Time Systems

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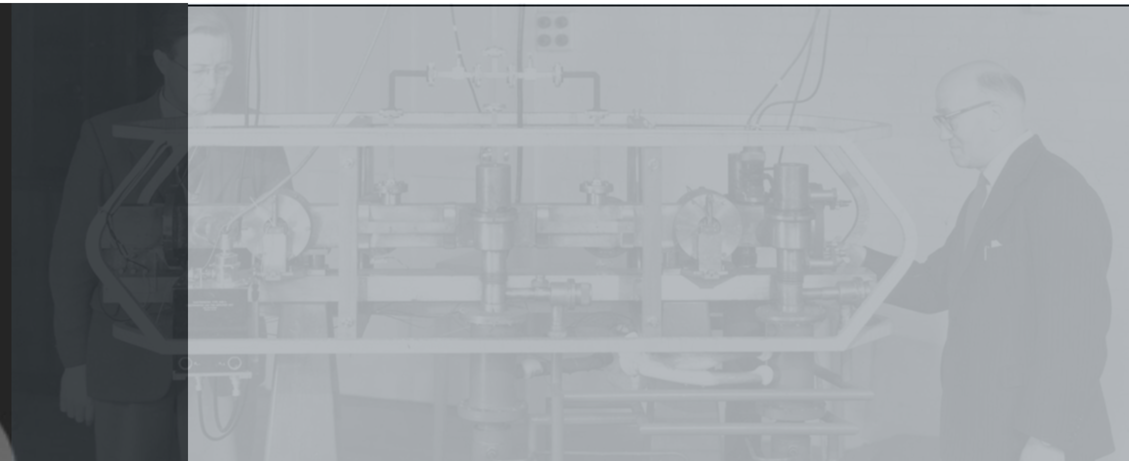

What is time?

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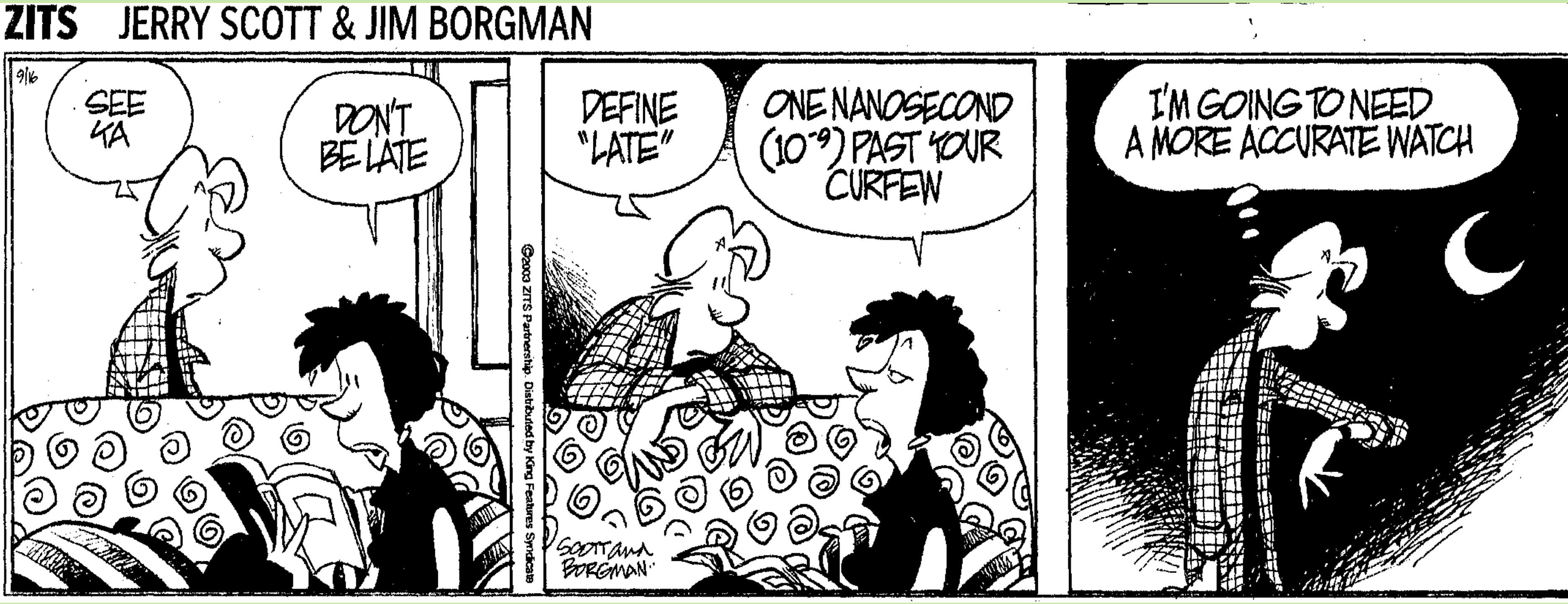


The Critique of Pure Reason, by Immanuel Kant

- Time is not something which subsists of itself, or which inheres in things as an objective determination, and therefore remains, when abstraction is made of the subjective conditions of the intuition of things. For in the former case, it would be something real, yet without presenting to any power of perception any real object. In the latter case, as an order or determination inherent in things themselves, it could not be antecedent to things, as their condition, nor discerned or intuited by means of synthetical propositions a priori. But all this is quite possible when we regard time as merely the subjective condition under which all our intuitions take place. For in that case, this form of the inward intuition can be represented prior to the objects, and consequently a priori.

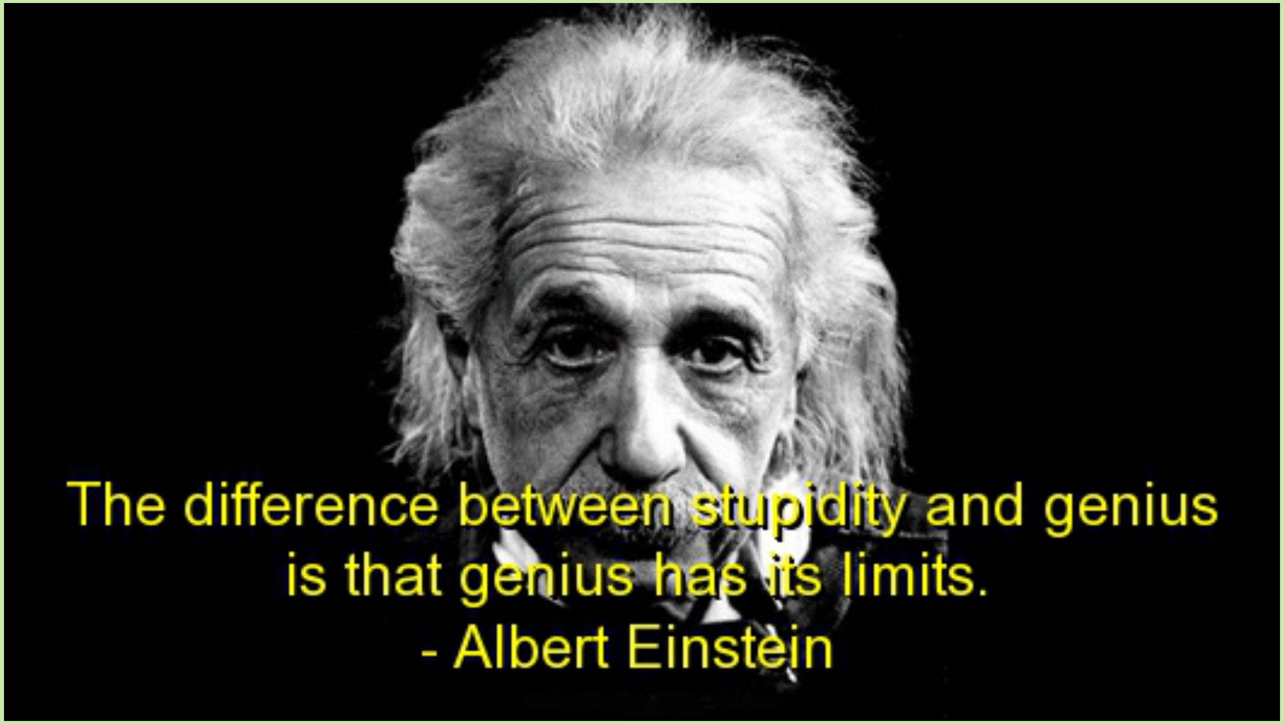
- Translated by me…time is not a thing in itself, so you cannot really measure it

Wikipedia

Time is a measure in which events can be ordered from the past through the present into the future, and also the measure of durations of events and the intervals between them. Time is often referred to as the fourth dimension, along with the three spatial dimensions.

????

- So we all have an idea what time is, until we are asked to explain it…but that's OK.



Practical time systems

There are several time systems used in astronomy and navigation.

- Time as seen on your watch is related to Universal Time Coordinated (UTC). Previously called Greenwich Mean Time (GMT)
  - UTC is based on atomic time standards (cesium/maser clocks) and is based on the averaged time of atomic clocks (~400) operated globally.
  - The International Earth Rotation Service (IERS) coordinates these activities and publishes corrections to the time systems operated in each country. The IERS was established in 1987 by the International Astronomical Union and the International Union of Geodesy and Geophysics, it provides data on Earth orientation, on the International Celestial Reference System/Frame, on the International Terrestrial Reference System/Frame, and on geophysical fluids. It maintains also Conventions containing models, constants and standards.

