Considering Timescale Requirements for the Future

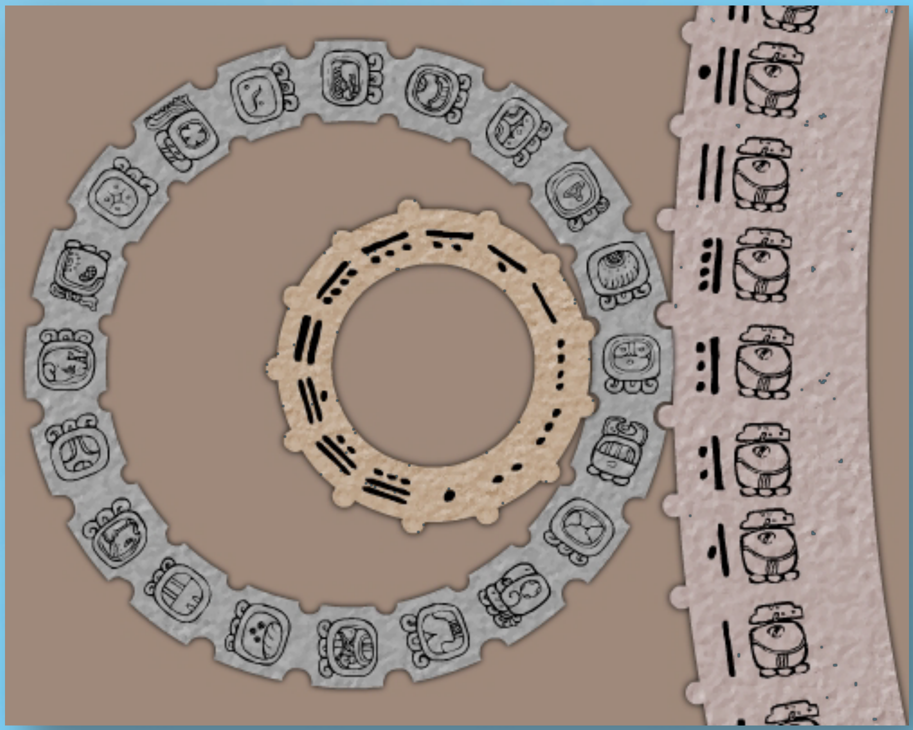
Prediction is very difficult, especially about the future.

Markus M. Ronner, 1918

Time Scale Definitions

- An arrangement of events used as a measure of duration
- A useful time scale is generated by any process which enables dates to be assigned to events

(6th General Assembly of the International Astronomical Union Grenoble, France (1976) Resolution No. 4 by Commissions 4 (Ephemerides) and 31 (Time))



Measurement Scales

Measurement is 'the assignment of numerals to things so as to represent facts and conventions about them.' … in the broadest sense, … defined as the assignment of numerals to objects or events according to rules. The problem then becomes that of making explicit

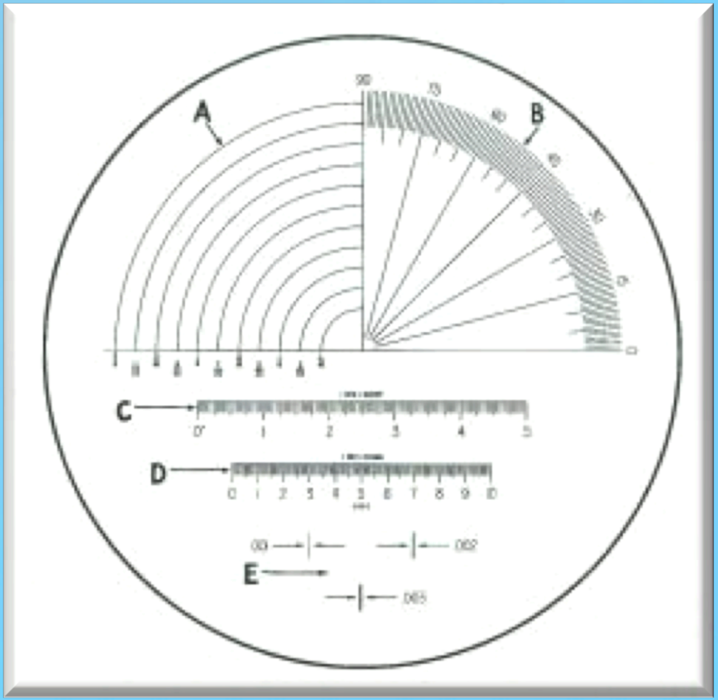
a) the various rules for the assignment of numerals,

b) the mathematical properties (or group structure) of the resulting scales, and

c) the statistical operations applicable to measurements made with each type of scale. (Stevens, 1946)

Four Properties of scales

1. **Identity**. Each value on the measurement scale has a unique meaning.
2. **Magnitude**. Values have an ordered relationship to one another. That is, some values are larger and some are smaller.
3. **Equal intervals**. Scale units along the scale are equal to one another over all levels of the scale.
4. **A minimum value of zero**. The scale has a true zero point, below which no values exist.



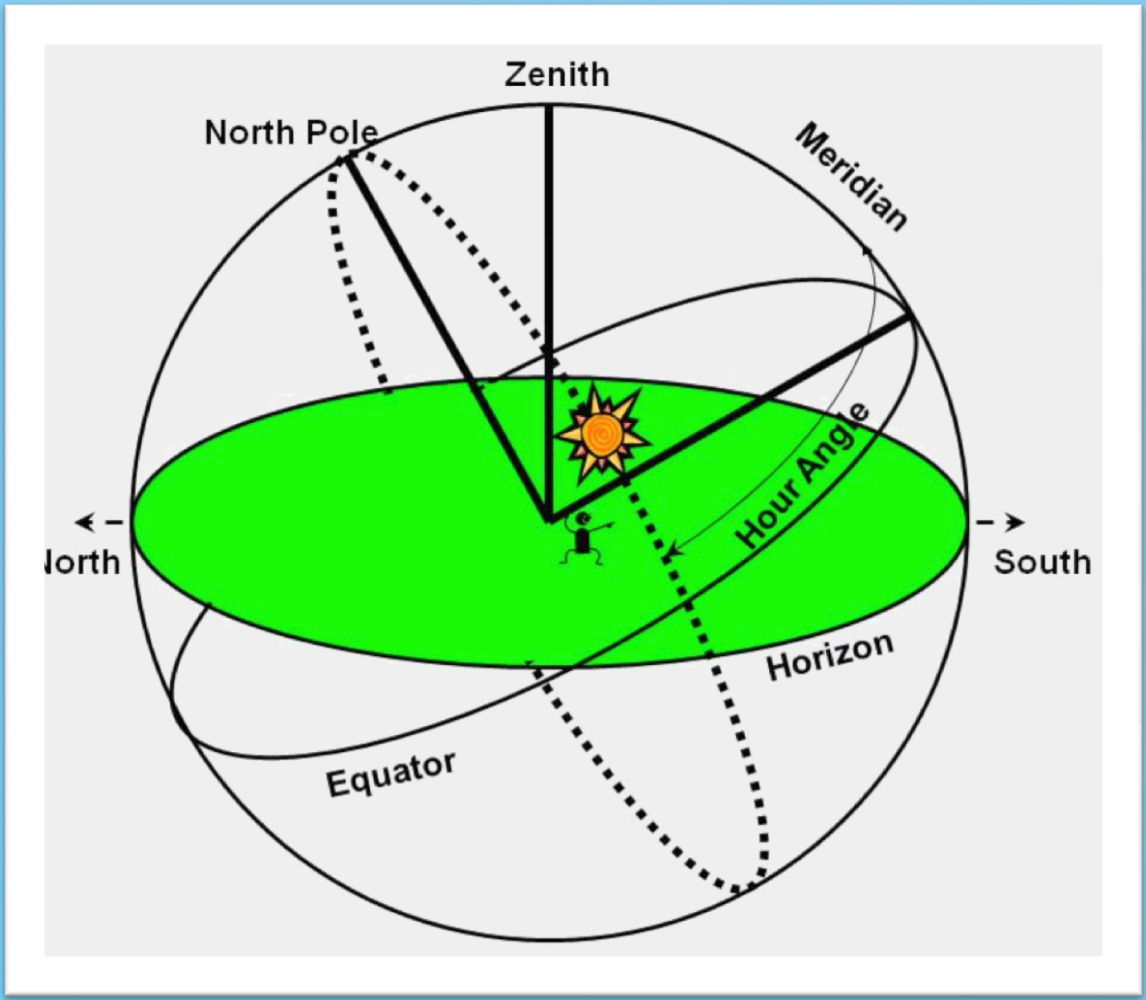
Time

- Interval scale of measurement with properties
  - Identity
  - Magnitude
  - Equal intervals over all levels of the scale
- Lacks minimum value of zero
  - scale form remains invariant when a constant is added.

Any particular scale, sensory or physical, may be objected to on the grounds of bias, low precision, restricted generality, and other factors, but the objector should remember that these are relative and practical matters and that no scale used by mortals is perfectly free of their taint. (Stevens, 1946)

