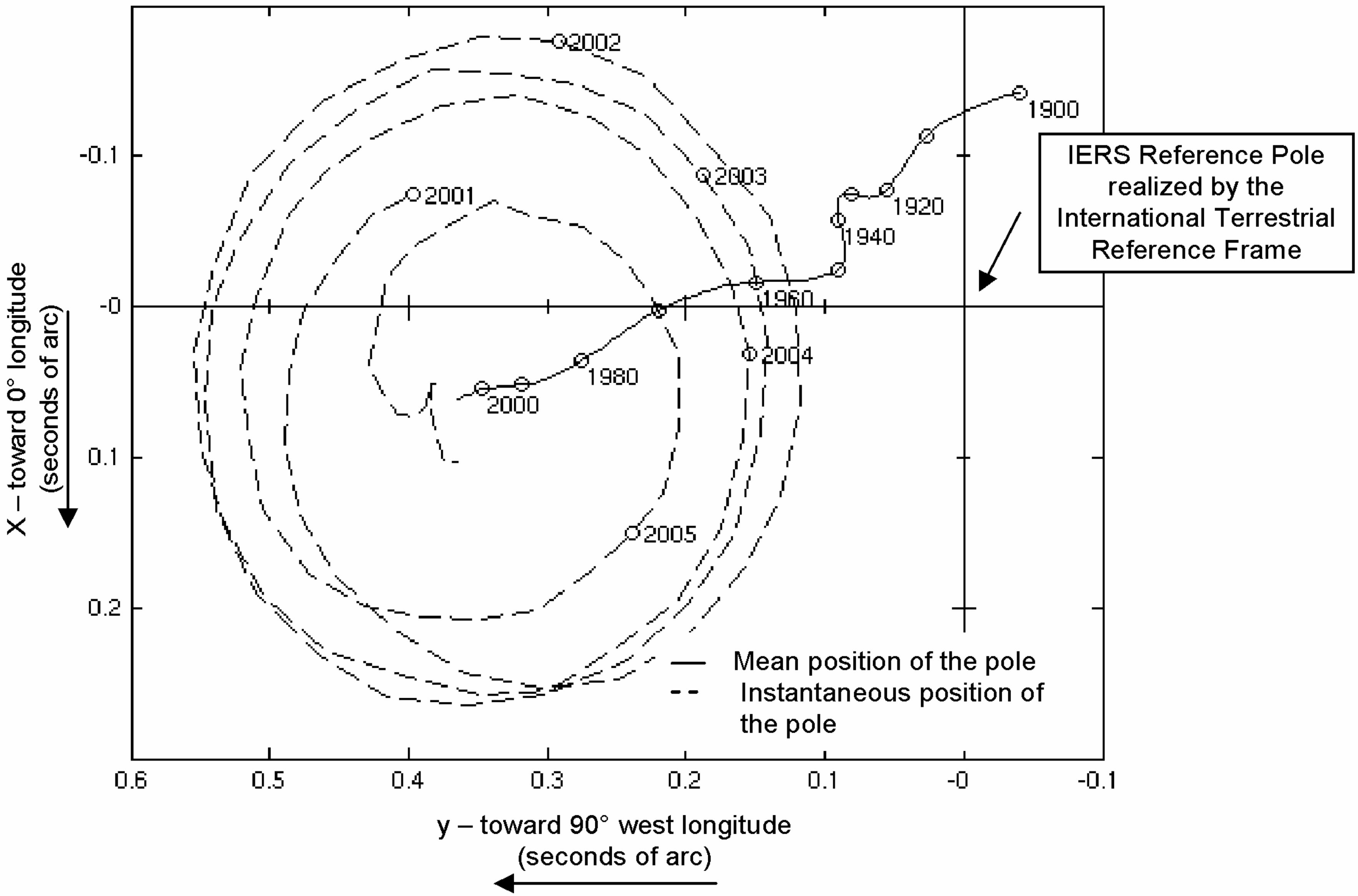
Comparison of Different Time Scales



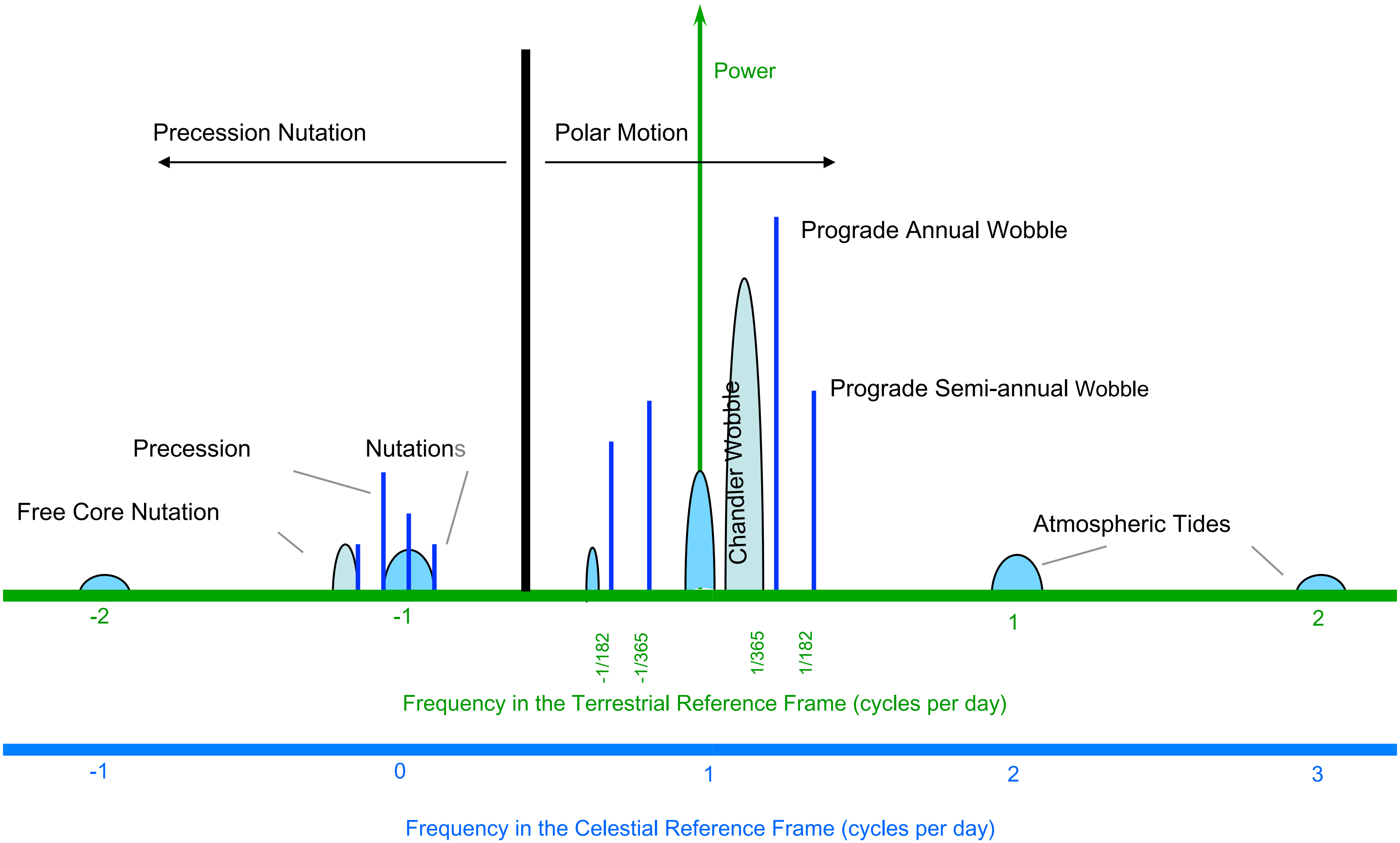


CIP
Z_{ITRS}
Precession/Nutation
Z_{ICRS}
Polar Motion
Earth Rotation

Polar Motion

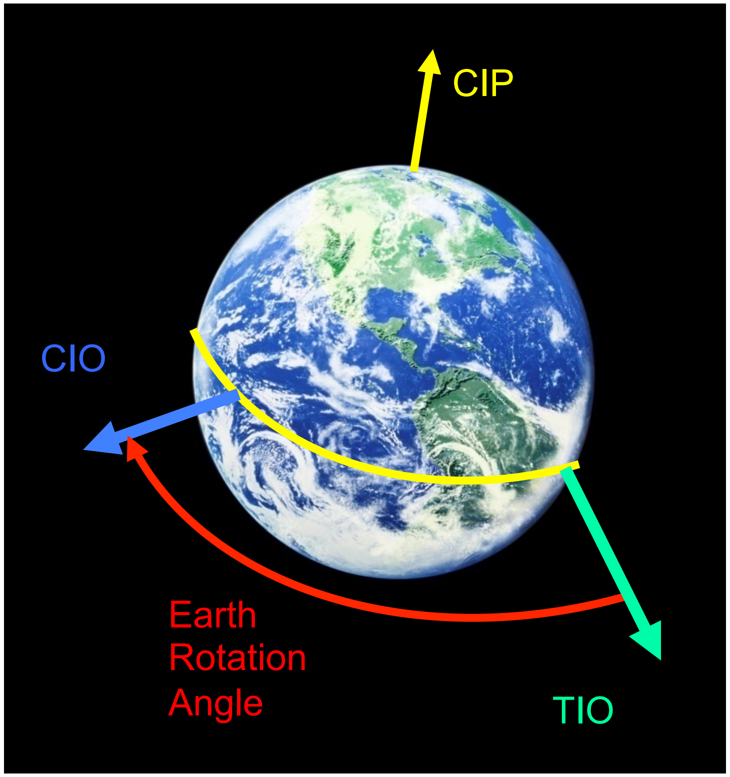


Polar Motion Components



Earth Rotation Angle (ERA)

- Measured along the intermediate equator of the Celestial Intermediate Pole (CIP) between the Terrestrial Intermediate Origin (TIO) and the Celestial Intermediate Origin (CIO).
- Related to UT1 by



$$ERA(T_U) = \theta(T_U)$$

$$= 2\pi\,(0.779\,057\,273\,264\,0 + 1.002\,737\,811\,911\,354\,48 T_U)$$