Main Message

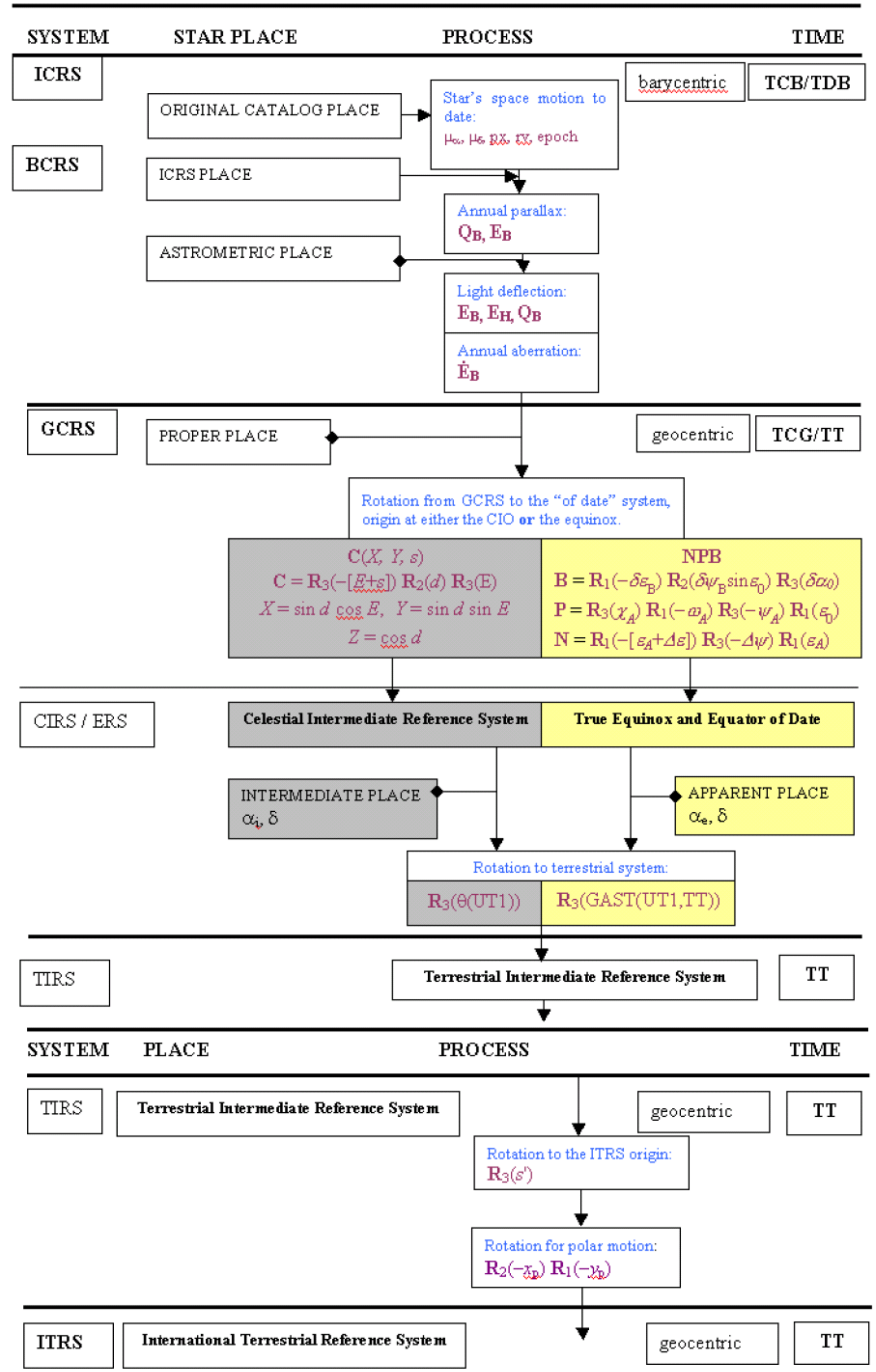
Transformation from the celestial to terrestrial system is based on standards and models set by the IAU and IUGG, including IERS Earth Orientation Parameters (EOP).

These include

(i) polar motion (represented by the x and y coordinates of the direction of the pole in the terrestrial system), which is quasi-periodic and essentially unpredictable, (measured by VLBI)

(ii) Universal Time, UT1 that provides the variations in the Earth's diurnal angle of rotation and

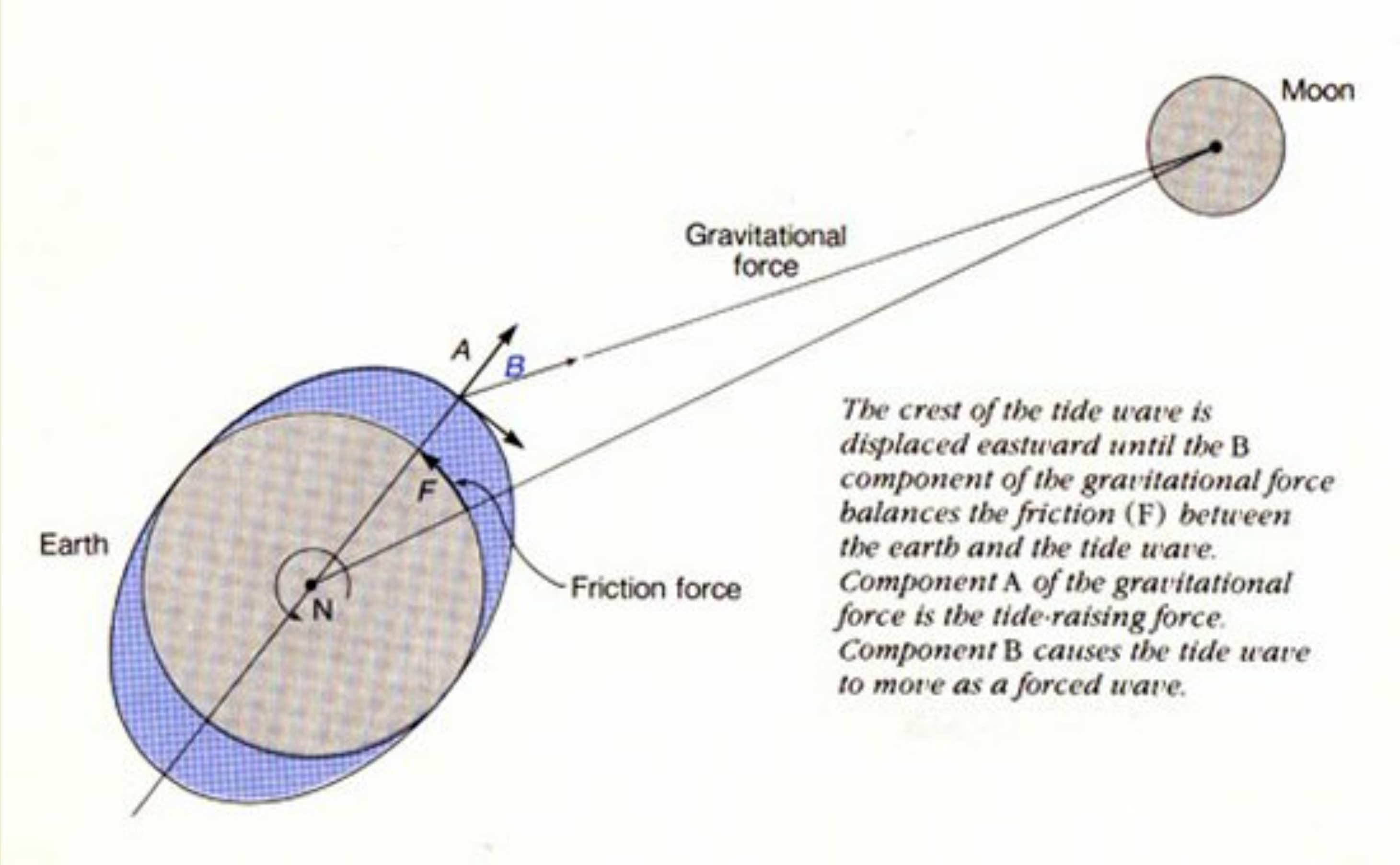
(iii) small adjustments (denoted dX and dY) to the celestial direction of the pole as predicted by the a priori precession-nutation model



Time systems…

- Time as defined by atomic clocks has a constant rate.
- As we live on Earth, our perception of time is linked to the rotation of the Earth.
- This rotation rate is not uniform. Compared to UTC the Earth "clock" loses 1 second every 18 months; this is not uniform either as there are fluctuations due the exchange of angular momentum, resulting from mass movement of the Earth (atmospheric winds, processes in the fluid core). The 1 sec/18mths is an accumulative effect due to Earth-Moon gravitation coupling that causes the Earth to rotate slower by 1.7 ms per century (the reason for leap seconds).
- Time defined by the rotation of the Earth is called UT1 and realizes the mean solar day. A solar-day is the average time it takes for the Sun to move from midday to midday. Mean solar time is the hour angle of the mean Sun plus 12 hours; this is realized by the UT1 time scale.
- Currently, UT in relation to International Atomic Time (TAI) is determined by Very Long Baseline Interferometry (VLBI) observations of quasars, and can determine UT1 to within 4 milliseconds.
- UTC has discontinuities, leap-seconds, that are added to keep it aligned with UT1. (The SI second was already a little shorter than the then-current value of the second of mean solar time when it was introduced. Leap seconds were introduced in the mid-1960s).