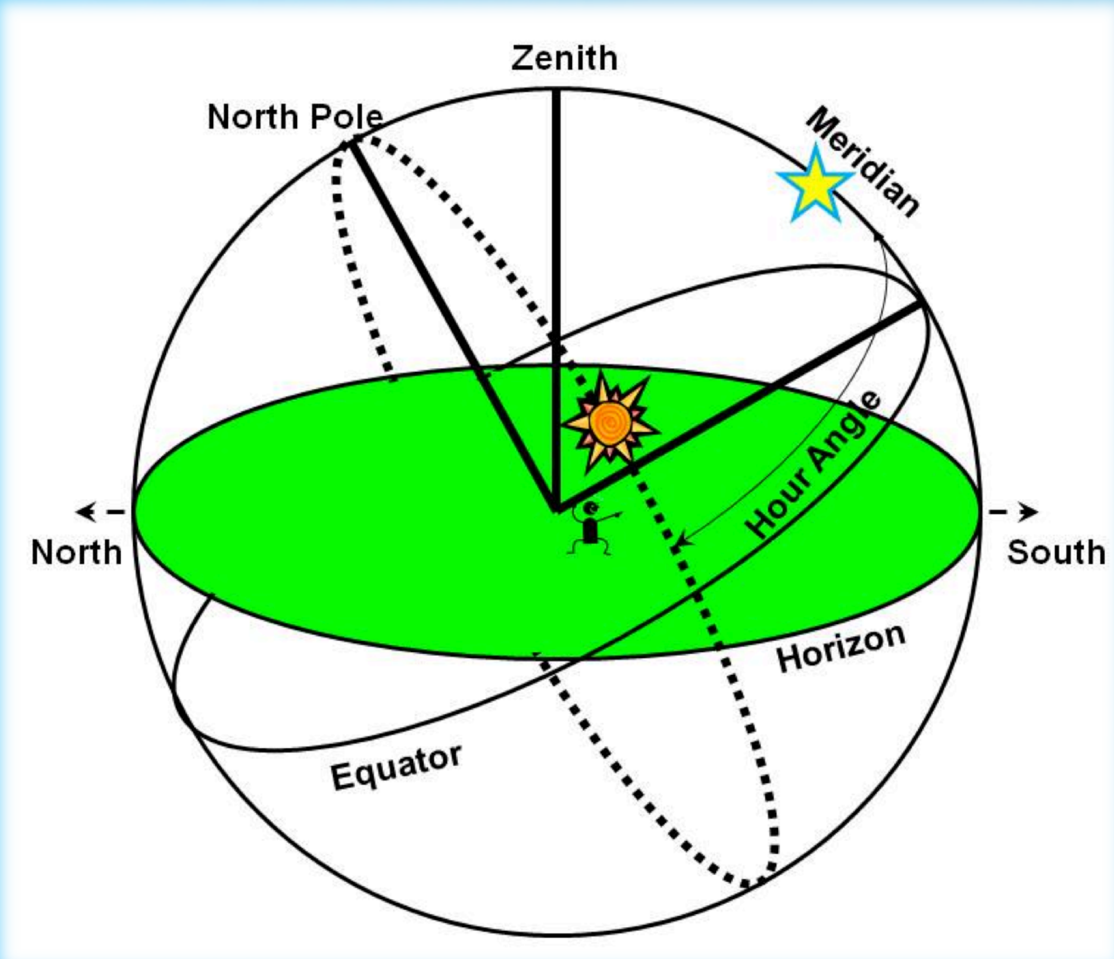
Rathaus Wurzburg
12-14th Century

Apparent Solar Time



Could be local or at some special place like Greenwich

Using Stars



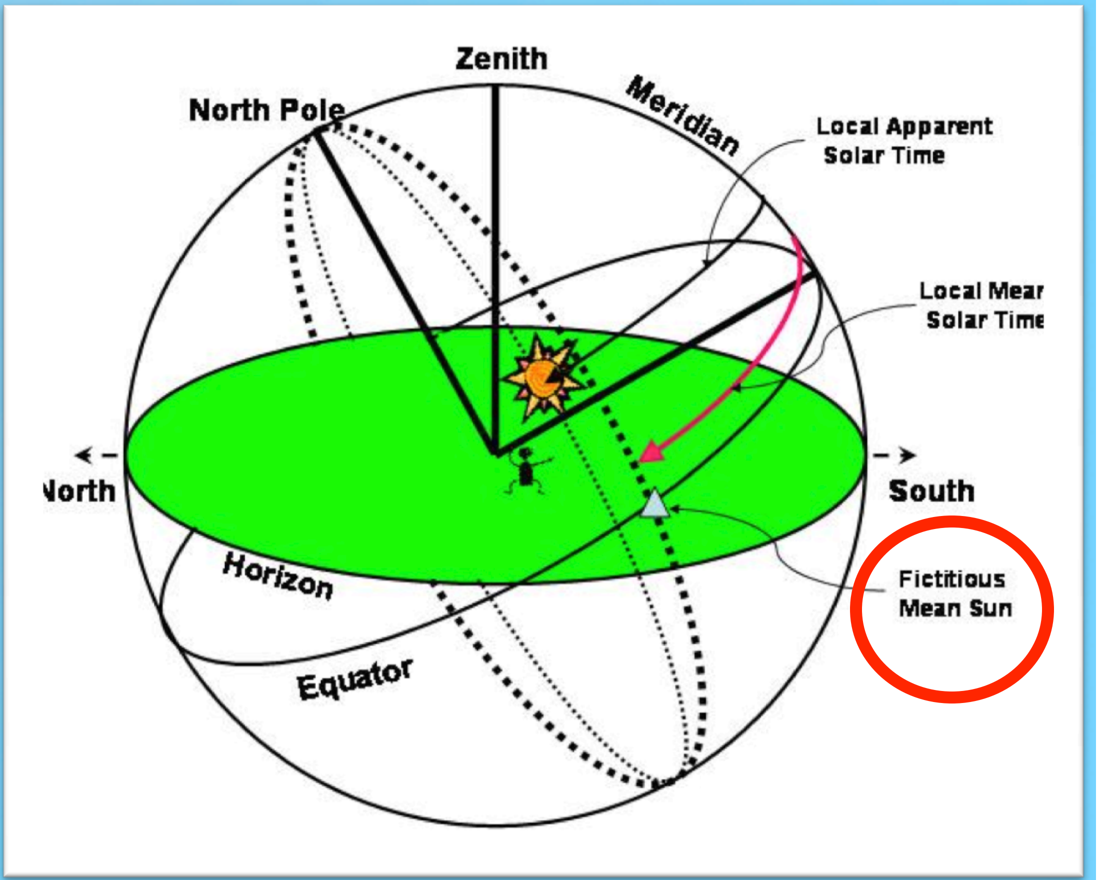
Easier and more accurate IF you know the direction of the Sun with respect to the stars

But…

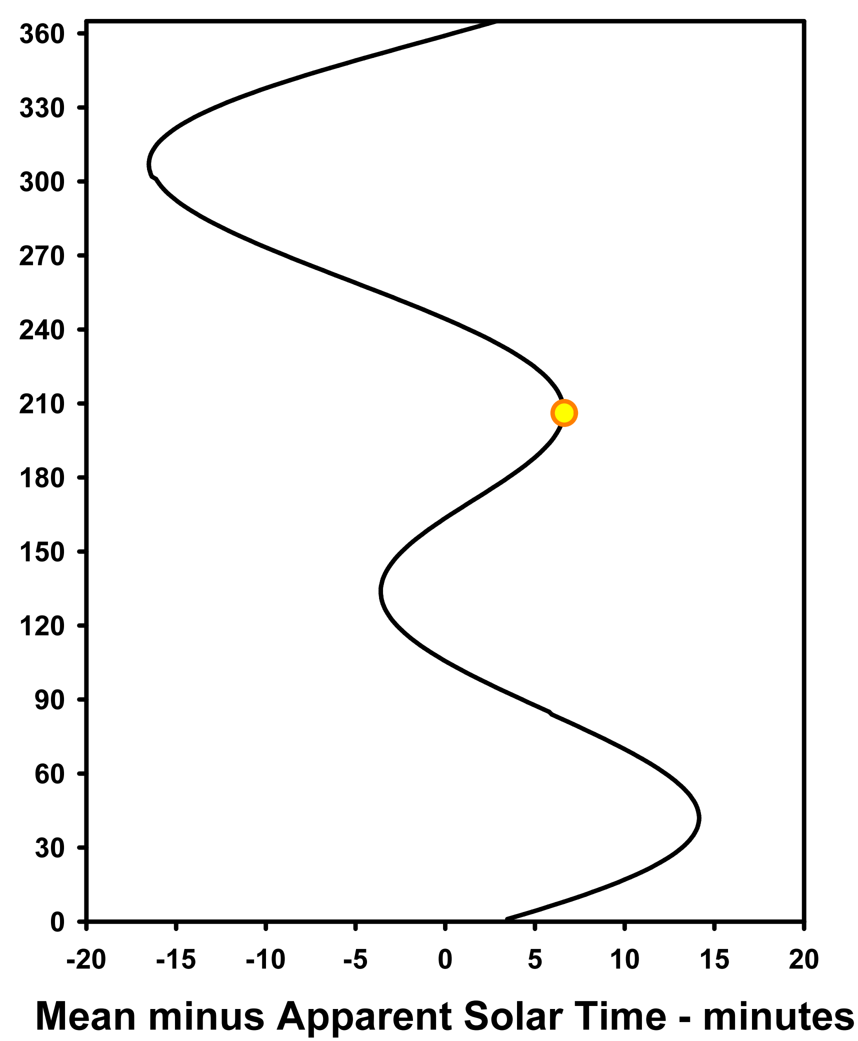
- Length of the apparent solar day varies during the year because Earth's orbit is inclined and is really an ellipse.
- Ptolemy (300 AD) knew this

So…

- We need a Sun that behaves

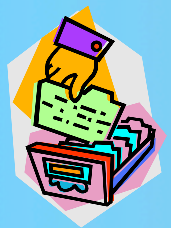


Mean Solar Time



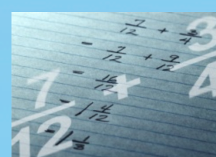
Equation of Time

Astronomical Timekeeping



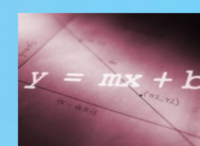
Catalogs of Positions of Celestial Objects