T_u = (Julian <u>UT1</u> date - 2451545.0),

- Variations in the rotational speed of the Earth and rotation angle conveniently represented by UT1-UTC (in time units).

Modern Applications of Earth Orientation Data

- Critical information required to transform between Earth-based and space-based reference systems.
  - Navigation systems (*e.g.* GPS, GALILEO)
  - Artificial Earth satellite orbits
  - Space navigation

Rotation angle (observed/predicted)

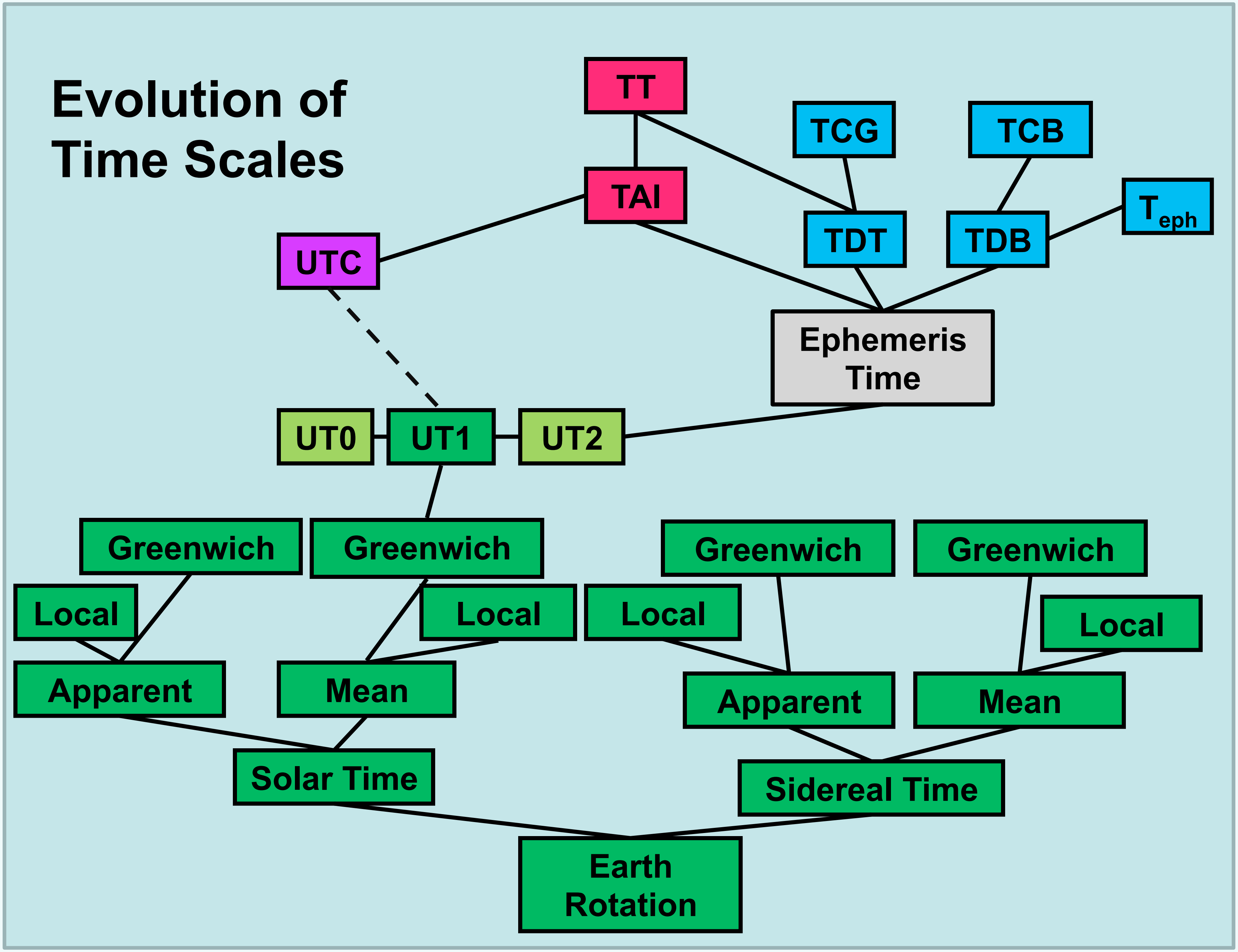
Reference pole motion in space (model)

Reference pole motion on Earth (observed/predicted)