Earth-Moon tidal coupling



Source: http://www.aerospaceweb.org

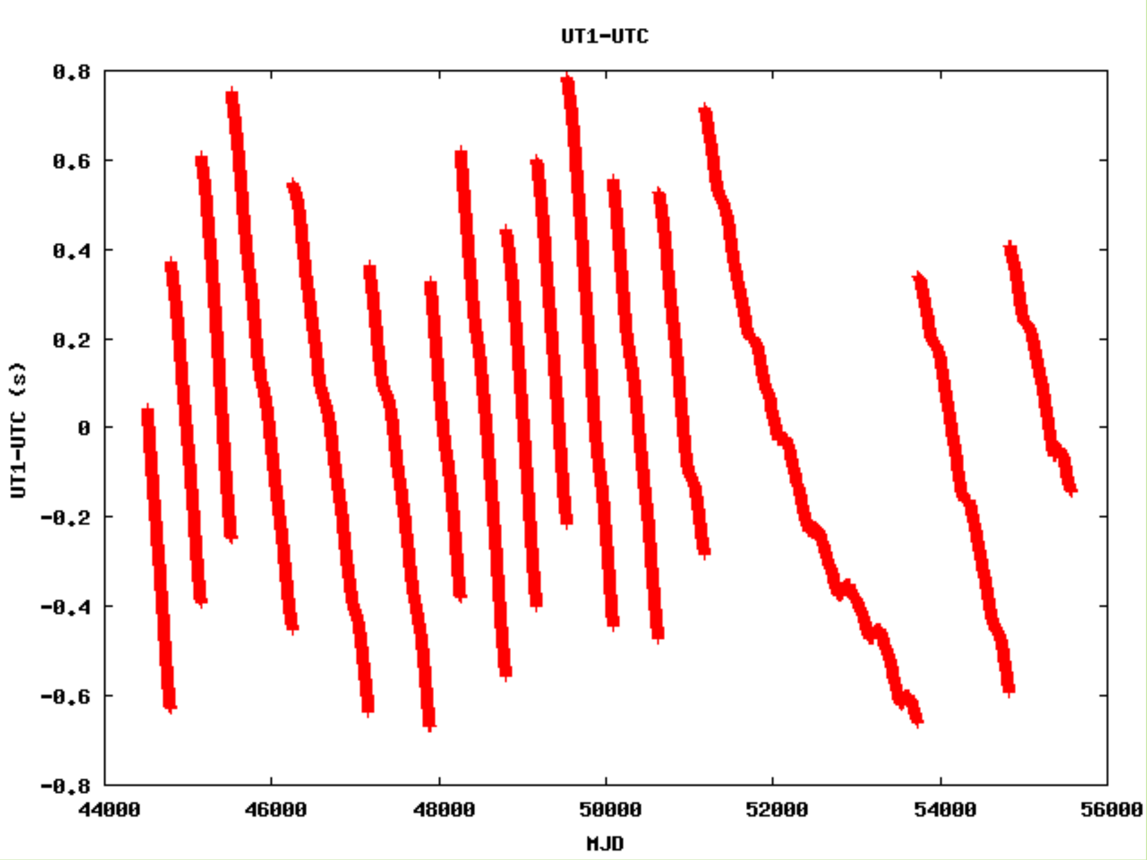
Leap Seconds

- Leap seconds are a conventional attempt to align Earth rotation time (angle) with clock time (UTC)
  - |UT1-UTC| < 0.9 s
- Leap seconds occur at end of June or December but the time between leap seconds is unpredictable
  - Expected to occur with increasing frequency
  - Problematic for operational systems
- International Telecommunications Union (ITU) is considering a redefinition of UTC to eliminate leap seconds
  - UT1 and UTC would diverge
  - The last leap second was introduced in UTC on 31 December 2016 at UTC 23:59:60, difference TAI vs. UTC 37 secs

Source: The Fundamental Reference Systems Tutorial (USNO)

UT1-UTC

- Dominant motions
  - Trend
  - Decadal
  - Annual/semiannual
  - Tidal
- Other smaller amplitude motions
- Causes of UT1-UTC
  - Tidal deceleration
  - Internal changes in inertia tensor
  - Atmosphere (winds)
  - Solid Earth tides



Source: The Fundamental Reference Systems Tutorial (USNO)

UT1-UTC Spectrum

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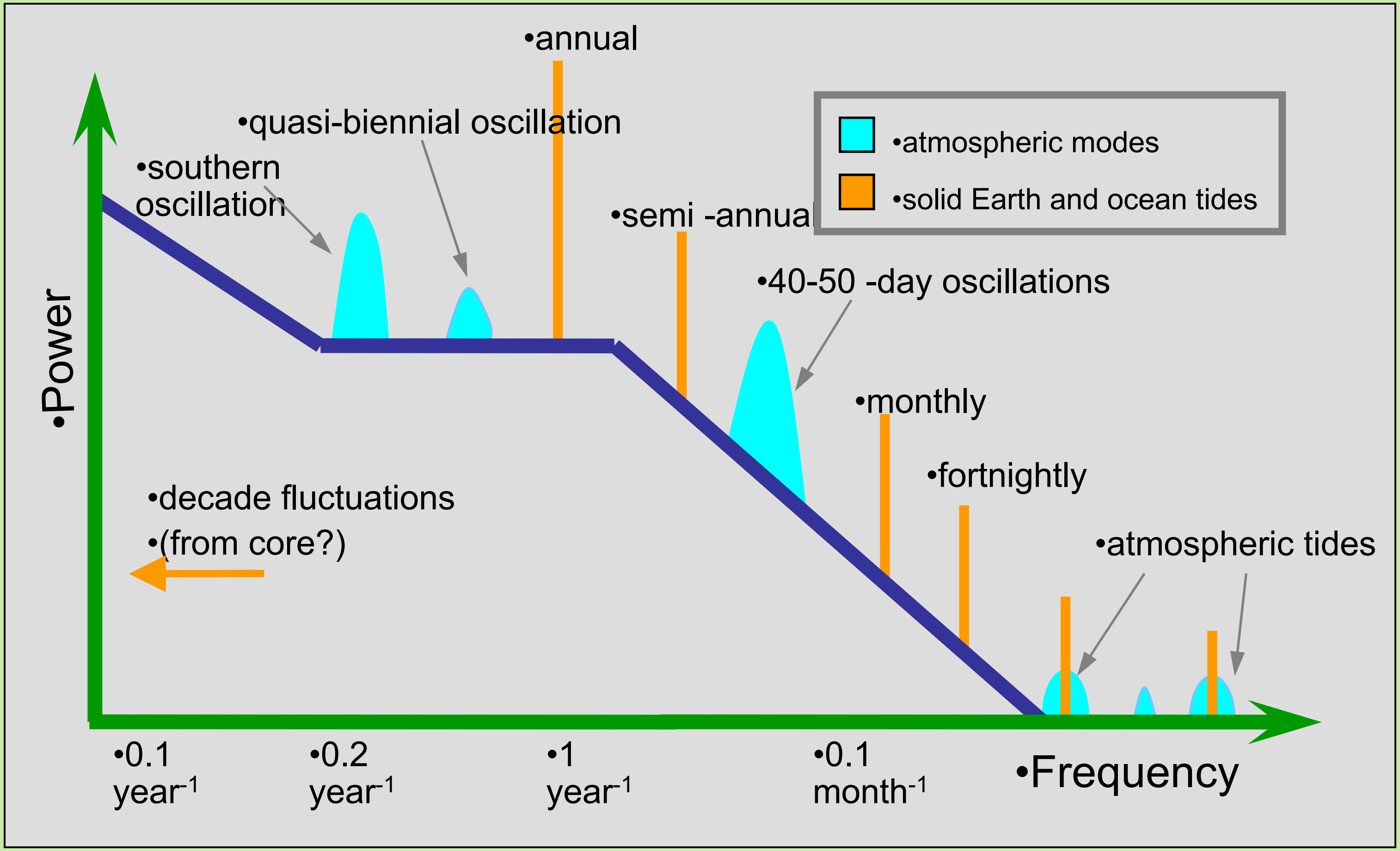
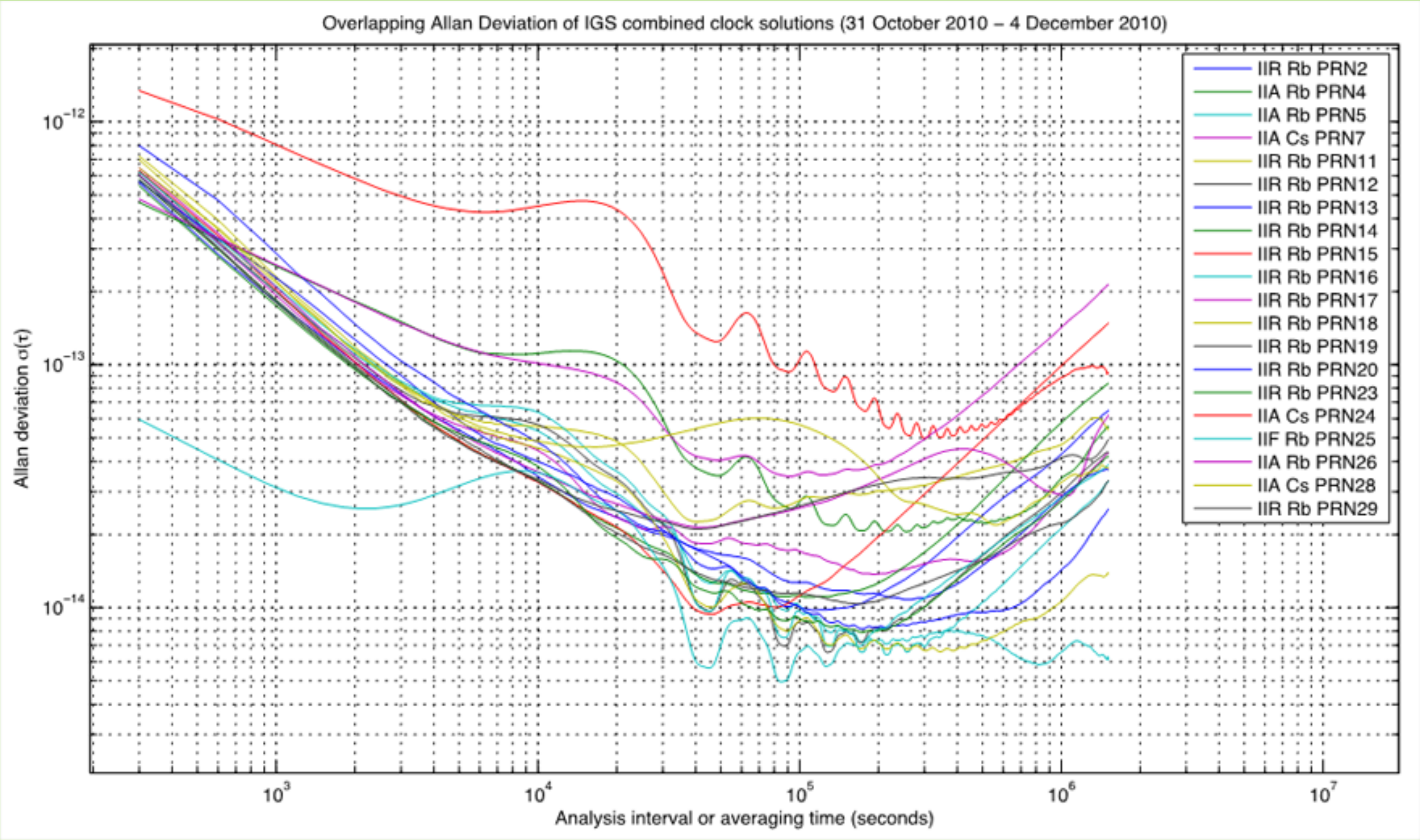


Source: The Fundamental Reference Systems Tutorial (USNO)

Time systems…

- The IERS publishes differences between UT1 and UTC and decide when leap seconds need to be added.
- Sidereal time (the time scale based on the Earth's rate of rotation relative to the fixed stars) is derived from UT1 and measures times in sidereal seconds.
- As the Earth moves in its orbit during the day, the length of time for stars to come to the same place in the sky is a little bit shorter.