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



Observations

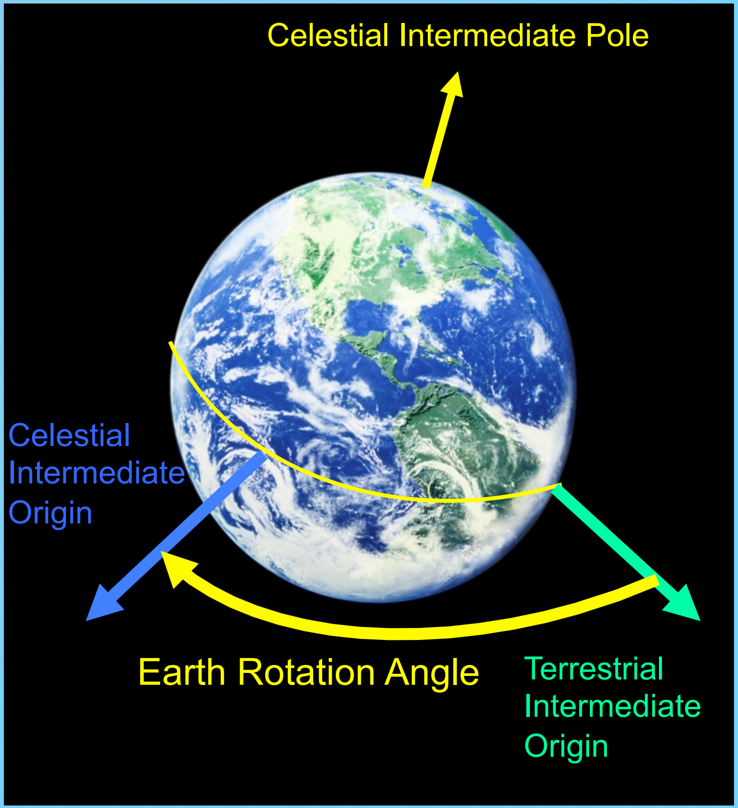
Determine Clock Corrections

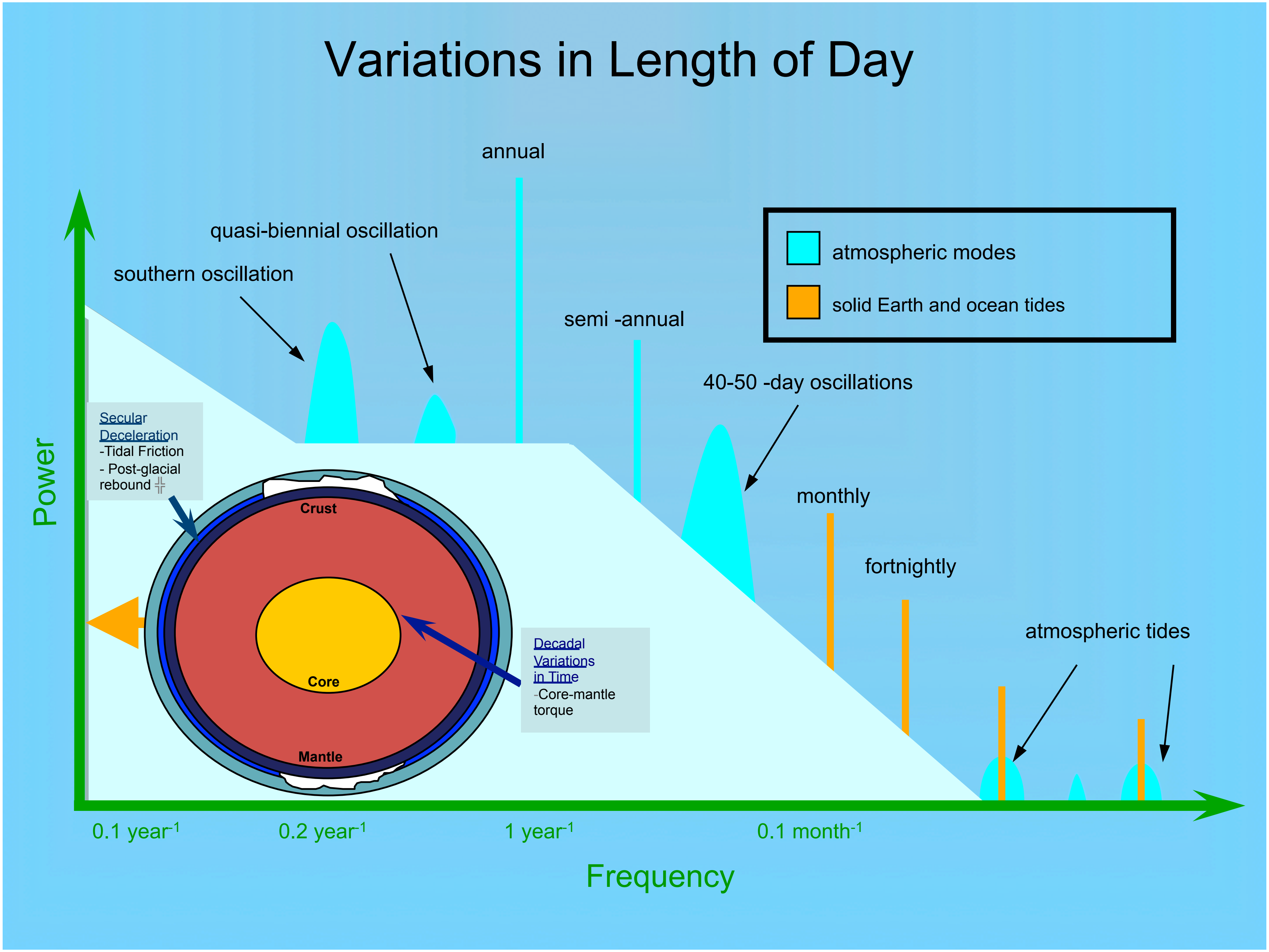


Universal Time (UT)

- 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
annual
quasi-biennial oscillation
southern oscillation
semi -annual
atmospheric modes
solid Earth and ocean tides
40-50 -day oscillations
monthly
fortnightly
atmospheric tides
Secular Deceleration
-Tidal Friction
- Post-glacial rebound
Crust
Core
Mantle
Decadal Variations in Time
-Core-mantle torque
Power
0.1 year^{-1}
0.2 year^{-1}
1 year^{-1}
0.1 month^{-1}
Frequency

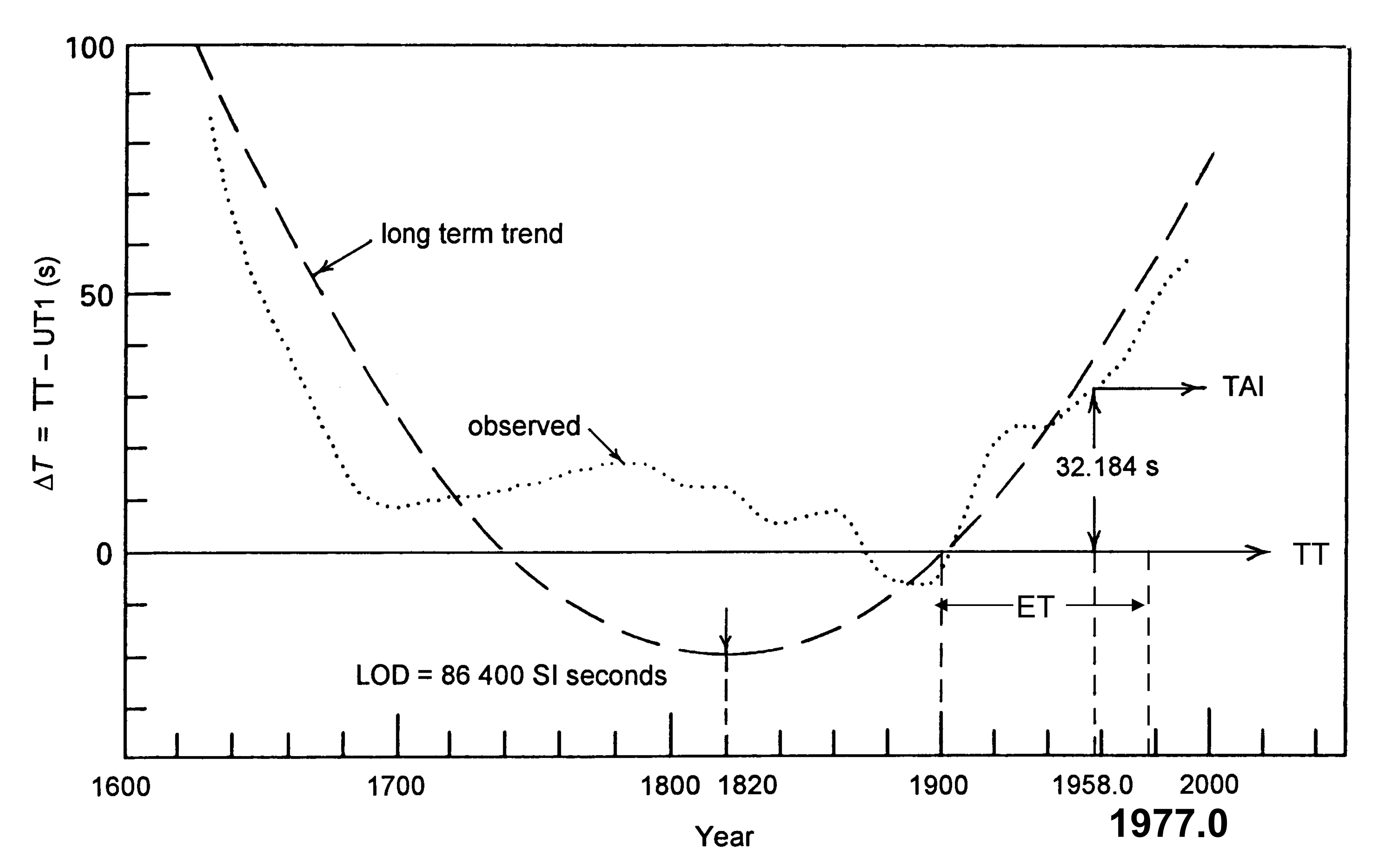
Ephemeris Time (ET)

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

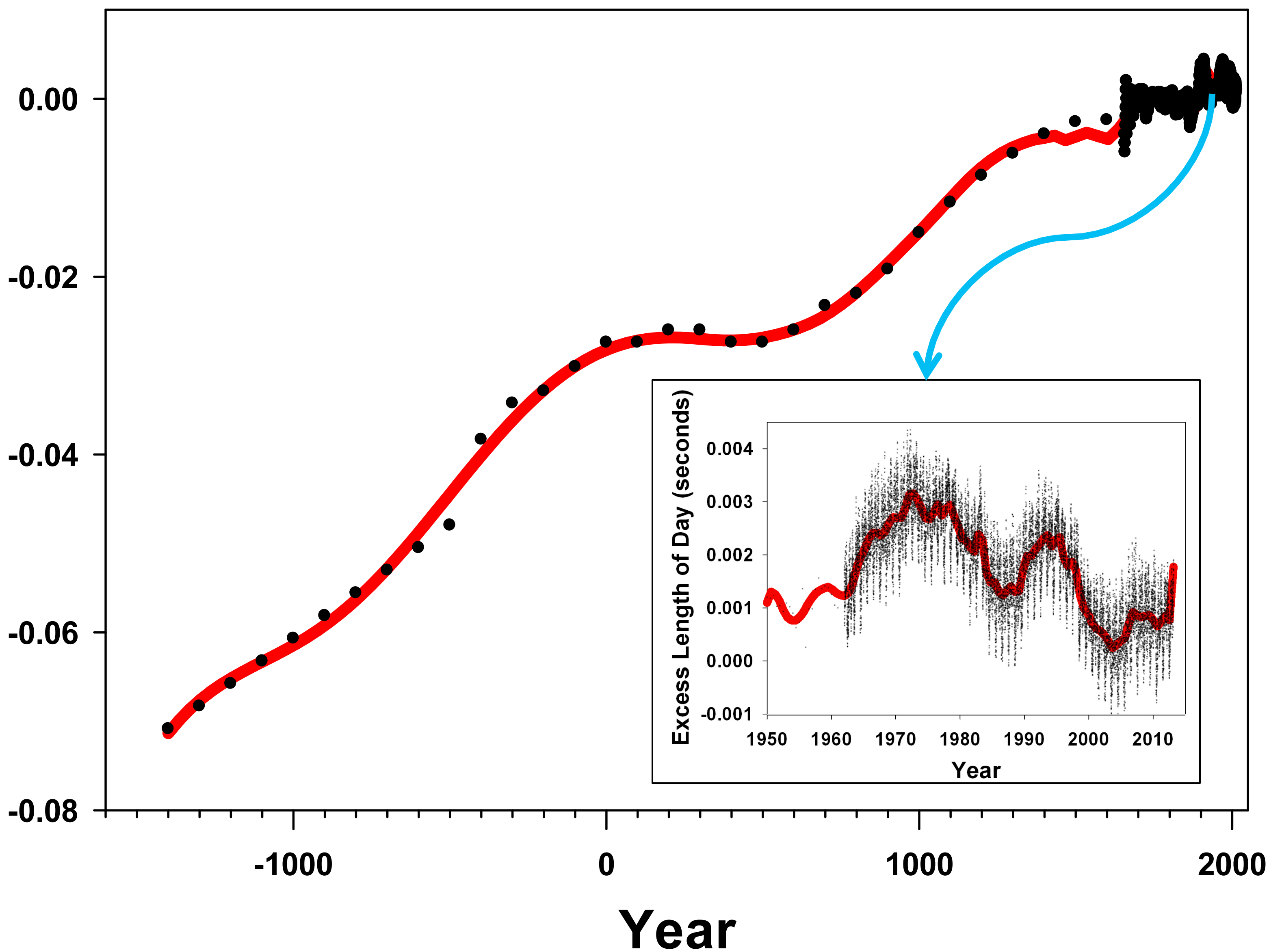
Defined by Newcomb's value for the length of the Tropical Year 1900, but in practice measured by observations of the Moon with respect to the stars