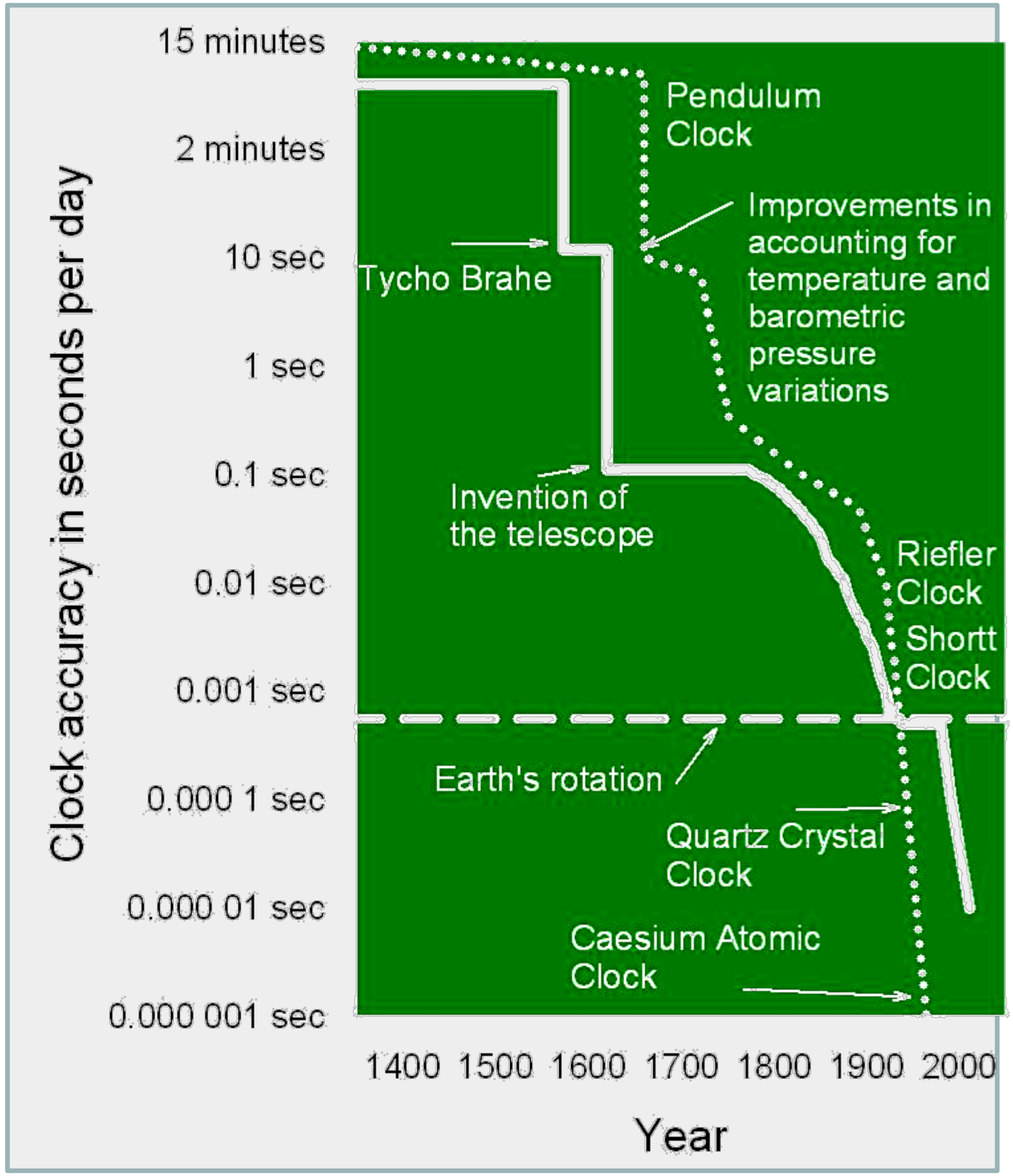
$$[CRS]=PN(t)\,R(t)\,W(t)\,[TRS]$$

Space "Coordinate"

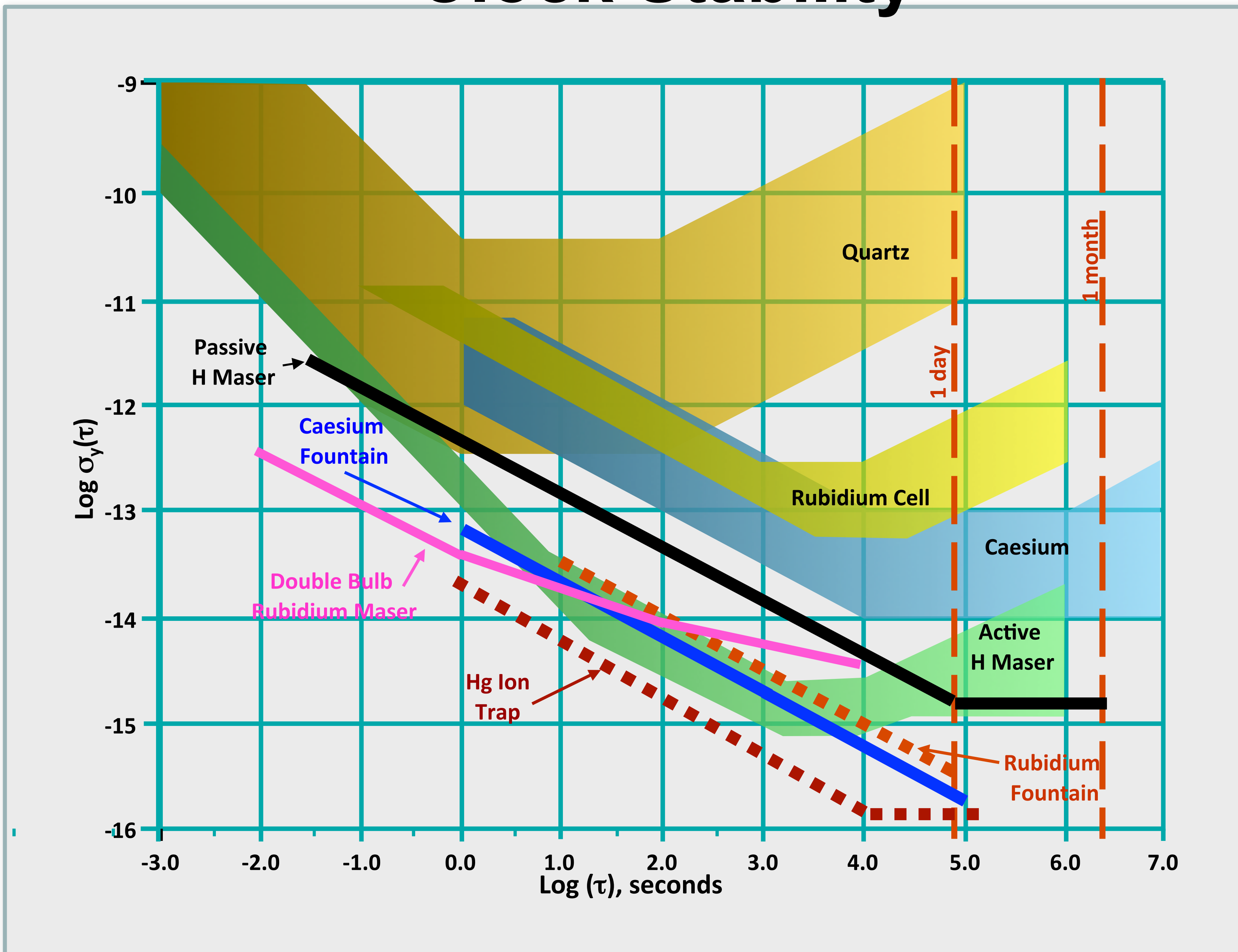
Earth "Coordinate"


Evolution of Time Scales
TT
TCG
TCB
TAI
T_{eph}
UTC
TDT
TDB
Ephemeris Time
UT0
UT1
UT2
Greenwich
Greenwich
Greenwich
Greenwich
Local
Local
Local
Local
Apparent
Mean
Apparent
Mean
Solar Time
Sidereal Time
Earth Rotation