GPS constellation stability



Source: http://www.insight-gnss.org/WP3.html

Allan Variance;
A graphical look at clock performance

National Research Foundation

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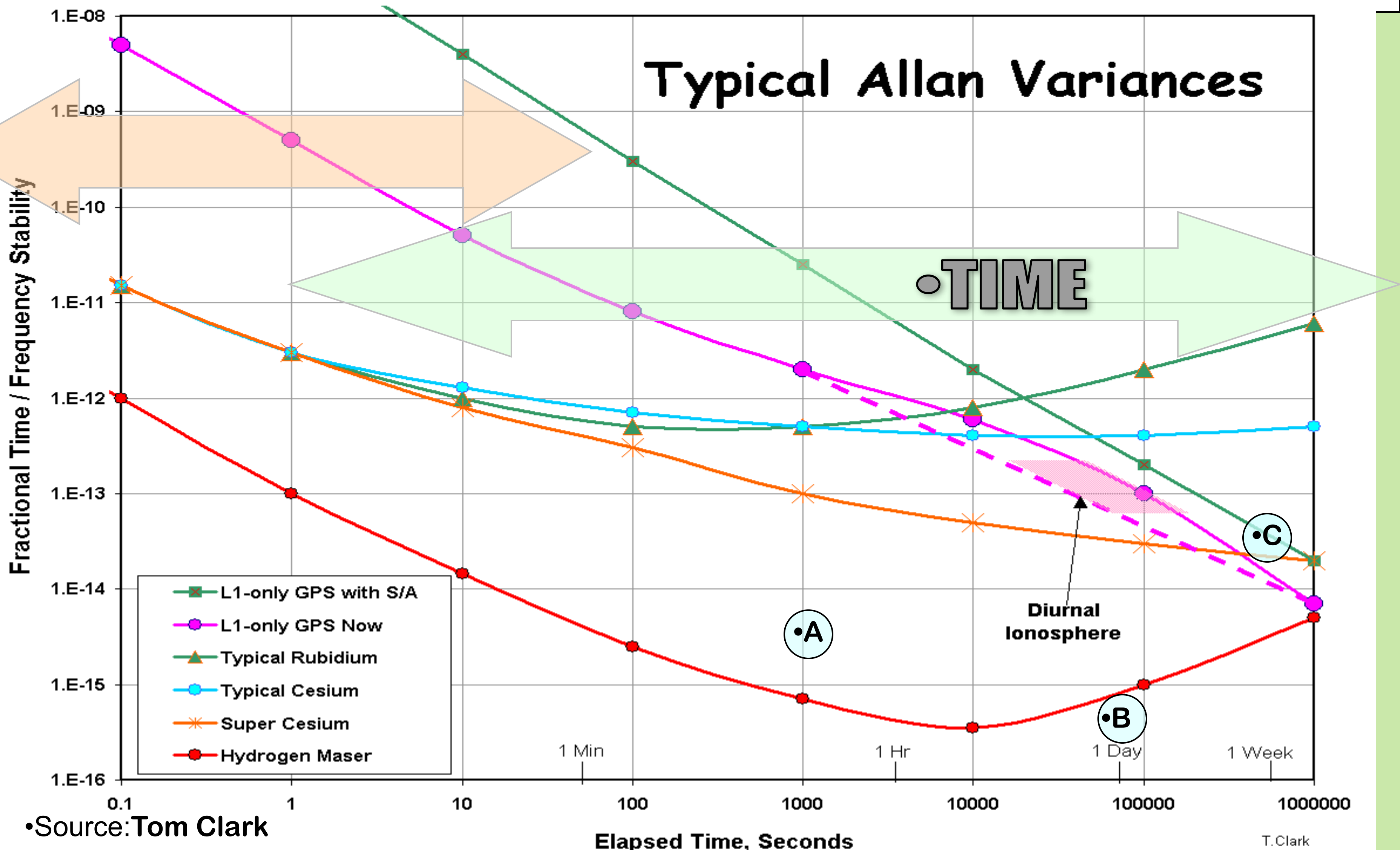

•Source: **Tom Clark NASA/GSFC & NVI**

What Timing Performance Does VLBI Need?

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- The VLBI community (Radio Astronomy and Geodesy) uses Hydrogen Masers at 40-50 remote sites all around the world. To achieve ~10° signal coherence for ~1000 seconds at 10 GHz we need the two oscillators at the ends of the interferometer to maintain relative stability of $\approx [10°/(360° \cdot 10^{10}\text{Hz} \cdot 10^{3}\text{sec})] \approx 2.8 \cdot 10^{-15}$ @ 1000 sec. A

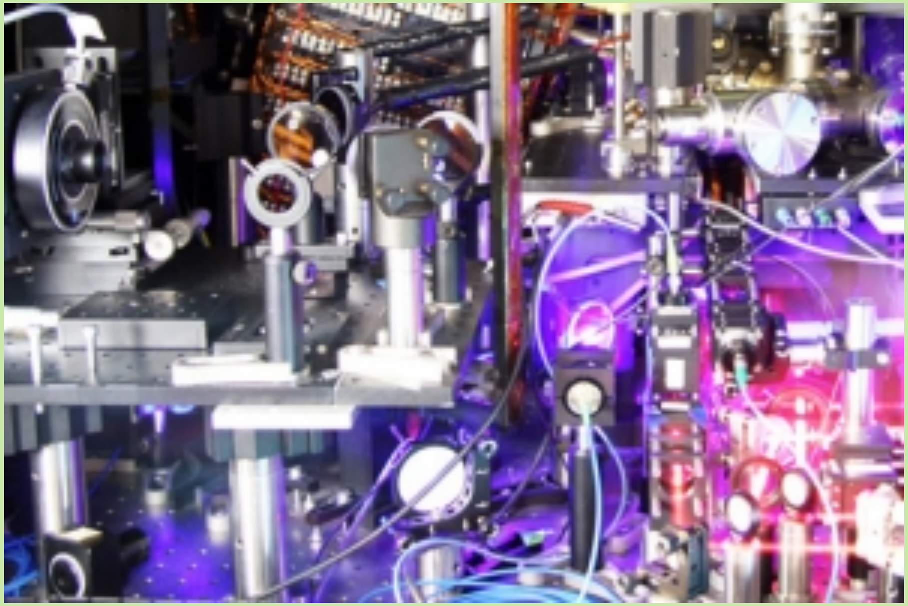
- In Geodetic applications, the station clocks are modeled at relative levels ~30 psec over a day $\approx [30 \cdot 10^{-12}/86400\ \text{sec}] \approx 3.5 \cdot 10^{-16}$ @ 1 day. B

- To correlate data acquired at 16Mb/s, station timing at relative levels ~50 nsec or better is needed. After a few days of inactivity, this requires $\approx [50 \cdot 10^{-9}/ 10^{6}\ \text{sec}] \approx 5 \cdot 10^{-14}$ @ 10^{6} sec. C

- Since VLBI defines [UT1-UTC], we need to control the accuracy_ of our knowledge of [$UTC_{(USNO)}$ - $UTC_{(VLBI)}$] to ~100 nsec or better.

Most stable clock?

- The world's most stable optical atomic clock resides at the University of Colorado. The strontium-(Sr-) lattice clock is so stable that its frequency measurements don't vary by more than 1 part in 100 quadrillion (1×10^{-17}) over a time period of 1000 seconds, or 17 minutes. (See http://jilawww.colorado.edu/yelabs/news/most-stable-clock-world)



Basics

- ***Concepts***
  - ***Frequency***
    - ***Repeatable phenomenon***
    - ***Length of the time unit***
  - ***Epoch***
    - ***Naming convention***
- ***Sources of Time***
  - ***Astronomy***
    - ***Based on Earth's rotation***
  - ***Atomic Clocks***
    - ***Based on frequency of an atomic transition***

•Next slides are from the Fundamental Reference Systems Tutorial presented by George Kaplan, Brian Luzum, and John Banger
Available at maia.usno.navy.mil/

Time Scales

•*Earth Rotation*

•Sidereal Time

- Measure of Earth's rotation angle wrt Celestial Reference Frame
- Determined by conventional expression

•UT1 (Universal Time)

- Measure of Earth's rotation angle wrt Sun
- Determined by conventional expression
  - Earth Rotation Angle
  - Greenwich Mean Sidereal Time
- UT0 = UT1 including polar motion
- UT2 = UT1 with conventional Seasonal Correction

•*Earth Revolution*

•Ephemeris Time

•*Dynamical Time*

•Terrestrial Dynamic Time (TDT)

•Barycentric Dynamic Time (TDB)

•*Space-Time Coordinates*

•Terrestrial Time (TT)

•Geocentric Coordinate Time (TCG)

•Barycentric Coordinate Time (TCB)

•*Atomic Time*

•Echelle Atomique Libre (EAL)

•International Atomic Time (TAI)

•Coordinated Universal Time (UTC)