- 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)



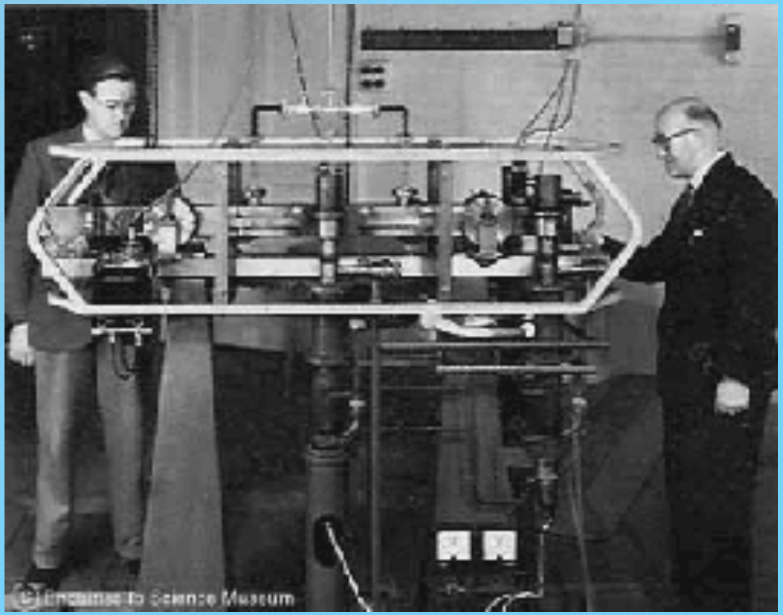
0.00
-0.02
-0.04
-0.06
-0.08
-1000
0
1000
2000
Year
Excess Length of Day (seconds)
0.004
0.003
0.002
0.001
0.000
-0.001
1950
1960
1970
1980
1990
2000
2010
Year

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

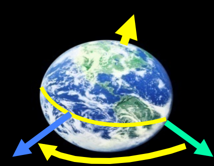


International Atomic Time (TAI)

- 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)

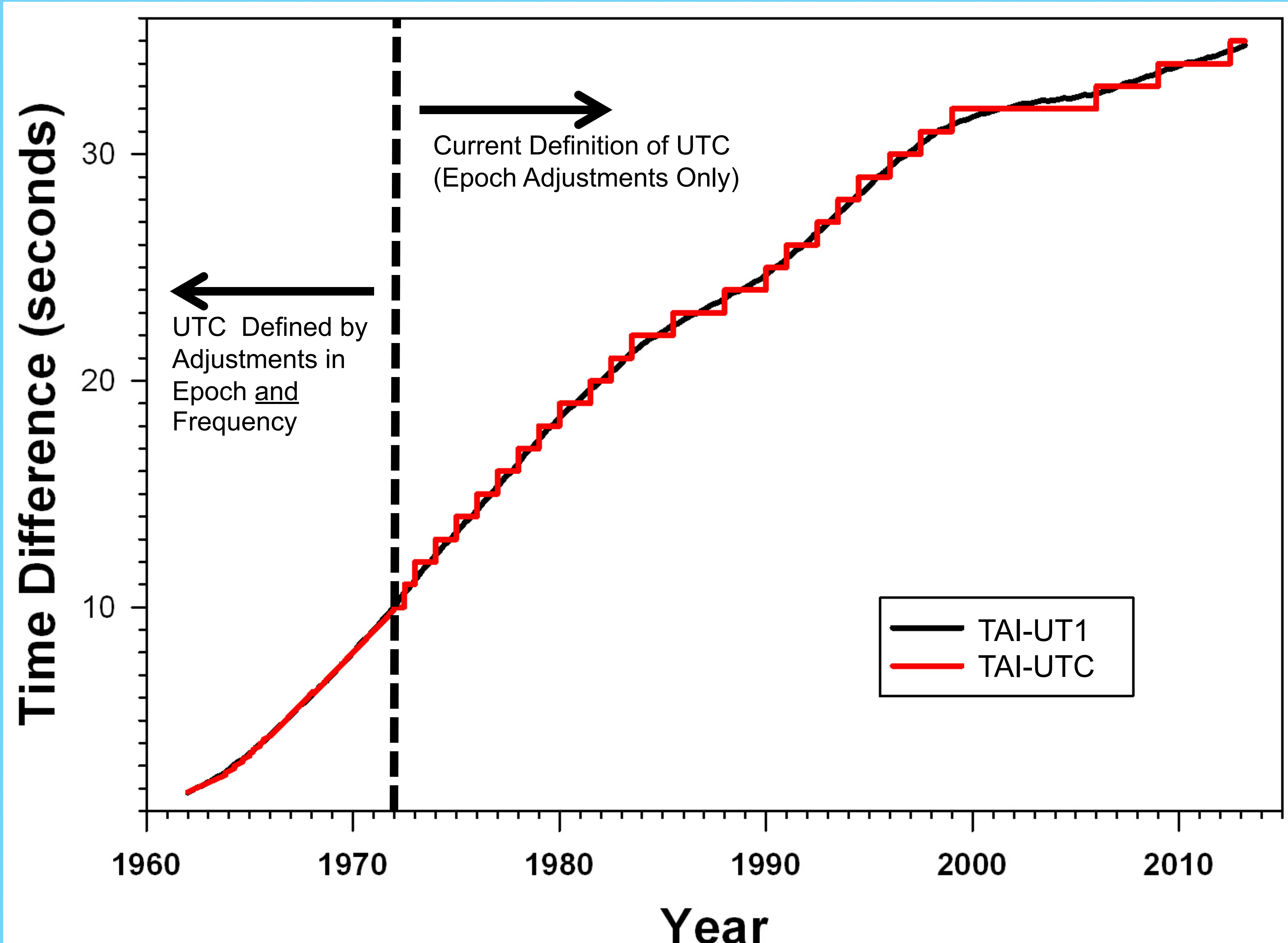
- Name adopted officially in 1967
- From 1961 to 1972 UTC used frequency offsets and steps (less than 1 s) to maintain agreement with UT2 within about 0.1 s
- In 1970 formalized by International Radio Consultative Committee (CCIR), predecessor of International Telecommunication Union (ITU), to correspond 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



1 second adjustments

Leap Seconds may be introduced as the last second of any UTC month.
December and June Preferred, March and September second choice.

UTC



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

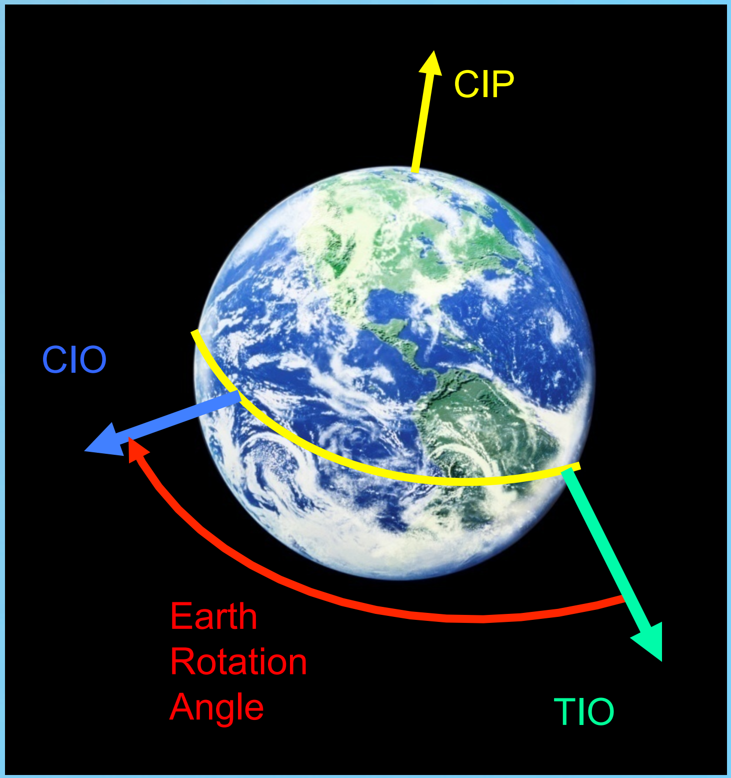
Earth Rotation Angle (ERA)