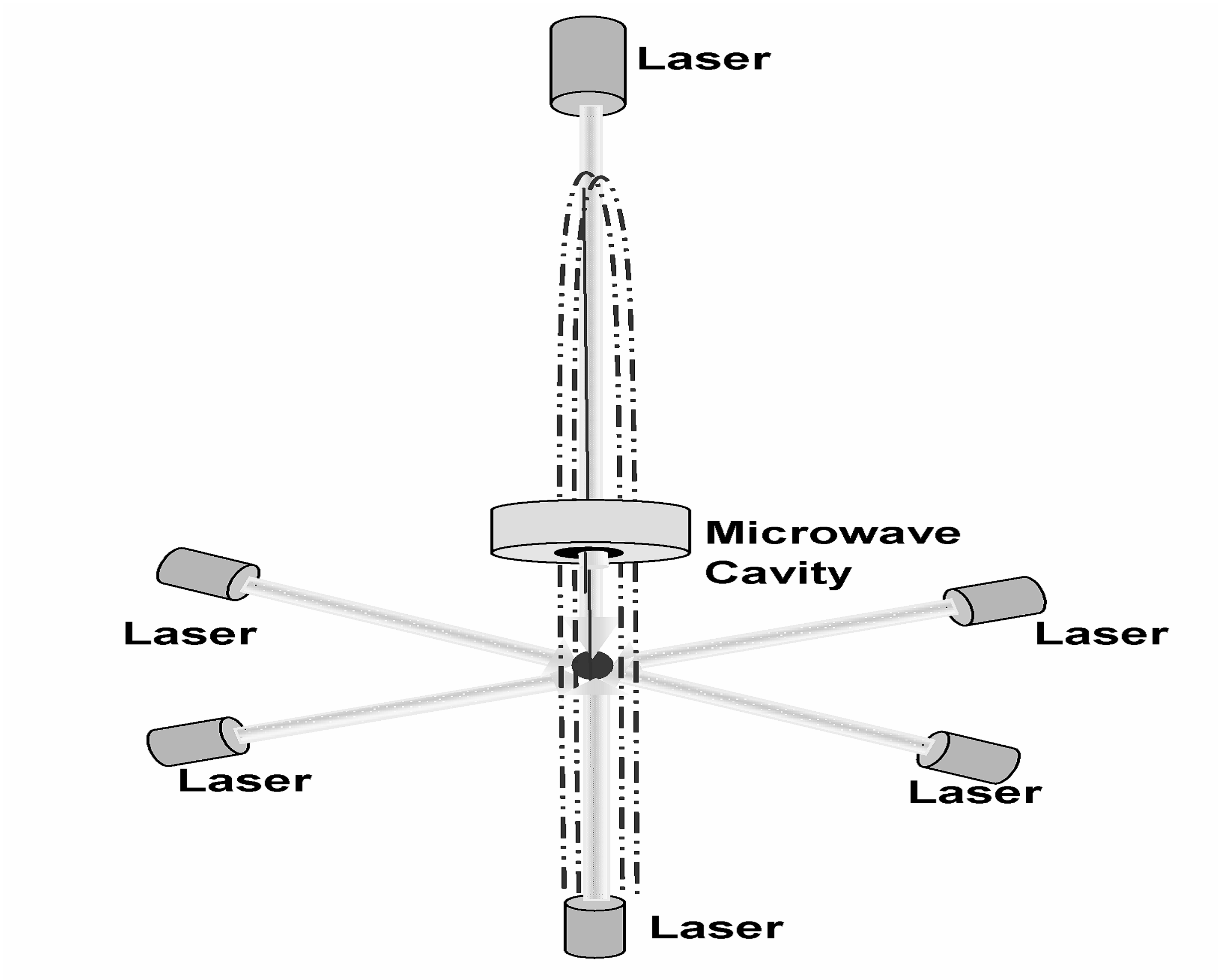
Time-keeping Precision



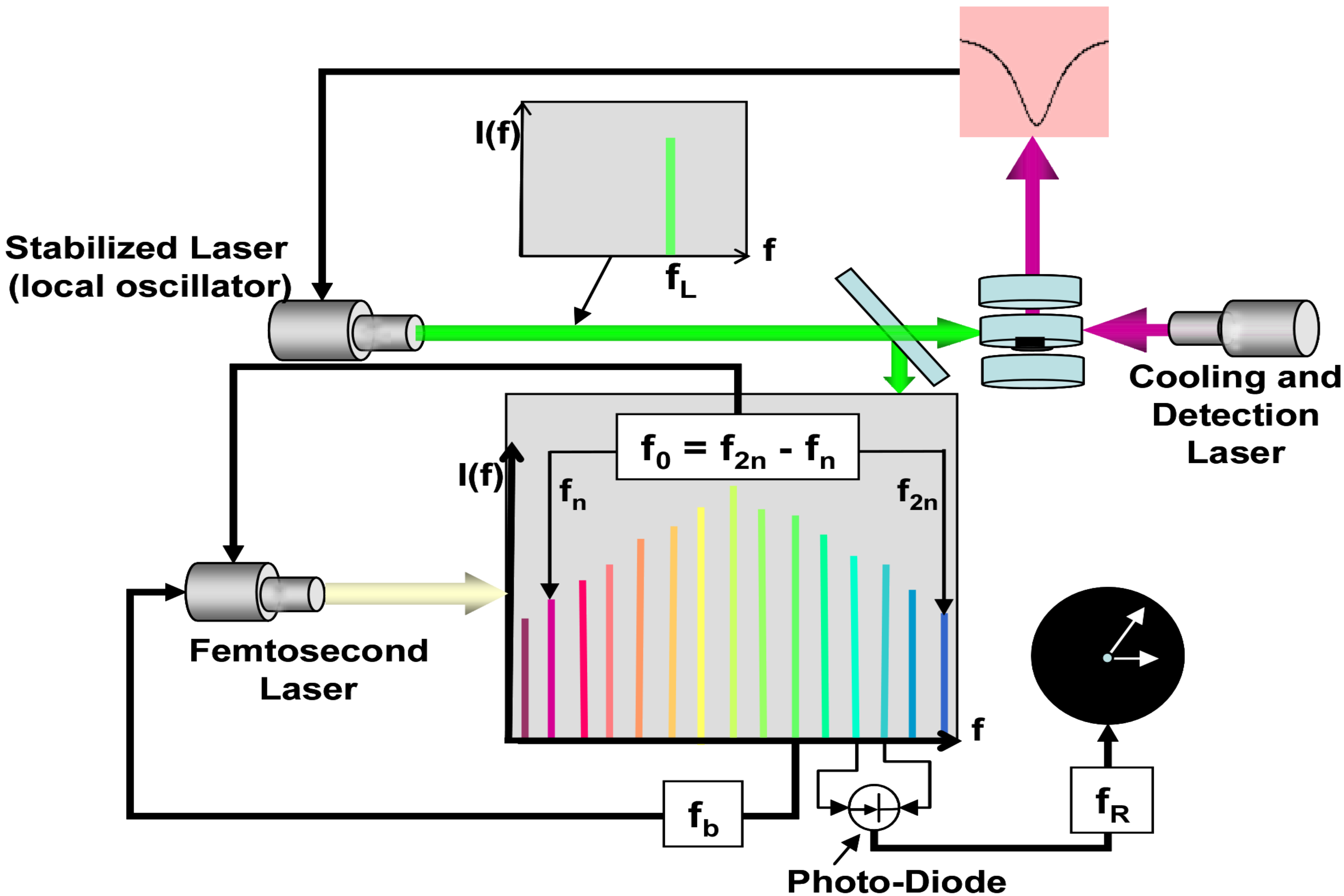
Clock Stability



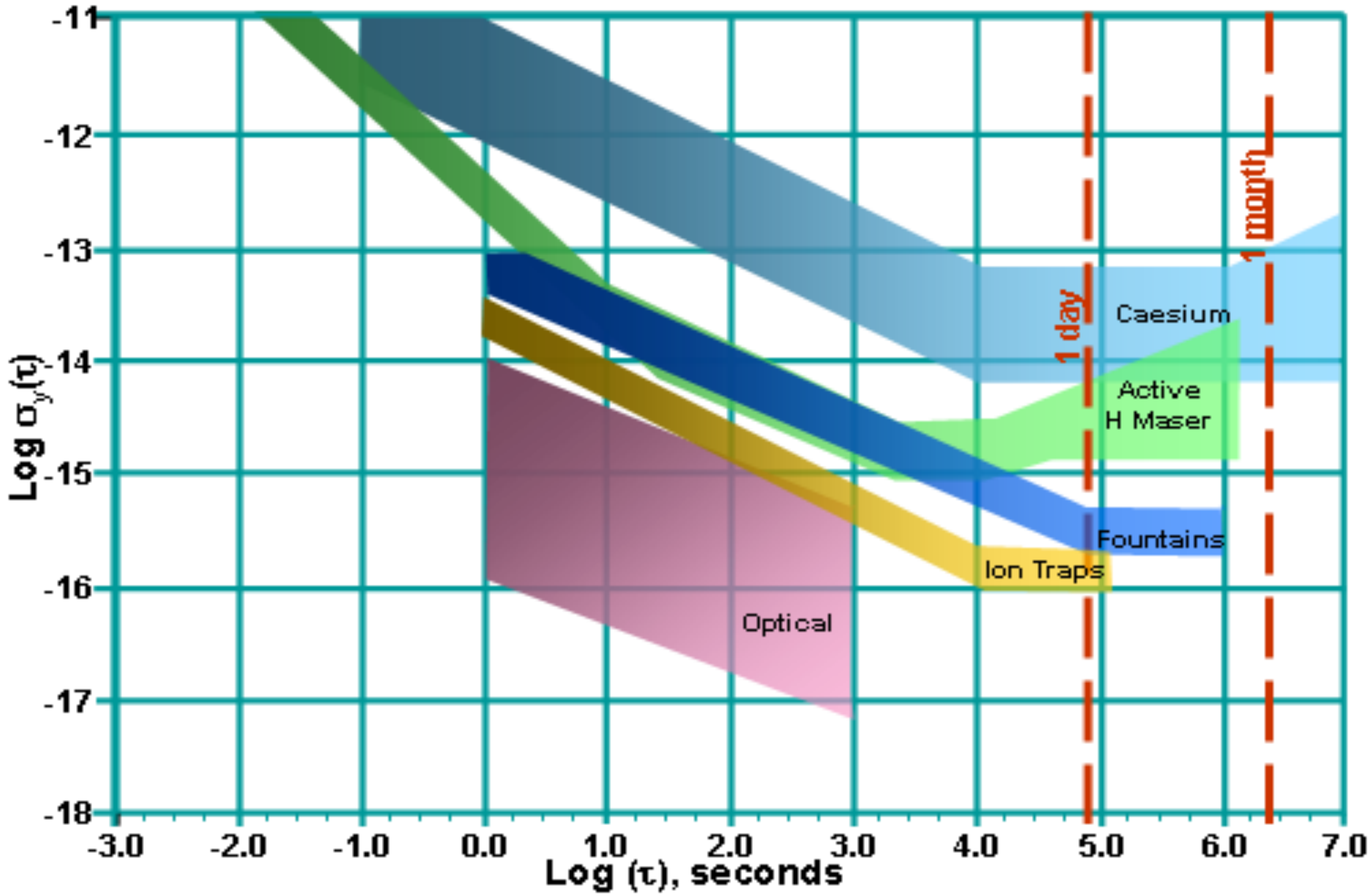
Cesium Fountain



Optical Clock

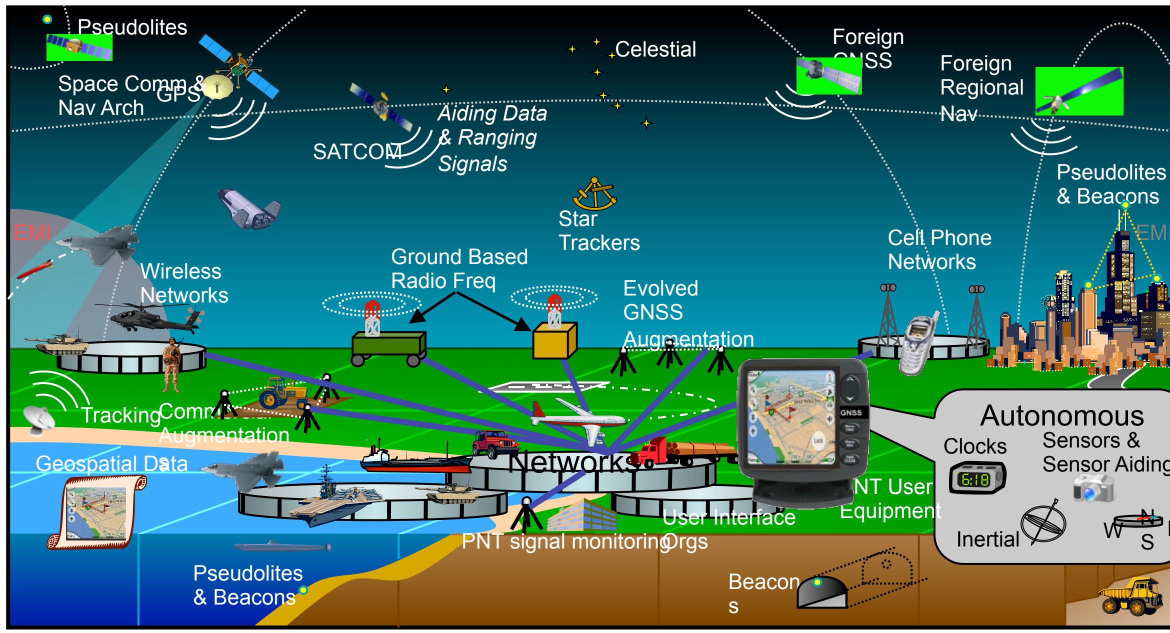


Microwave and Optical Time Standards Stabilities



Modern Applications of Time & Frequency

- Telecom Service
- Networks
- Cable Operators
- Government / Aerospace & Defense
- Enterprise IT
- High Frequency Trading
- Broadcast Infrastructure
- Underwater Exploration and Navigation
- Energy / Utilities
- RFID
- Intelligent Transportation Systems
- Industrial Processes
- Air Traffic Control
- Spacecraft Navigation
- Scientific Research & Development



20^{th} Century Developments

- Time Zones
- Variable Earth Rotation
- General Relativity
- Quartz Crystal Clocks
- Radio Astronomy
- Atomic Time Standards
- International Time Systems
- Laser Ranging
- Dynamical Time Scales
- Space Navigation Systems
- VLBI
- Earth Orientation Sciences
- Extragalactic Sources for Reference Frames

Redefinition of UTC 2000 - 2012

- ITU WP 7A Proposal
- Surveys, Discussions, Studies
  - Surveys favor the *status quo*
  - Lack of cost estimates
  - No consensus
- Opposing votes in ITU-R
  - Working Party 7A
  - Study Group 7
- Forwarded to Radiocommunications Assembly in 2012