- * TAI corrected by leap seconds
- * Basis for civil time

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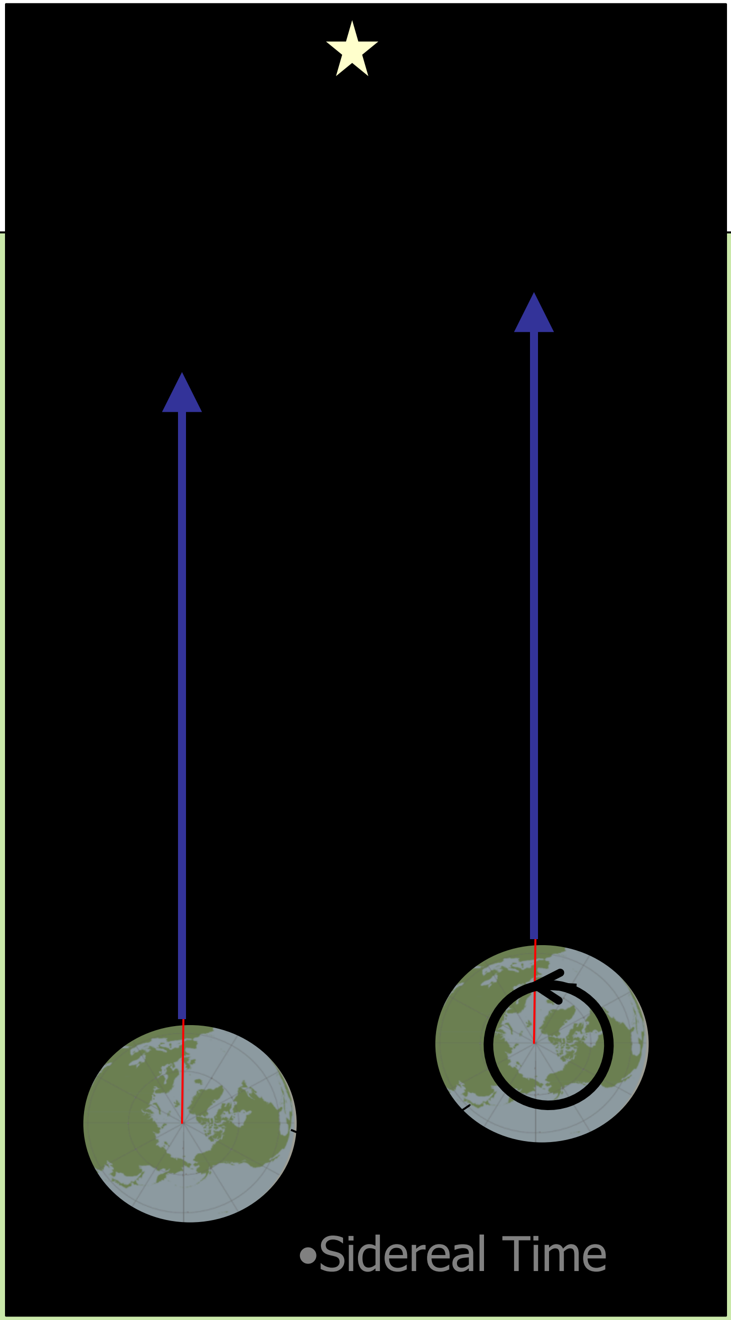
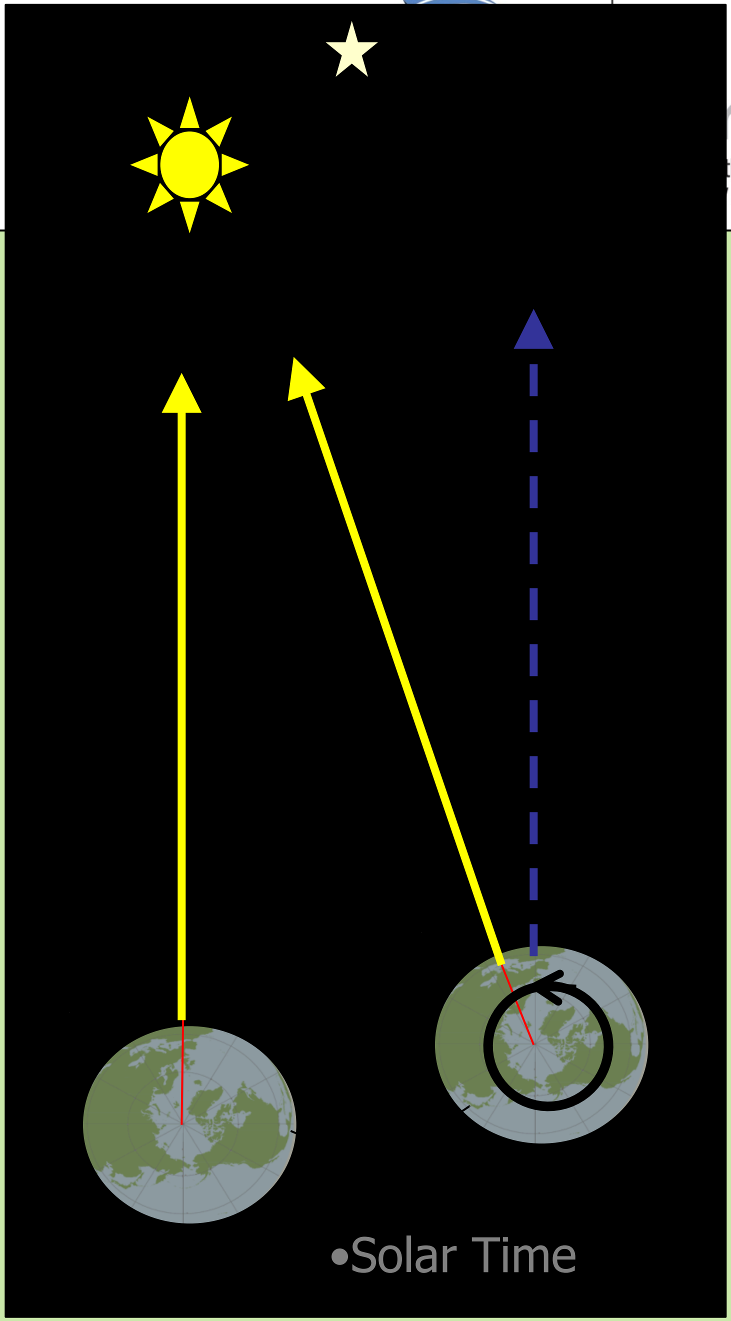
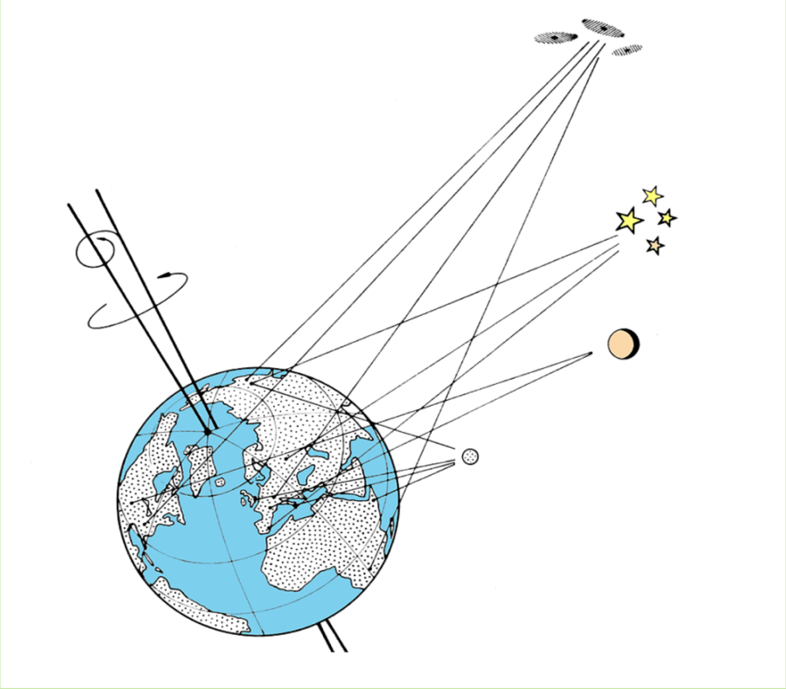

•Sidereal Time

•Solar Time

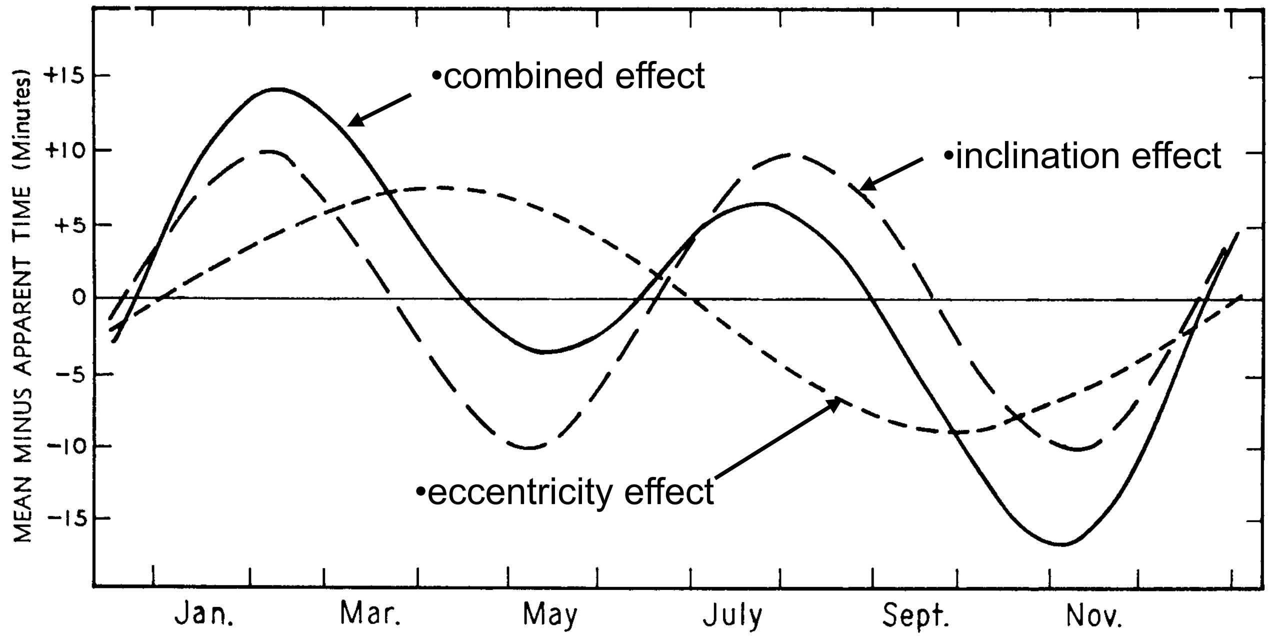
Universal Time (UT)