- 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

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

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

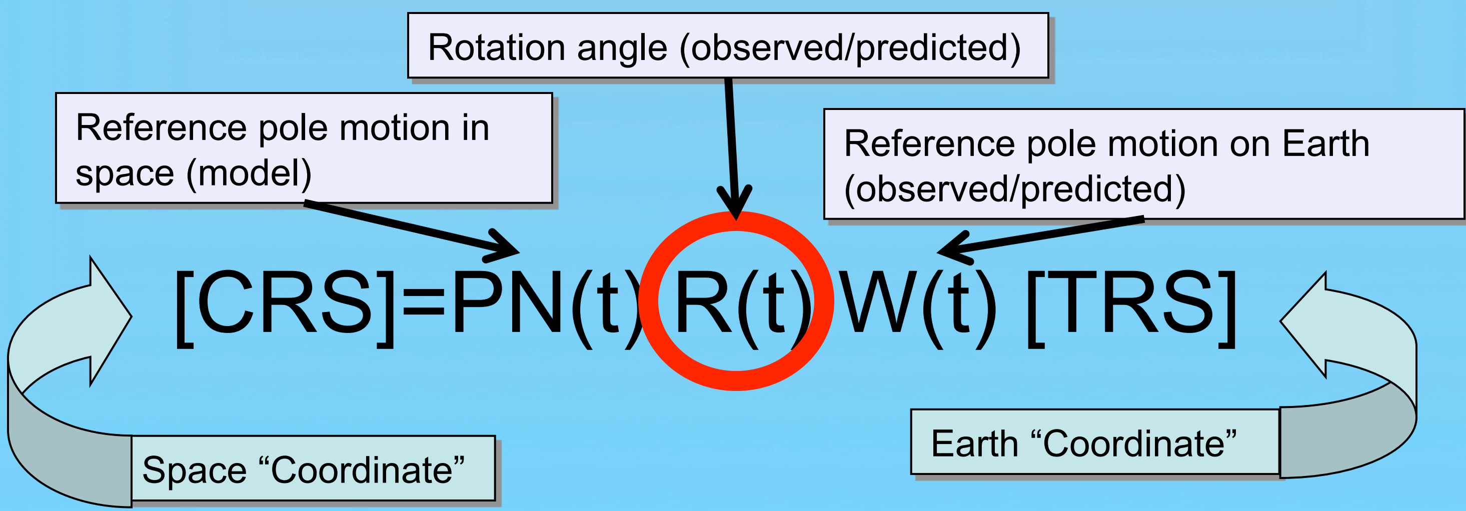
T_u = (Julian UT1 date - 2451545.0),



- 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



Precision of IERS Data

IERS Bulletin A

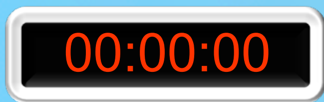
Yr	Mo	Da	MJD	x	error	y	error	UT1-UTC	error
				"	"	"	"	s	s
2013	4	5	56387	0.05228	0.0001	0.37807	0.00009	0.151744	0.000008
2013	4	6	56388	0.05285	0.0001	0.37873	0.00009	0.149911	0.000008
2013	4	7	56389	0.05321	0.0001	0.37934	0.00009	0.148022	0.000008
2013	4	8	56390	0.05362	0.0001	0.38011	0.00009	0.146145	0.000008
2013	4	9	56391	0.05422	0.0001	0.38118	0.00009	0.144308	0.000008
2013	4	10	56392	0.05495	0.0001	0.38236	0.00009	0.142556	0.000007

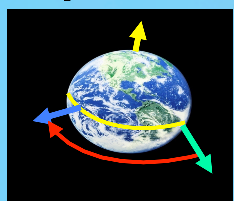
Estimated accuracy of predicted UT1 - UTC (s)

10 d	20 d	30 d	40 d
0.0014	0.0024	0.0032	0.0040

IERS provides UT1 – UTC with a precision of 1 to 10 *micro*seconds in near real-time

Conceptual Difference Between UTC and UT1

- UTC 

  - standard time with sub-nanosecond per day stability
  - Used worldwide to order events and meet precise schedules
  - Widely disseminated
- UT1 
  - Used to determine the angle of rotation of the Earth in space
  - Originally called a time, but never used as a time scale
  - Used by specialists
  - Dissemination:
    - By IERS in Bulletin A in the form UT1 – UTC
    - Encoded in UTC
    - GNSS?
  - Precision:
    - From Bulletin A: ±1 to 10 microseconds
    - From UT1 = UTC with leap seconds: up to ±0.9 second

There is a need to disseminate UTC via signals. There is no need to disseminate UT1 by encoding UTC because it is easily available with far greater accuracy.

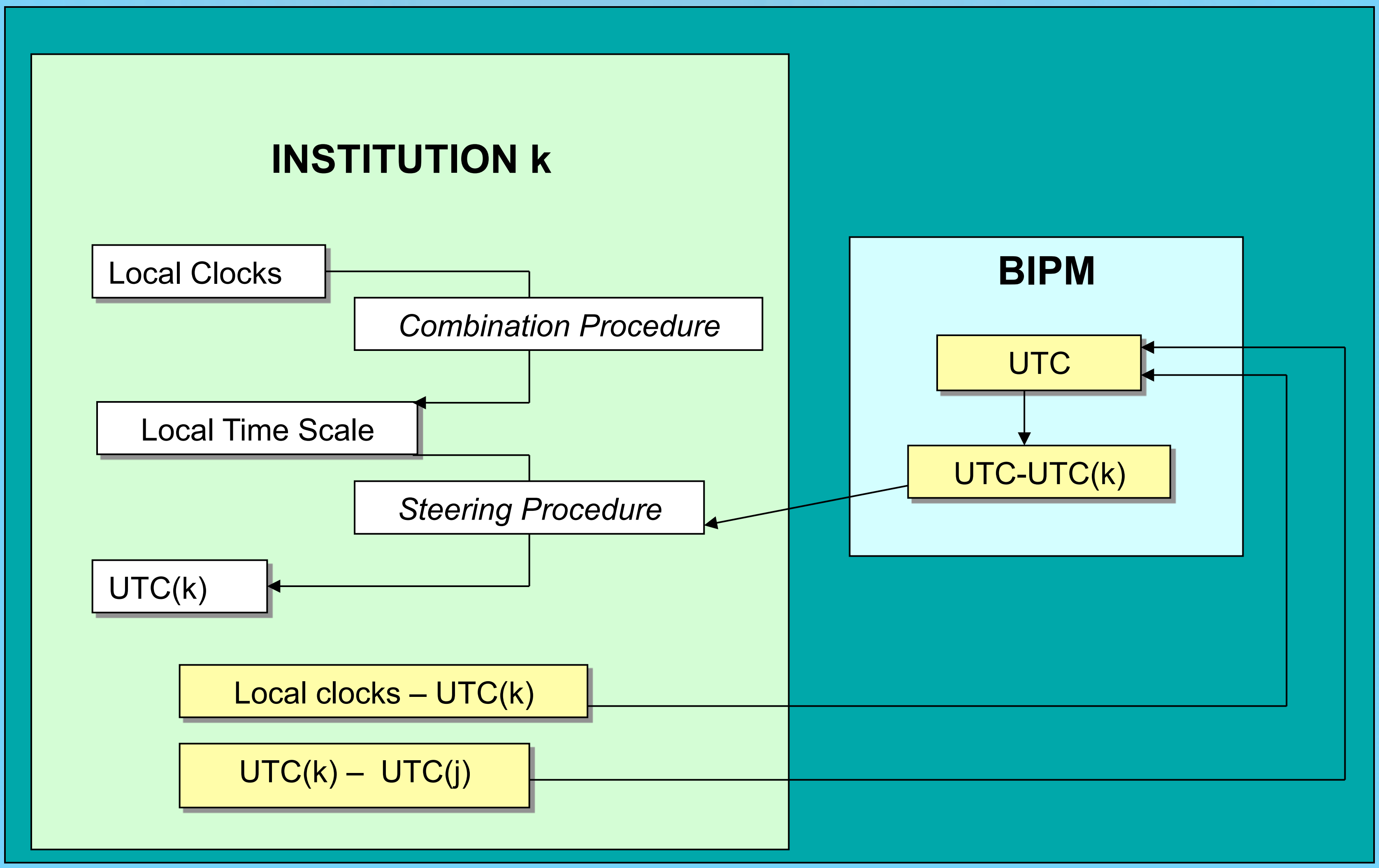
Name of UTC

- "Coordinated" refers to coordination among national laboratories. It never referred to "coordination" with the Sun.
  - —originally referred to informal agreement between Royal Greenwich Observatory and U. S. Naval Observatory to coordinate adjustments to their master clocks based on astronomical observations.
- "Universal" refers to the use of the same time for the entire Earth
  - —Began with International Meridian Conference in 1884

> "The scheme set forth in the recommendations has in view three principal objects, *viz*:
>
> 1. To define and establish a universal day for securing chronological accuracy in dates common to the whole world.
> 2. To obtain a system of universal time on a basis acceptable to all nations, by which, everywhere, at the same time, the same instant may be observed.
> 3. To establish a sound and rational system of reckoning time which may eventually be adopted for civil purposes everywhere, and thus secure uniformity and accuracy throughout the globe."
>
> - *International Meridian Conference, 1884*

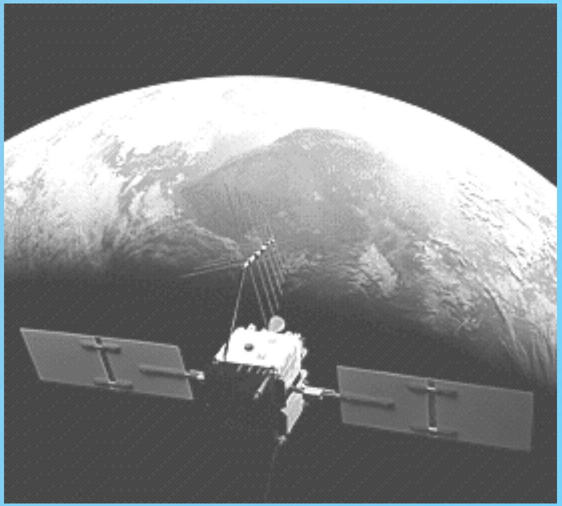
  - —Although time defined by the motion of a fictitious point based on the Sun's motion was the only time available then, it does not imply solar time.
- Not changed in 1972 when leap seconds replaced small steps and frequency offsets.