Status of Redefinition of UTC

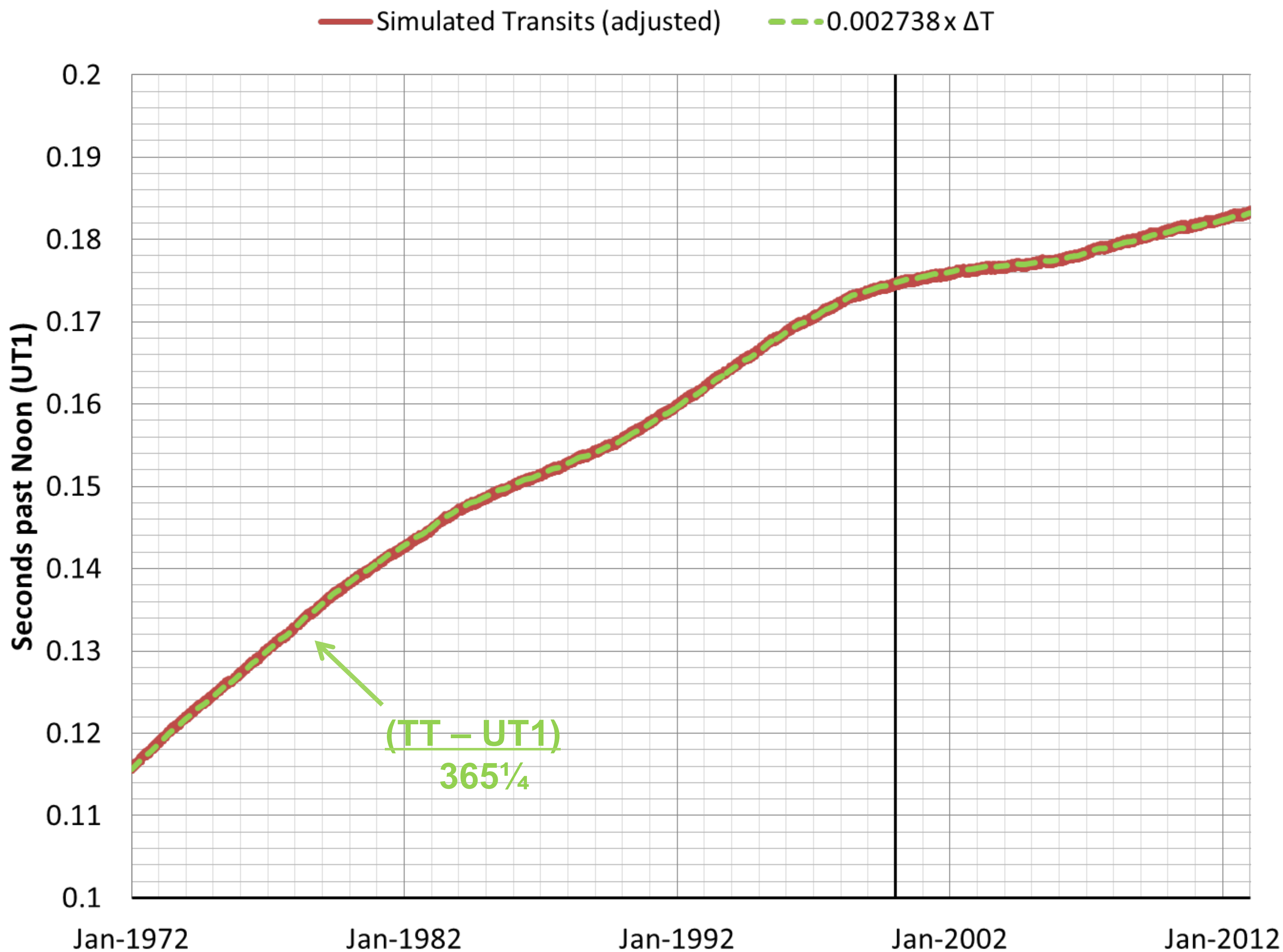
- Radio Communications Assembly Jan 2012
  - 190 countries could vote
  - ISO resolution concerning changing the name
  - Equal division of For, Against, Undecided
  - Delay Decision until 2015
  - Call for a Study
    - continuous reference time-scale
    - other technical options
    - broader implications
  - IAG WG 1.1.1
    - Nothing Gained by changing

How Well Has UT Kept Up w/ GMT

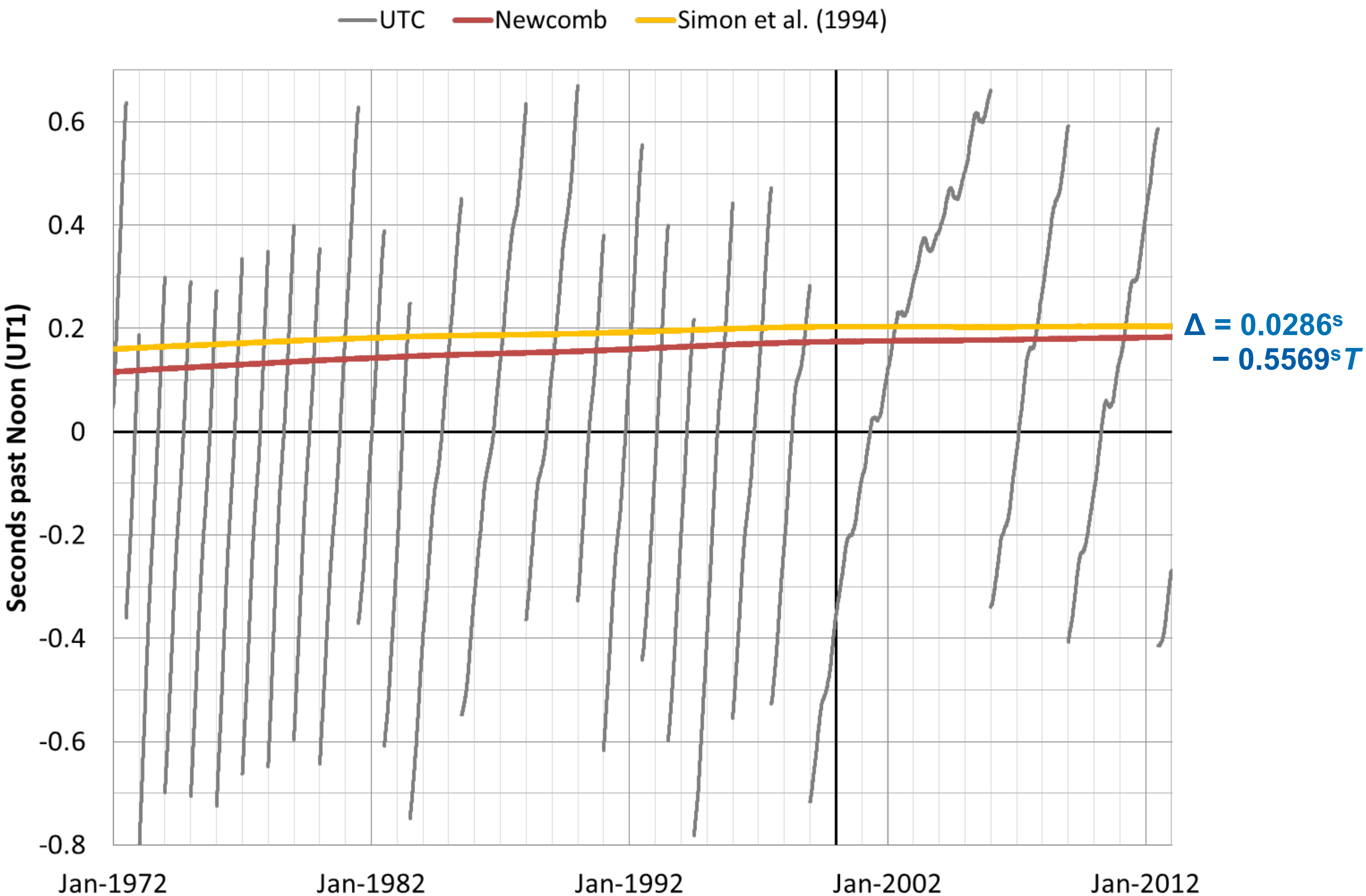
- Expected discrepancy: ~(TT-UT) / 365¼
- Guinot (2011)*
  - UT1 preserved as a representation of GMT w/ "*a departure which may reach one or two seconds…*"
    - Imprecise solar-transits relative to stars: ~0.1^s
    - Algorithm changes to BIH "mean observatory": 10's of ms
    - Non-uniformity from polar motion: ~30 ms at Greenwich
    - Plate tectonics: centimeters (μs) per annum.
    - Longitude origin perturbed w/ terrestrial system changes (0.356^s)