- Time measured by the Earth's rotation with respect to the Sun
  - 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

- Three Forms
  - UT1 is measure of Earth's rotation angle
    - Defined
      - By observed sidereal time using conventional expression
        - » GMST= f_1(UT1)
      - by Earth Rotation Angle
        - » q = f_2(UT1)
  - UT0 is UT1 plus effects of polar motion
  - UT2 is UT1 corrected by conventional expression for annual variation in Earth's rotational speed



Mean Time vs. Apparent Time



- *Time interval between successive passages of the Sun over a meridian is not constant*
  - *Inclination of the Earth's axis*
  - *Eccentricity of the Earth's orbit*

- *Difference between mean time and apparent time is called the "equation of time"*
  - *Mean noon precedes apparent noon by 14.5 minutes on February 12*
  - *Apparent noon precedes mean noon by 16.5 minutes on November 3*

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- Earth Revolution
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  - Terrestrial Time (TT)
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- *Atomic Time*
  - **Echelle Atomique Libre (EAL)**
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Atomic Time

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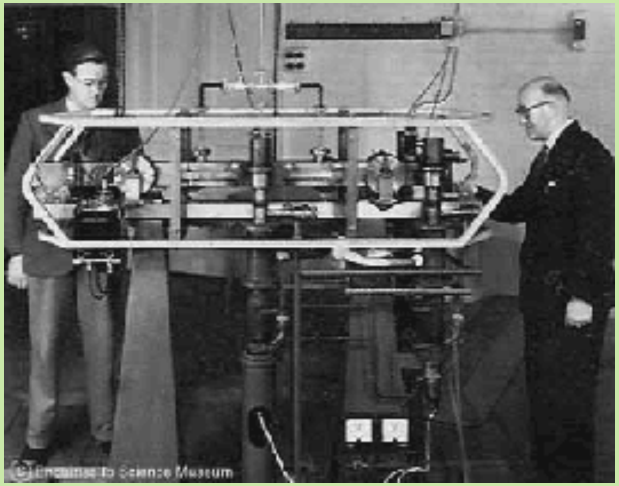
- *First cesium-133 atomic clock established at National Physical Laboratory (NPL) by Essen and Parry in 1955*
- *Frequency of cesium transition measured in 1955 in terms of the second of UT2*
- *9 192 631 830 $\pm$ 10 Hz*
- *Frequency of cesium transition measured by Markowitz, Hall, Essen, and Parry during 1955 – 1958 in terms of the second of ET*
- *9 192 631 770 $\pm$ 20 Hz*
- *Definition of the SI second adopted by the 13th CGPM in 1967*
- *Second of atomic time = second of Ephemeris Time (ET)*

•**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 cesium-133 atom**



•International Atomic Time (TAI)

- Coordinate time scale in a geocentric reference frame with the SI second realized on the rotating geoid as the scale unit
- Continuous atomic time scale determined by Bureau International de l'Heure (BIH) since 1958, now maintained by Bureau International des Poids et Mesures (BIPM)
- TAI = UT2 on January 1, 1958 0 h (UT2 has the effect of the annual seasonal variations in the rotation of the Earth)
- Follow-on from
  - A.1 (maintained at USNO with input from 9 other laboratories originally. - now only USNO)
  - AM (at BIH with input from many laboratories
  - A3 at BIH with input from 3 best laboratories
  - Others
- Became AT (or TA) in 1969, TAI in 1971

Agilent 5071A
primary frequency standard

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Coordinated Universal Time (UTC)

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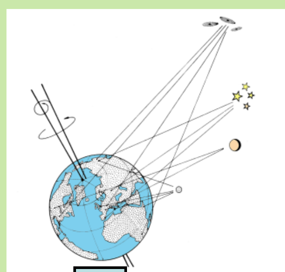
- Name "Coordinated Universal Time" (UTC) adopted by IAU in 1967
- From 1961 to 1972 UTC contained both frequency offsets and fractional (less than 1 s) steps to maintain agreement with UT2 within about 0.1 s
- In 1970 formalized by International Radio Consultative Committee (CCIR) of International Telecommunication Union (ITU) in 1962 ITU-R TF.460-6 STANDARD-FREQUENCY AND TIME-SIGNAL EMISSIONS(1970-1974-1978-1982-1986-1997-2002)
- Incorporated by reference into the Radio Regulations



•Leap Seconds may be introduced as the last second of any UTC month.

•December and June preferred, March and September second choice.

•Adjustments

•TAI

•UTC

Coordinated Universal Time (UTC)

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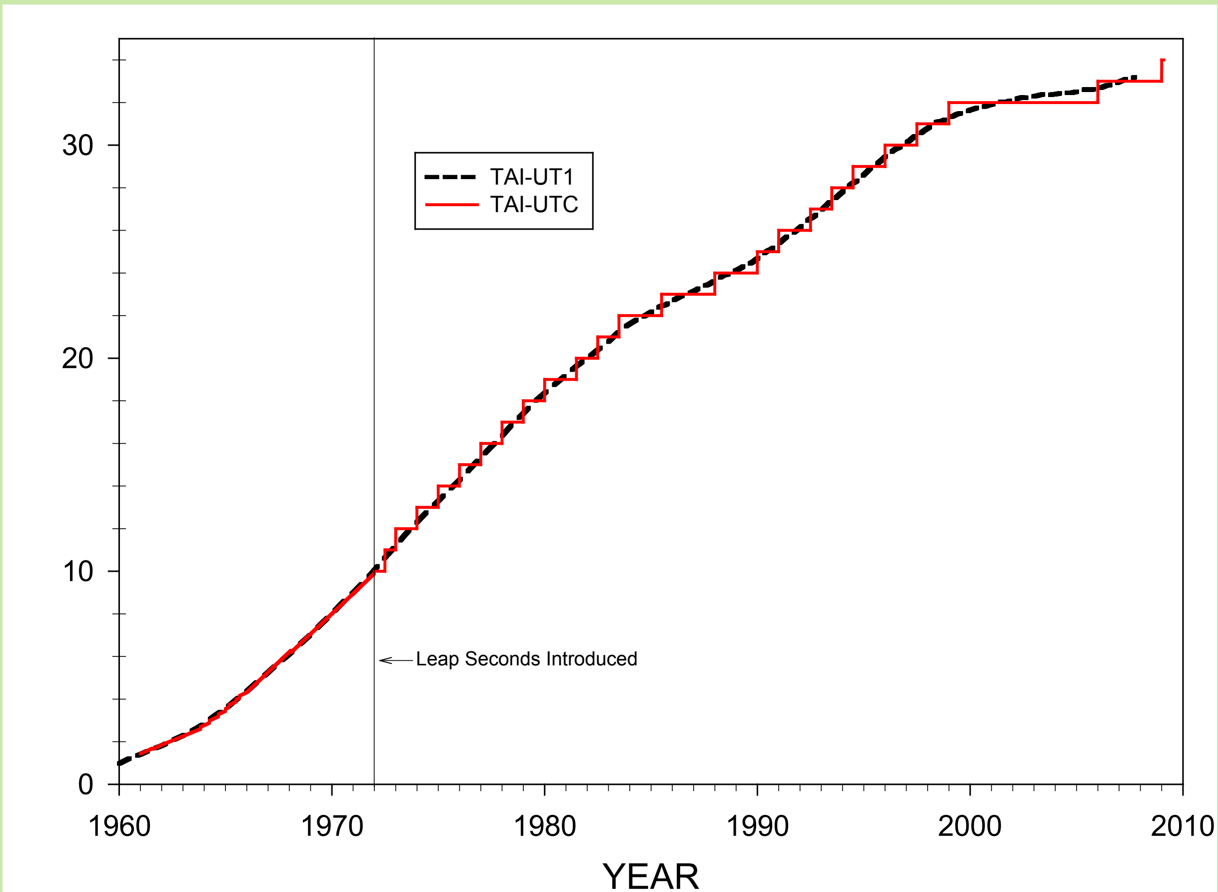
- In 1972 present UTC system was implemented, with 1 s (leap second) steps but no frequency offsets to maintain agreement with UT1 within 0.9 s
- Definition of UTC is a compromise to provide both the SI second and an approximation to UT1 for celestial navigation in same radio emission



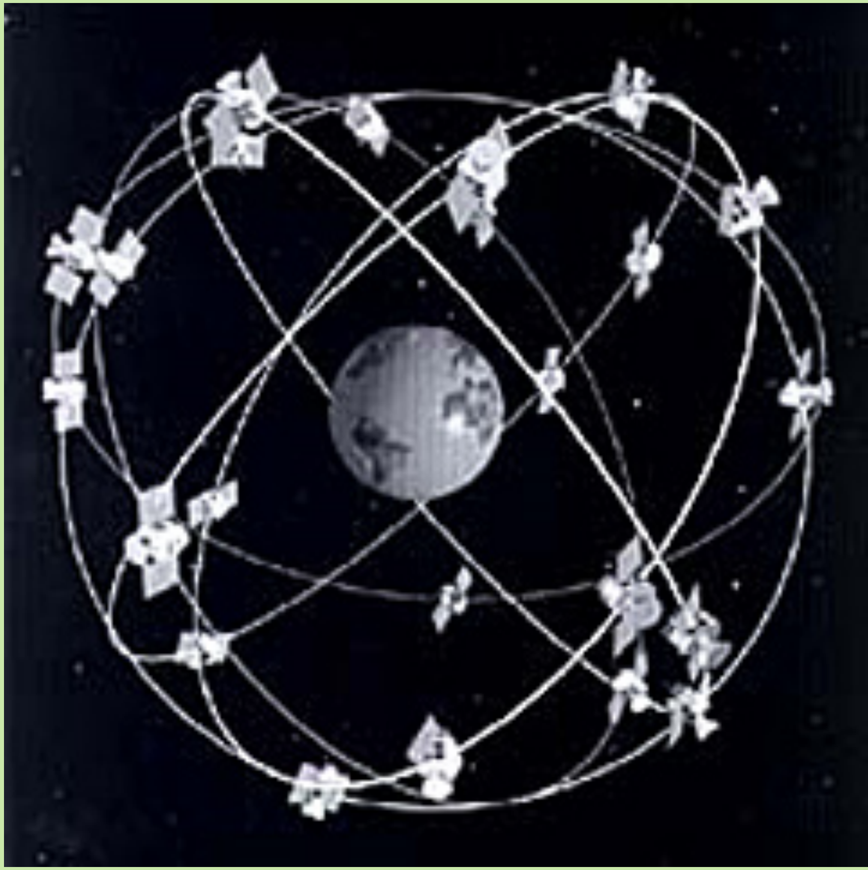
GPS System Time (GPS Time)