Realization of UTC



Dynamical Time

- Defined in 1976 by IAU
- Distinguish between time scales with origins at the geocenter and the solar system barycenter
- Terrestrial Dynamical Time (TDT)
  - At the instant 1977 January 01 d 00h 00m 00s TAI, the value of the time scale for apparent geocentric ephemerides is 1977 January 1d 00h 00m 32.184 exactly.
  - Unit is a day of 86400 SI seconds at mean sea level.
  - Maintains continuity with ET
- Barycentric Dynamical Time (TDB) in 1979
  - The timescales for equations of motion referred to the barycenter of the solar system is such that there will be only periodic variations between these timescales and those of the apparent geocentric ephemerides.
  - By choosing an appropriate scaling factor TDB determined from TDT by a conventional mathematical expression



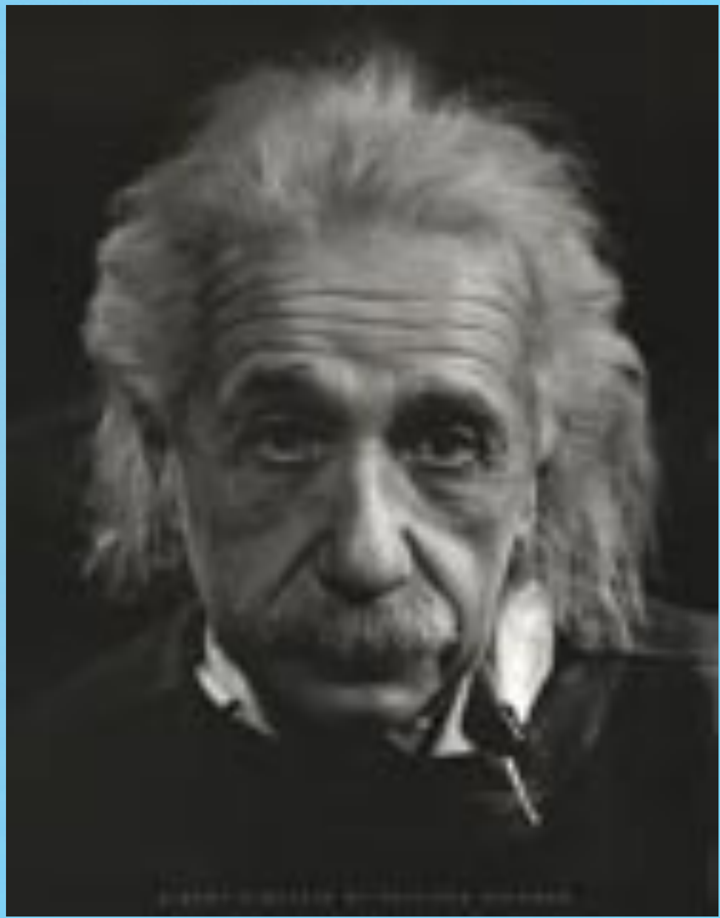
Relativistic Time Scales

- 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

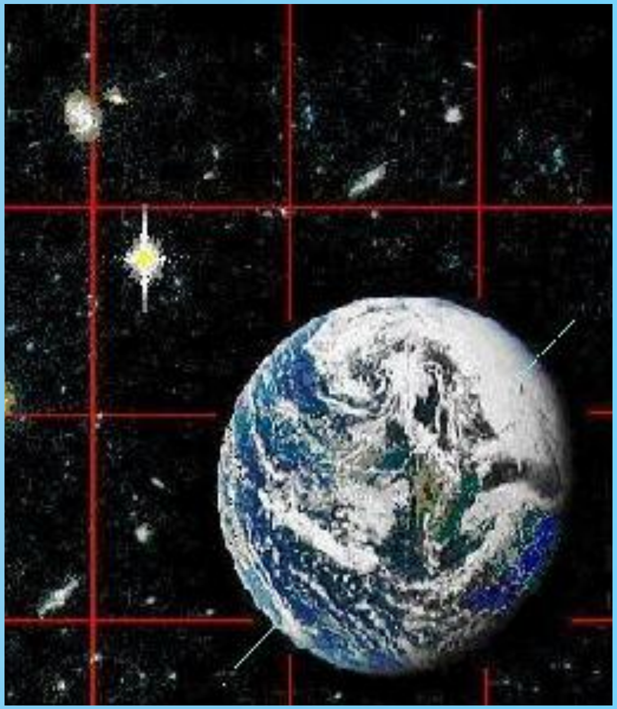
❖ Coordinate time: Time coordinate in given space-time coordinate system

- 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.

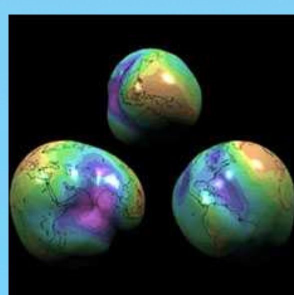


Coordinate Time

Geocentric Coordinate Time (TCG)

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

- 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)

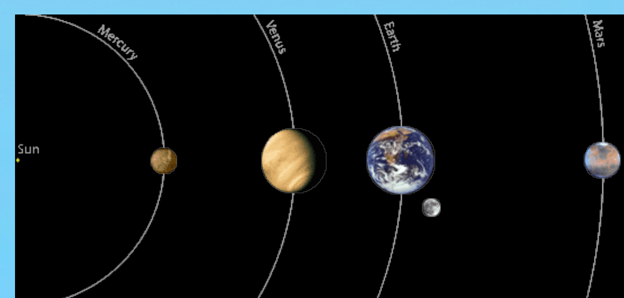
$$\mathrm{TCB} - \mathrm{TT} = \frac{1}{c^2}\int \left(U_{E\,ext}(\mathbf{r}_E) + \frac{1}{2}v_E^2 \right) dt + L_G\,\Delta D + \frac{1}{c^2}\mathbf{v}_E\cdot(\mathbf{r}-\mathbf{r}_E)$$
$$= L_C\,\Delta D + P + L_G\,\Delta D + \frac{1}{c^2}\mathbf{v}_E\cdot(\mathbf{r}-\mathbf{r}_E)$$

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

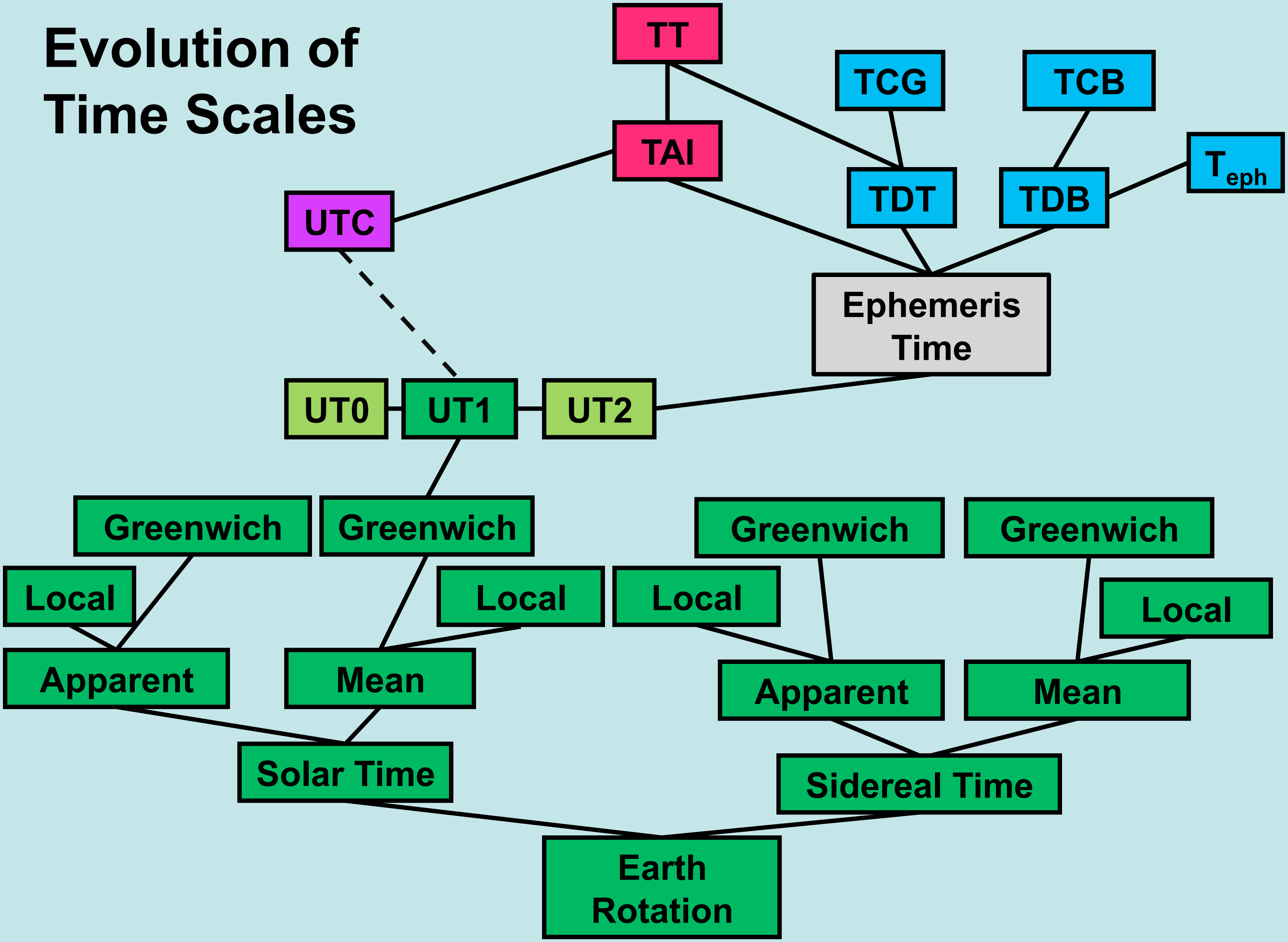
- TCB and TDB differ in rate

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

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



Evolution of Time Scales



Eliminate Leap Seconds?

Currently under study by ITU-R with input from International Congress of Weights and Measures, International Astronomical Union, International Union of Geodesy and Geophysics, *etc.*

Why?

- Frequency of leap seconds likely to increase
- Software issues
  - Unpredictable: can't be programmed in advance
  - days of 86,401 seconds and 61-second minutes
  - Time-stamping 23h 59m 60s
  - Reliance on continuous second counts?
- Communications problems
  - coordination of events during a leap second
- Growth of time scales
- Reduce reliability of infrastructure systems depending on time and introduce the possibility of catastrophic failure (particularly in Asia)
- Costly to implement

Do we want to continue to stop every clock in the world at unpredictable intervals for 1 second with ever increasing frequency?