***Guinot, B. (2011) "Solar time, legal time, time in use." *Metrologia*, Vol. 48, pp. S181-S185.**

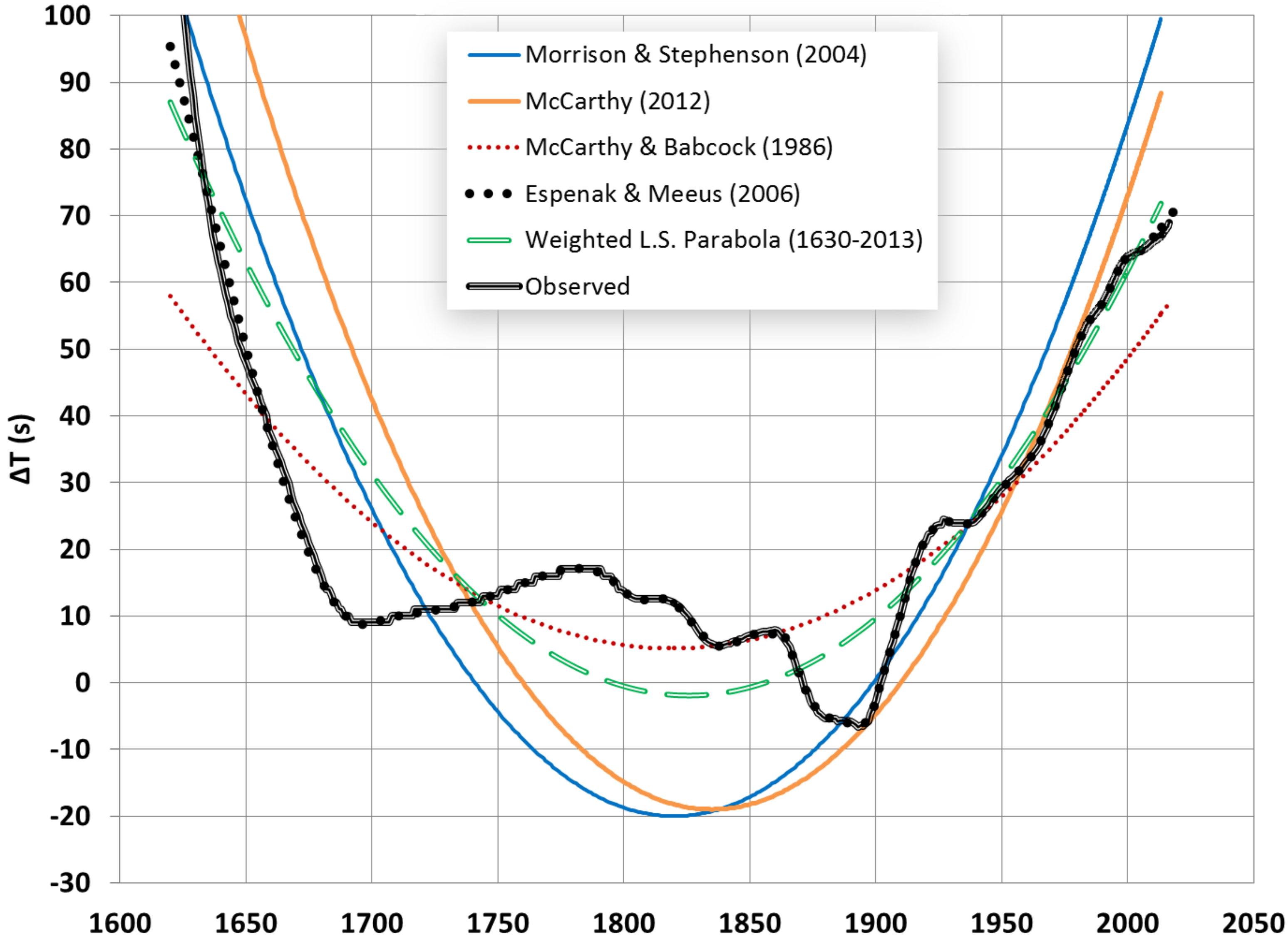
Simulated Transit Times



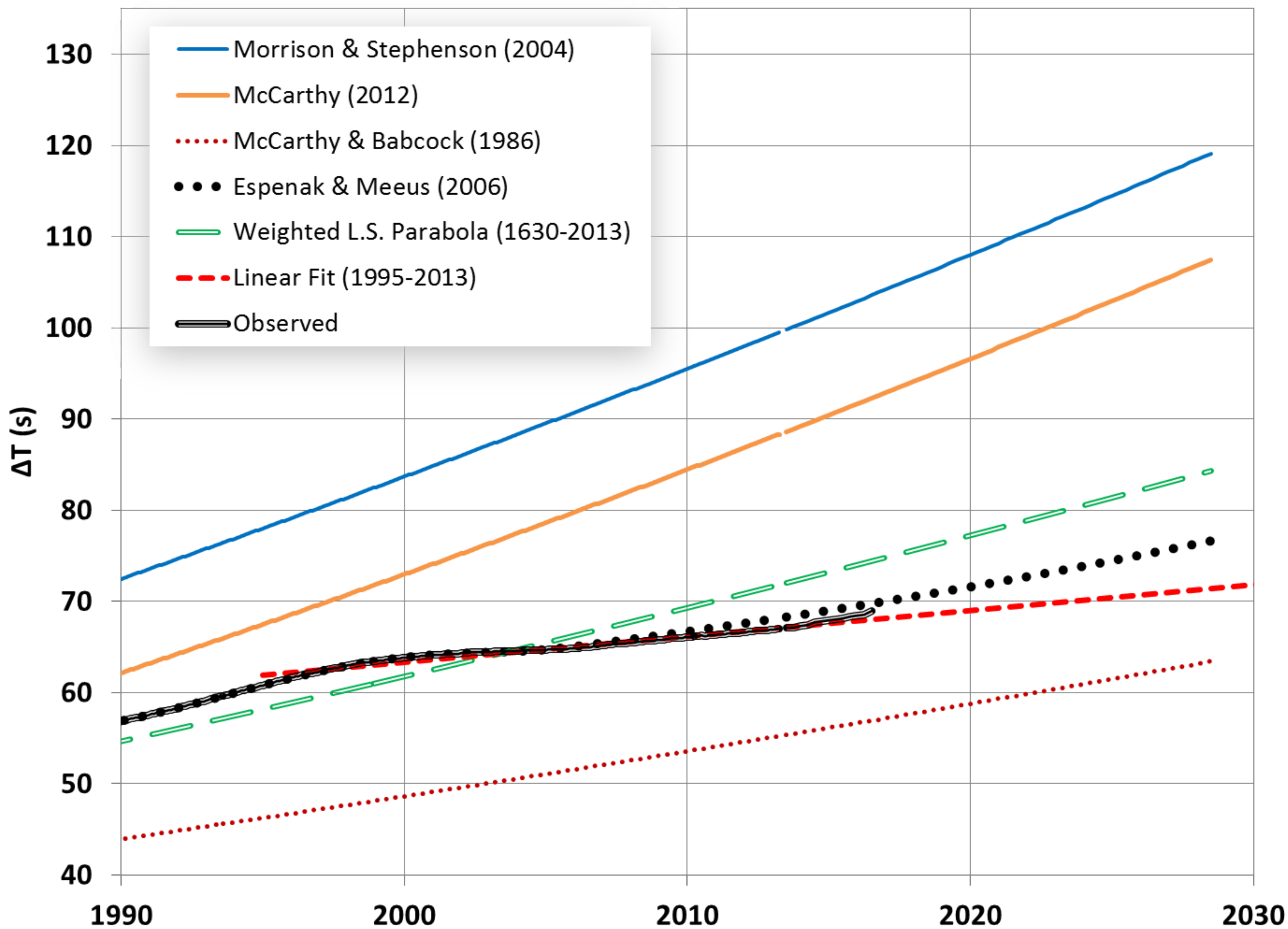
Modern Mean Sun



Past ΔT Behavior



Future ΔT Behavior



Options and Requirements

	UTC as is	UTC sans leap seconds	UTC sans leap seconds (renamed)	UTC with leap minutes	UTC & TAI	UTC & TAI + n seconds	UTC & GNSS
Constant time interval	X	X	X	X	X	X	X
Constant Frequency	X	X	X	X	X	X	X
Synch with Earth Rotation	X				X	X	X
Current software Compatible	X				X	X	X
Meets future Requirements	X	X	X	X	X	X	X
Astronomical pointing	X				X	X	X
Meets legal times	X				X	X	X
Simple conversion to "days"		X	X		X	X	X
Current Global Navigation Systems	X				X	X	X
Public perceptions of time	X			?	X	X	X