- Each satellite carries a suite of cesium or rubidium atomic clocks
- Satellite and global tracking network atomic clocks are used to form a common statistical time scale known as GPS Time
- No leap seconds
- Origin is midnight of January 5/6, 1980 UTC
- Steered to within 1 μs of UTC(USNO), except no leap seconds are inserted
- Relationships with TAI and UTC (within statistical error)
- GPS Time = TAI – 19 s = constant

- Re-computed every 15 minutes based on satellite ranging measurements made by GPS monitor stations
- OCS software estimates clock differences of GPS satellite and monitor station clocks
- Satellite clock differences uploaded to each satellite approximately once a day
- The additional correction contained in the GPS broadcast message allows a GPS timing user to produce TAI or UTC time.

Implementing GPS Time

- USNO continuously monitors GPS satellites
  - Provides GPS Master Control Station differences between GPS Time and UTC(USNO)
- Master Control Station Kalman Filter (MCSKF) generates clock solutions to minimize UTC(USNO)-GPS
- Corrections to create both GPS Time and GPS's delivered prediction of UTC(USNO) are applied in GPS receiver by applying correction contained in the GPS data message
- VLBI stations use GPS to steer maser clocks, we are therefore linked to USNO(UTC).



Telling GPS Time

- GPS Time counts in weeks and seconds of a week from midnight of January 5/6, 1980 UTC
- Weeks begin at the Saturday/Sunday transition
- Days of the week are numbered, with Sunday being 0; Saturday is day 6
  - GPS week 0 began at the beginning of the GPS Time Scale (60 x 60 x 24 x 7)
  - Week 0 started at 00:00:00 UTC on Sunday, 6th January 1980, so the week number 'rolled over' from 1023 to 0 at 23:59:47 UTC on Saturday, 21st August 1999.
  - Software problems>SNR8's failed
- ***Within each week the time denoted as the second of the week***
  - ***Number between 0 and 604,800 (60 x 60 x 24 x 7)***

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Relativistic Time Scales

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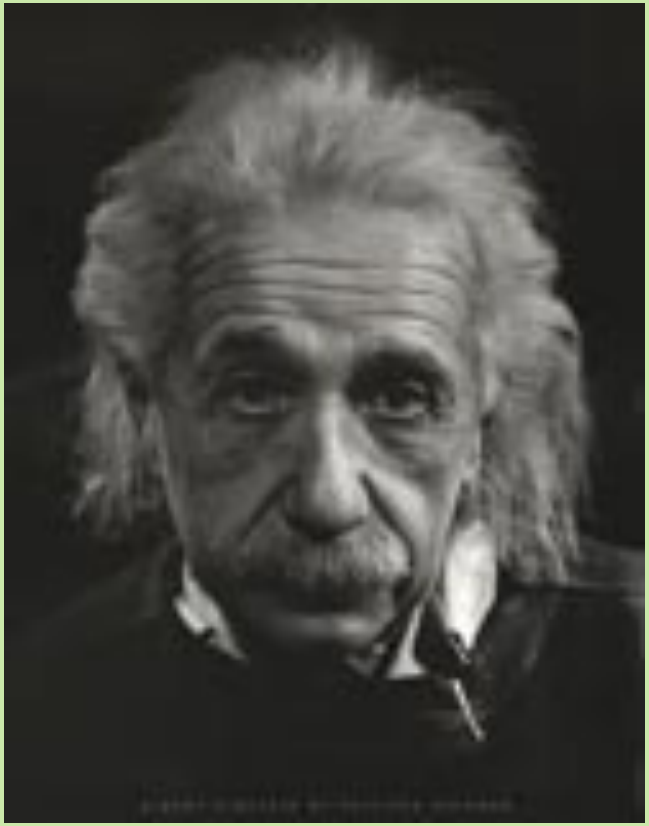
- ***Ephemeris Time (ET) was based on the Newtonian theory of gravitation and made no distinction between proper time and coordinate time***
  - ***Proper time: Reading of an ideal clock in its own rest frame***
  - ***Coordinate time: Time coordinate in given space-time coordinate system***
- ***Between 1976 and 2000, the IAU adopted new relativistic time scales consistent with the general theory of relativity whose unit is the SI second***
- ***Note that relativistic times are theoretical***
  - ***Time not kept on a clock***



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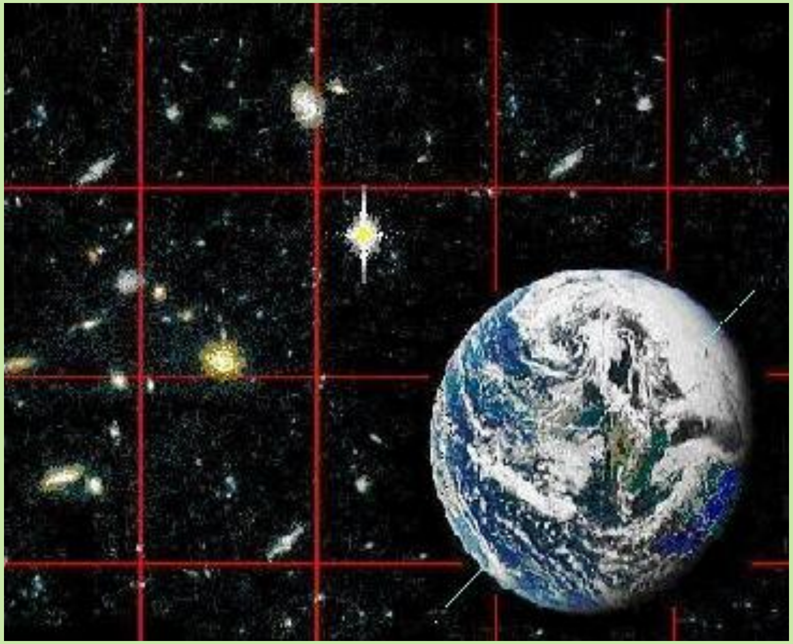
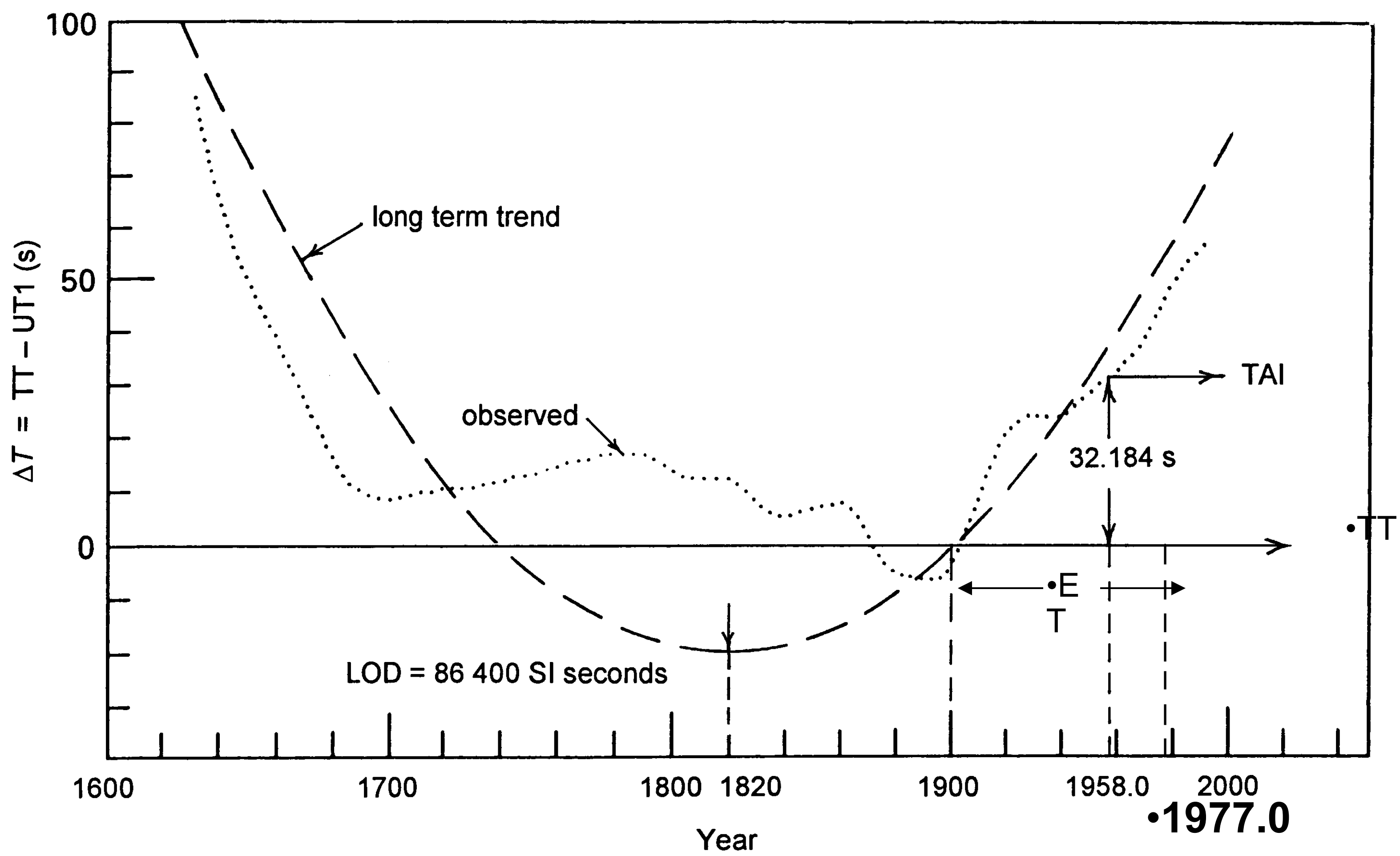
Terrestrial Time (TT)