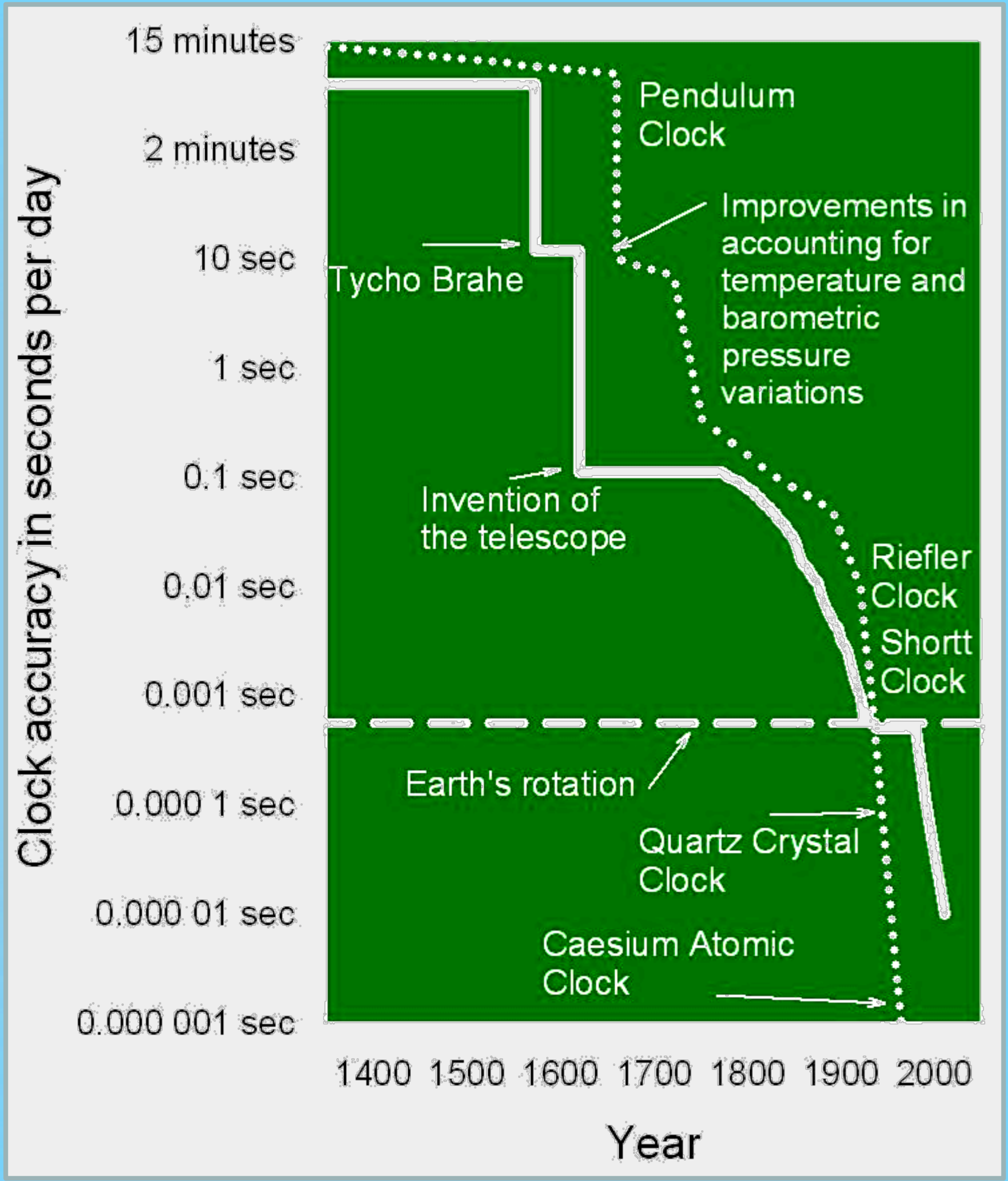
But…

- Legacy Software
  - Assumptions that |UT1-UTC|<1 second
  - Legacy formats
  - Telescope pointing
- Legal definitions
  - Mean solar time?
- Religious observances
  - Sunrise, noon, sunset?
- Relationship to direction of the Sun

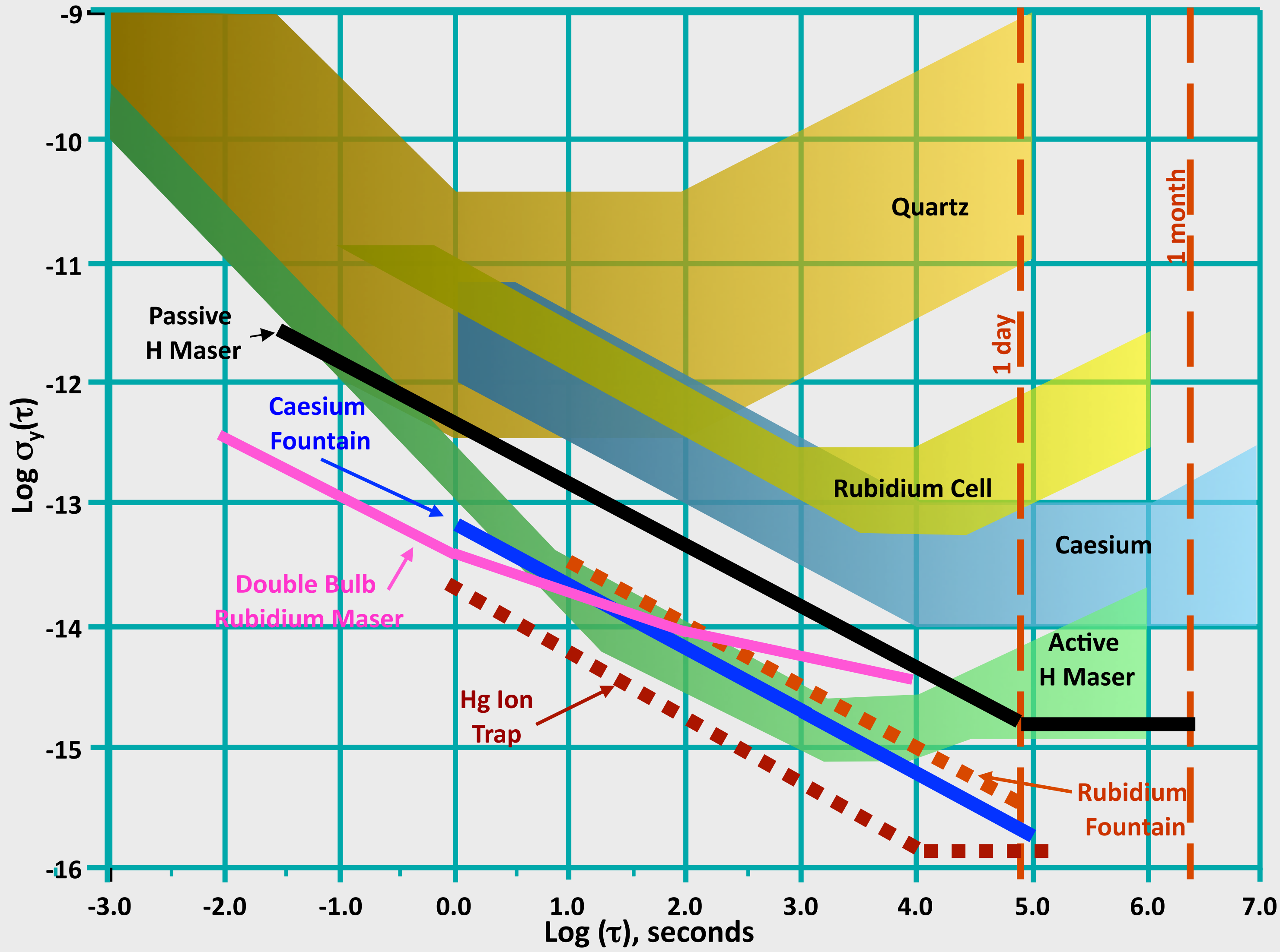
Desirable Features in a Standard Timescale

- Consistent with measurement ability
- Unit intervals are accurately equal
- Origin is accurately defined
- Unambiguous naming convention
- Easily transferrable
- Consistent with other physical standards
- Continuous
- Relationship to direction of the Sun in the sky

Timekeeping Precision



Clock Stability



Time Transfer Capability

- Current state of the art is sub-picosecond precision and single ps accuracy (over short distances)
- Limited by systematic errors (environmental)

Continuity

- Let $f(t)$ be a function defined on an interval around T_L. *f(t)* is said to be **continuous from the left** at T_L iff

$$\lim_{t \to T_L^-} f(t) = f(T_L)$$

- *f(t)* is said to be **continuous from the right** at T_L iff

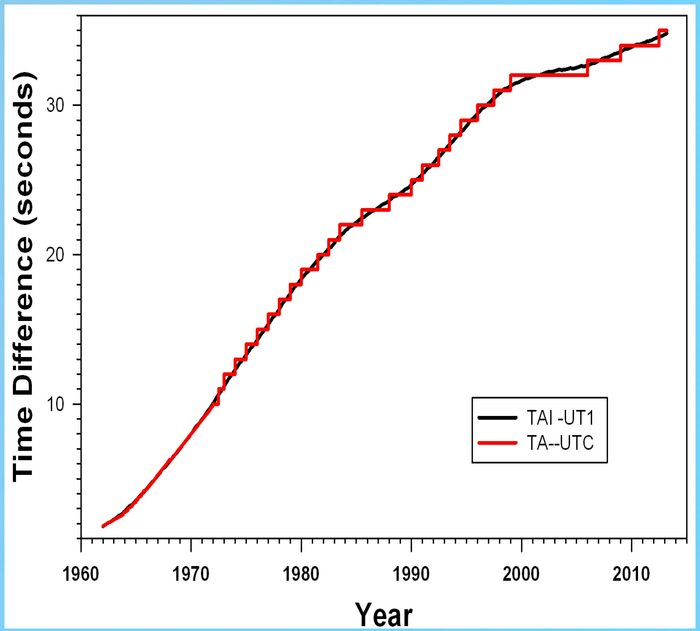
$$\lim_{t \to T_L^+} f(t) = f(T_L)$$

- *f(t)* is said to be **continuous** at T_L iff

$$\lim_{t \to T_L} f(t) = \lim_{t \to T_L^-} f(t) = \lim_{t \to T_L^+} f(t) = f(T_L)$$