Personal Recommendation

- Recognize current practices
  - Retain UTC as is
  - Officially recognize a distinct uniform atomic time scale for those who need such a time scale
    - Real-time TAI(k)
    - GNSS-based time scale
    - Some other offset from TAI
  - Other options for method of introducing leap second in time scales
    - Example: clock slewing for imprecise applications

Personal Recommendation

- Options with no cost increases or organization problems
  - CIPM coordination of background reference time scales, TAI, GNSS
  - Follow ITU-R recommendations for distributing UTC
    - “DTAI” per Recommendation 460-6
  - GNSS distribution of GNSS time scales
- Basically recognizing current practice

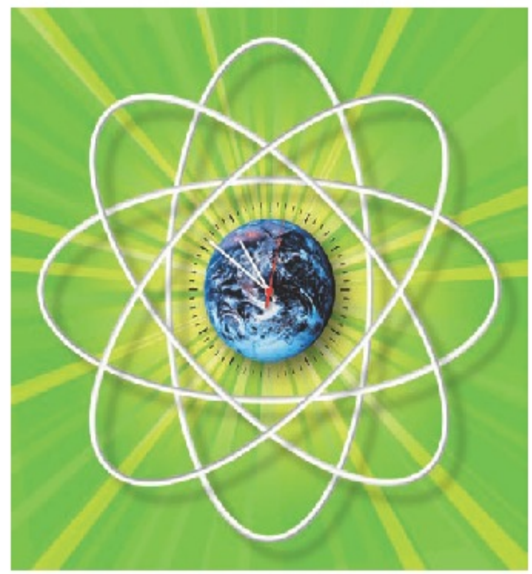
What is Next?

- Studies per WRC resolution
- Studies should consider
  - user requirements
  - options
    - pros and cons of each
- Educate all nations concerning all issues
  - Not just telecommunication/metrology concerns
- Decision in 2015?

Dennis D. McCarthy and
P. Kenneth Seidelmann

WILEY-VCH

TIME
From Earth Rotation to Atomic Physics



McCarthy · Seidelmann

Time – From Earth Rotation to Atomic Physics

WILEY-VCH

Filling the need for a book that presents the current technology as well as the underlying historical and physical background, this publication informs scientists, engineers, and those interested in the foundations of modern timekeeping how precise time and frequency are made available for modern-day use. The authors draw on their longstanding research experience with timekeeping and high-precision measurements to describe the discovery of the irregular motions of the Earth, the development of mechanical and atomic clocks, the introduction of dynamical timescales, and the development of the study of the Earth's orientation in space. Also discussed are astronomical and satellite observations used to improve solar system dynamics and Earth kinematics along with the applications of the theory of relativity to the topics of timekeeping and time transfer.

Indispensable for high-precision measurements and applications in astronomy, space sciences, and geodesy, and relevant for physical measurements, navigation, and communication, this monograph can be used equally as a course book or as accompanying work at advanced undergraduate, graduate, and professional levels.

Dennis D. McCarthy worked in the Time Service and Earth Orientation Departments of the U.S. Naval Observatory (USNO) for the past 40 years, reaching the position of Director of Time at USNO. He has been involved in both the improvements in time keeping and time transfer, and the advances in the observational determination, analyses and prediction of accurate Earth orientation. Dr. McCarthy is the author of a large number of papers on time scales and Earth orientation.

P. Kenneth Seidelmann worked in the Nautical Almanac and Orbital Mechanics Departments of the U.S. Naval Observatory for 35 years, reaching the level of Director of Astrometry at USNO. He has been involved in the development of astronomical ephemerides, relativistic dynamical time scales, space missions, and the applications of improved astrometric accuracy. He is currently a Research Professor at the University of Virginia. Professor Seidelmann is editor of the ‚Explanatory Supplement to the Astronomical Almanac', coauthor of ‚Fundamentals of Astrometry', and author of a large number of papers on fundamental astronomy.

ISBN 978-3-527-40780-4

9 783527 407804

www.wiley-vch.de

Some Options

- Retain *status-quo* UTC as is
- Redefine UTC:
  - Cease leap seconds
    - Proposed but not adopted in 2012
  - Cease leap seconds but also change name
  - Replace leap seconds with leap minutes
- Officially supplement current UTC with an atomic scale:
    - TAI?
    - GNSS time?
    - Other?
- Other Options?

Some Options

- Recognize alternative adjustment methods
  - Computer clock slewing before leap second
  - Google rubber second in June 2012

- Unlikely or non-viable options
  - Redefining the SI second
  - Replacing leap seconds with leap hours or leap minutes

Continuous Reference Time-Scale

- Is UTC *discontinuous*?
  - Primary definition of continuous?
    - parts in immediate connection
      - » contiguous
    - uninterrupted in sequence
    - definition does not prescribe means of labeling
- What are the requirements for:
  - UTC?
  - Continuous Reference Time-Scale?

Issues Concerning Recommendations to Redefine UTC

- Significance with respect to Radiocommunications
  - Technical, legal, and public issues
  - Continuous time scale
- Involvement of International Standards and Scientific Organizations
  - ITU-R non consensus
  - IAU, IERS, URSI, AAS, ISO
  - Software organizations
- Terminology
  - Change definition -> change name

Issues Concerning Recommendations to Redefine UTC

- Alternative Time Scales
  - GPS time already in use
  - TAI or equivalent, as a supplementary time scale
- User Preferences
  - Surveys favor *status quo*
  - Only minor anomalies with leap seconds reported
  - No substantial documentation supporting redefinition
- Software and Hardware Modifications
  - GNSS
  - Consult computer scientists and software developers

Issues Concerning Recommendation to Redefine UTC

- Distribution of UT1
  - Availability and distribution of UT1 by computer network
- Legal Considerations
  - Status of UTC as official time in countries
  - Mean Solar Time as official time in countries
- Re-education
  - Revision of literature and textbooks
    - Change of knowledge base affects large number of users otherwise unaffected
    - Potentially confusing to non-experts

Issues Concerning Recommendation to Redefine UTC

- Celestial Navigation and Almanacs
  - Changes in almanacs and explanations of use
  - Problem of navigation in an emergency
- Rate of Earth Rotation
  - Long and short term trends in Earth-rotation rate
- Long-Term Societal Effects
  - Long term adjustment procedure?

Reasons for Keeping UTC As Is

- Many country’ s legal codes call for mean solar time
- Current navigation systems software based on current definition
- Software based on UTC-UT1< 1 s
- Public perception of civil time based on solar time
- Extensive documentation in books based on current definition
- If changed away from mean solar time, changing back will be difficult
- Different definitions of UTC will cause confusion
- An atomic time scale is currently available from GNSS
- Leap seconds give the time keeping community publicity

Reasons for Redefining UTC Without Leap Seconds

- Software difficulties in including leap seconds
  - Computer systems based on only 60 seconds per minute
- Confusion between time scales with different epochs
- Problems introducing leap seconds in time scales
  - Communicating leap seconds
  - Updating databases
- Problems time tagging transactions when leap seconds occur
- Inconvenience of leap seconds

Reasons for Adding an Atomic Time Scale to Current UTC

- Satisfy all requirements
- Formalize what is currently being done
- Establish an official time scale without leap seconds