- ***In 1991 IAU renamed TDT (which succeeded ephemeris time (ET)) as Terrestrial Time (TT)***
  - ***Unit is the SI second on the geoid and is 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***
- ***To be used as the time reference for apparent geocentric ephemerides***
  - ***Any difference (except the offset) between TAI and TT is a consequence of the physical defects of atomic time standards, and has probably remained within the approximate limits of ± 10μs. It may increase slowly in the future as time standards improve. In most cases, and particularly for the publication of ephemerides, this deviation is negligible***



ΔT since 1600



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

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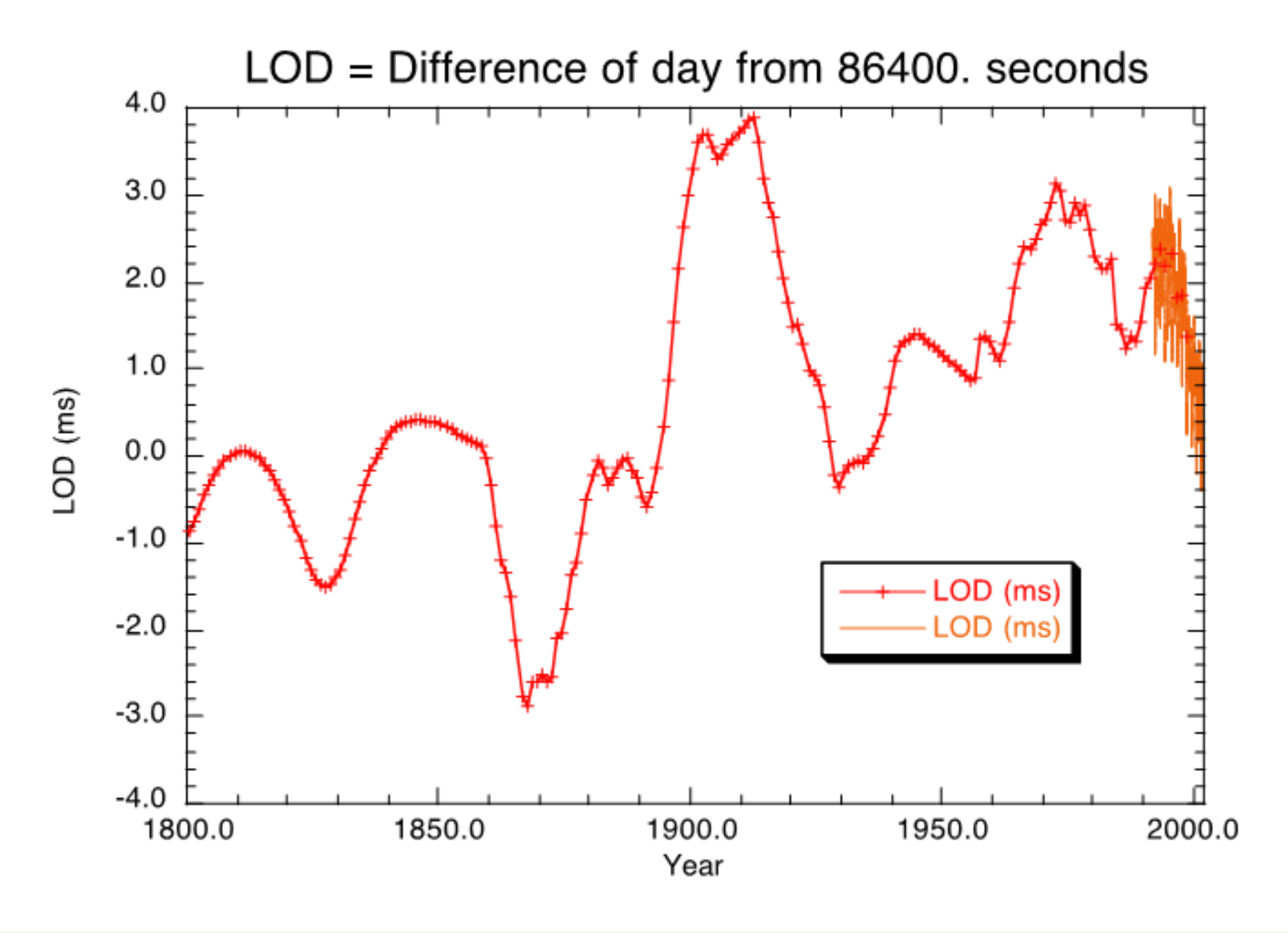

Scope

- Authoritative software
  - Tied to international standards
  - Produced or vetted by DoD SMEs
  - “Free”
- Source-code products
- Web-based calculator

Source-Code Products

- *Naval Observatory Vector Astrometry Software (NOVAS)*
- *Standards of Fundamental Astronomy (SOFA)*

NOVAS

Naval Observatory Vector Astronomy Subroutines

- Complete software package for positional astronomy
  - Instantaneous coordinates and radial velocity of any star or planet
    - e.g., apparent, topocentric, astrometric places
    - Observer at geocenter, on or near surface, on near-Earth spacecraft
  - Terrestrial → celestial transformation
  - "Building blocks" and support functions for these calculations
    - e.g., precession, nutation, frame bias, star-catalog transformations, etc.
- Produced and supported by USNO
- Used for US sections of The Astronomical Almanac
- Status
  - Version 3.1 released in March 2011
  - Python edition nearly completed

Scope

- Authoritative software
  - Tied to international standards
  - Produced or vetted by DoD SMEs
  - “Free”
- Source-code products
- Web-based calculator

Source-Code Products

- *Naval Observatory Vector Astrometry Software (NOVAS)*
- *Standards of Fundamental Astronomy (SOFA)*

NOVAS

Naval Observatory Vector Astronomy Subroutines

National Research Foundation | HartRAO Hartebeesthoek Radio Astronomy Observatory

- Complete software package for positional astronomy
  - Instantaneous coordinates and radial velocity of any star or planet
    - e.g., apparent, topocentric, astrometric places
    - Observer at geocenter, on or near surface, on near-Earth spacecraft
  - Terrestrial → celestial transformation
  - "Building blocks" and support functions for these calculations
    - e.g., precession, nutation, frame bias, star-catalog transformations, etc.
- Produced and supported by USNO
- Used for US sections of The Astronomical Almanac
- Status
  - Version 3.1 released in March 2011
  - Python edition nearly completed

SOFA

Standards of Fundamental Astronomy

National Research Foundation | HartRAO Hartebeesthoek Radio Astronomy Observatory

- Collection of routines which implement official algorithms for fundamental-astronomy computations
  - Primarily supports celestial ↔ terrestrial transformation
  - "astronomy" routines
    - e.g., calendars, time scales, precession, nutation, star space motion, and star catalog transformations
  - "vector/matrix" routines
- Service of IAU Division I
  - Managed by international review board
- Basis for IERS Conventions Chapter 5 software
- Used for UK sections of The Astronomical Almanac
- Status
  - Latest release 2010-12-01

NOVAS/SOFA Comparison

Similarities

- ***Both come from authoritative sources***
- ***Both support latest IAU resolutions***
- ***Both are consistent with IERS Conventions for practical levels of accuracy***
- ***Both have Fortran and C versions***
- ***Both contain "testbed" and demonstration programs***

NOVAS/SOFA Comparison

Differences

- ***Developed independently***
  - ***Except NOVAS uses SOFA code for IAU 2000A nutation***
- ***NOVAS currently has broader scope***
  - ***i.e., instantaneous coordinates of celestial bodies (Sun, Moon, planets, stars, etc.)***
- ***NOVAS contains its own improved "low-precision" nutation model***
  - ***2000K: 0.1 mas level, 1700 to 2300 (truncated IAU 2000A)***
  - ***Documented in USNO Circular 181***
- ***NOVAS uses an alternative algorithm for location of CIO***

NOVAS/SOFA Comparison

Differences (continued)

- ***SOFA includes support for older models***
  - ***e.g., IAU 1976 precession, IAU 1980 nutation***
- ***SOFA includes small corrections to IAU 2000A nutation***
- ***SOFA has finer structure***

NOVAS/SOFA Numerical Comparison

National Research Foundation
Hartebeesthoek Radio Astronomy Observatory

- ***Test**: Compare ITRF → GCRS transformation using SOFA and NOVAS*
  - *February 2009: latest Fortran SOFA and NOVAS F3.0g (beta)*
  - *May 2010: latest C editions of SOFA and NOVAS*
- ***Results:***
  - *Differences ~ 1.8 μas*
    - *Attributable to very small terms from IAU 2006 precession model that were included in SOFA implementation of IAU 2000A nutation model*
  - *Differences drop to ~ 0.2 μas when these terms are removed*
- ***Full discussion in NOVAS User's Guides***

Which Product Should I Use?

- ***Use NOVAS When…***
  - *You need coordinates of celestial bodies (Sun, Moon, planets, stars, etc.)*
  - *Your project requires use of DoD or GOTS code*

- ***Use SOFA When…***
  - *Your project requires use of official IAU code*
  - *You need to compute the actual transformation matrices*
  - *You also need code for now-obsolete models*

•Both products are authoritative, well-documented, relatively easy to use, and comply with IERS Conventions and IAU recommendations.

Relevant web sites

- http://www.npl.co.uk/60-years-of-the-atomic-clock/timeline/
- http://www.iers.org/IERS/EN/Home/home_node.html
- NOVAS
- http://www.usno.navy.mil/USNO/astronomical-applications/software-products/novas/

- SOFA
- http://www.iausofa.org/

- USNO Earth Orientation Matrix Calculator
- http://maia.usno.navy.mil/t2crequest/t2crequest.html

- http://www.ucolick.org/~sla/leapsecs/timescales.html