- If *f(t)* is defined by

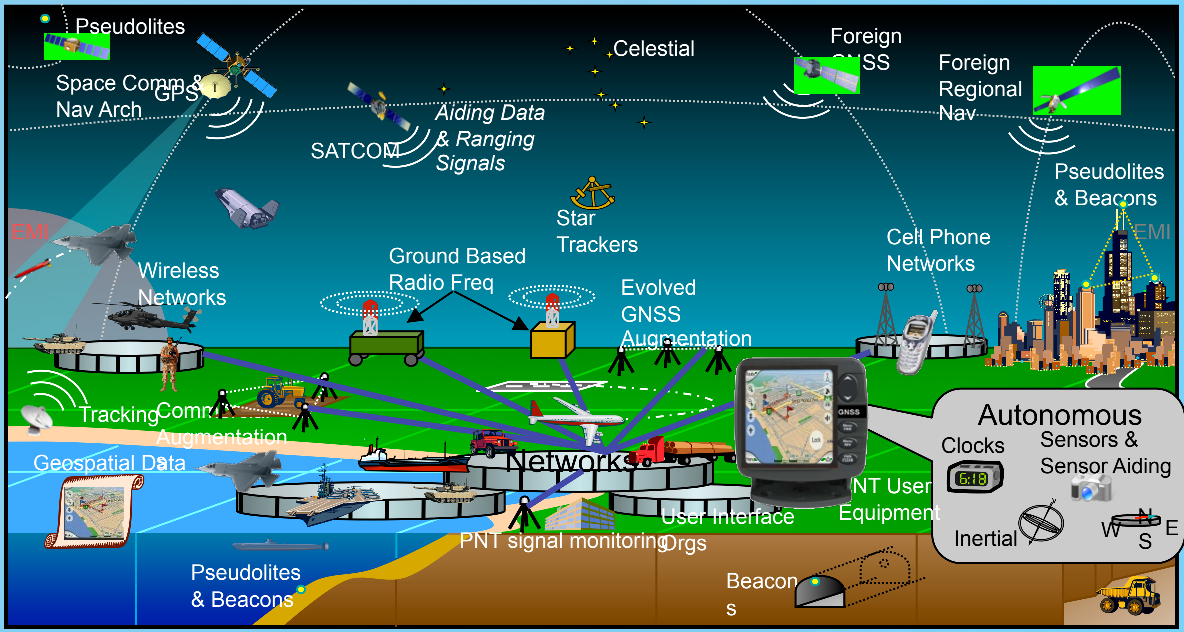
$$f(t) = \begin{cases} L, & t < T_L \\ L+1, & t \geq T_L \end{cases}$$



- the limit of this function as t approaches T_L from left is different from the limit as t approaches T_L from right. Thus the function is discontinuous at T_L.

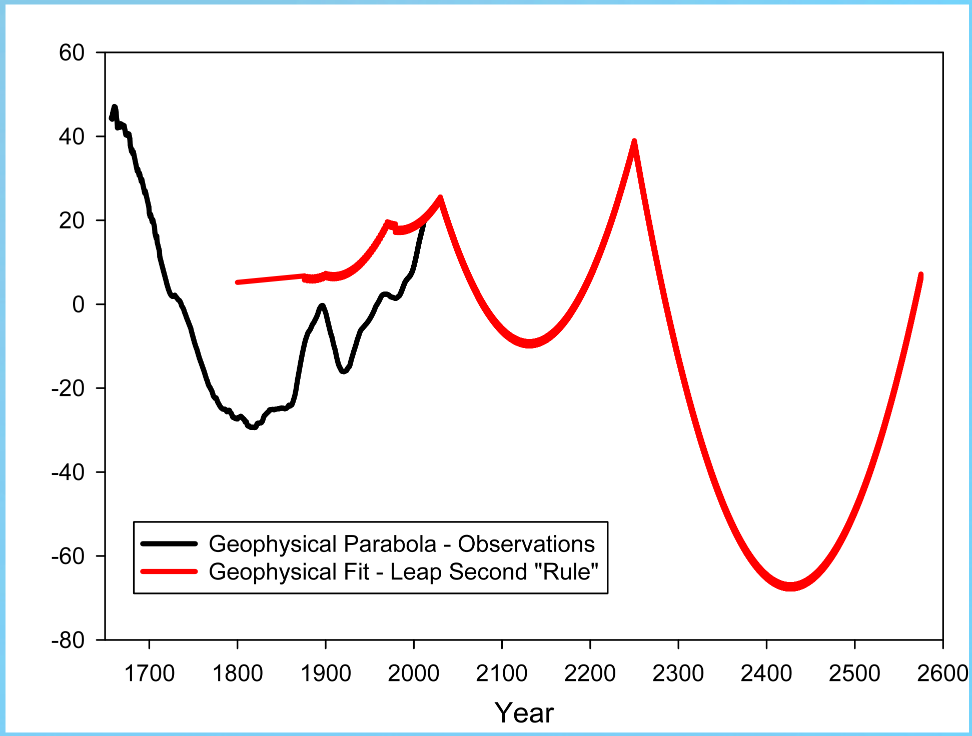
Modern Applications of Time & Frequency

- 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



Can we know when we will need to stop all the clocks in the world?

- Earth rotation difficult to predict far in advance
  - Tides slow it down but geophysical decadal variations have significant effects.
- Conventional rule would result in UT1-UTC of the order of a few minutes
- Conventional rule will require leap seconds
  - twice per year beginning in 2030
  - every quarter beginning in 2250
  - every month after 2600



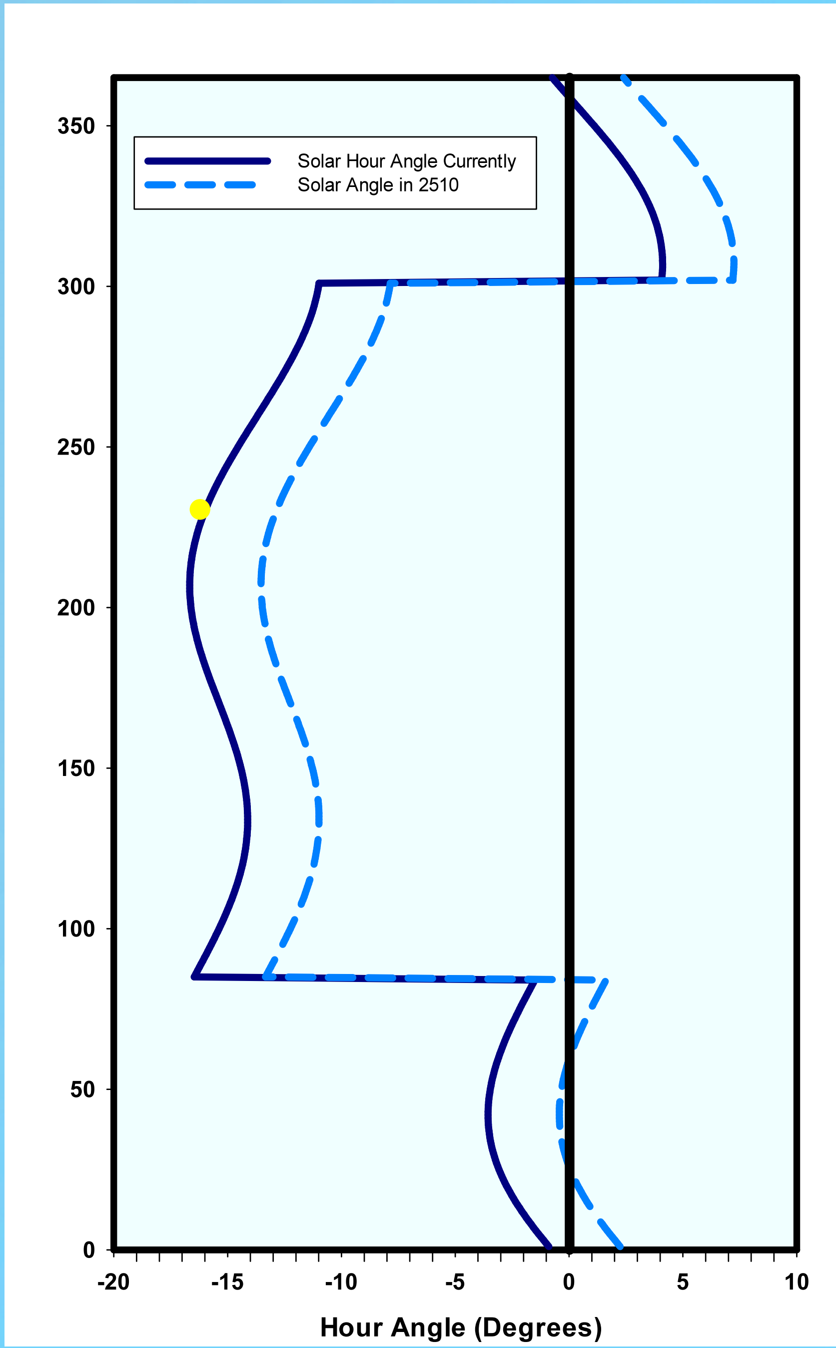
Relationship to direction of the Sun in the sky

1. Provides low-accuracy knowledge of Earth rotation for specialists.

   Telescope pointing software

   Some legacy orbit analysis software users

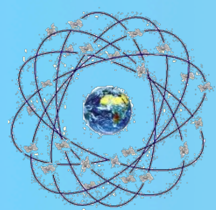
2. Provides loose connection between civil times and time that we historically determined from the Sun. (Those can differ now by up to 5 hours because of time zones, daylight savings time, *etc.*)



Other Time Scales ?

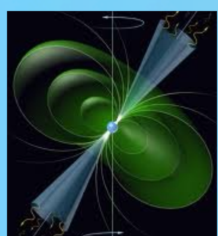
International Atomic Time (TAI):

- TAI is a background laboratory atomic timescale that is uniform (without leap seconds). However, it is not an alternative to UTC because it is not disseminated.



GNSS Time scales

- Internal scales used for position determination
- Formed from clocks that are adjusted and not able to be characterized



Pulsar Time Scale

- Under investigation by IAU
- Likely to contribute for long-term stability

Time scales for other planets?

Summary

- Future infrastructure will need a standard time scale to meet practical requirements
  - Consistent with measurement ability
  - Unit intervals are accurately equal
  - Origin is accurately defined
  - Unambiguous naming convention
  - Easily transferrable
  - Consistent with other physical standards
  - Continuous
- Users will want state-of-the-art time and frequency
- Users will want state-of-the-art Earth orientation information
- UTC is a *time*, UT1 is an *angle* describing Earth rotation
  - No need to provide UT1 by coded civil time or radio signal
- If definition of UTC is changed
  - Need to revise some legacy software
  - No perceptible impact on social activities and conventions likely
  - Significant reduction in the risk to national and international infrastructure
  - Significant cost reduction in implementation
- If definition of UTC is not changed
  - Leap seconds will increase
  - No perceptible impact on social activities and conventions likely
  - Increased risk to national and international infrastructure
  - Increased economic impact of leap seconds