GPS Time as Critical Infrastructure Application
Robust Time Dissemination & Chip Scale Atomic Clocks

SPACE-BASED POSITIONING NAVIGATION & TIMING
NATIONAL ADVISORY BOARD

Ninth Meeting
November 9 – 10, 2011

Crown Plaza Hotel
Alexandria, VA

Dr. Robert A. Nelson
Satellite Engineering Research Corporation
7710 Woodmont Avenue, Suite 1109
Bethesda, MD 20814 USA
301-657-9641

Coordinated Universal Time (UTC)

- Coordination of worldwide atomic time and frequency radio transmissions by BIH began in 1961
- Reference frequency of 9 192 631 830 Hz for cesium based on second of ET
- Details of UTC system were formalized by International Radio Consultative Committee (CCIR) of International Telecommunication Union (ITU) in 1962
- Name Coordinated Universal Time (UTC) adopted by IAU in 1967
- Definition of UTC is a compromise to provide both the SI second and an approximation to UT1 in same radio emission

$$\mathrm{UT1} - \mathrm{UTC} \leq 0.9 \text{ s}$$

UT1 – UTC

****

I E R S B U L L E T I N – A

Rapid Service/Prediction of Earth Orientation

****

3 November 2011 Vol. XXIV No. 044

IERS Rapid Service

MJD	UT1 - UTC	error
	s	s
11 10 28	-0.350807	0.000008
11 10 29	-0.351772	0.000009
11 10 30	-0.352606	0.000010
11 10 31	-0.353414	0.000009
11 11 1	-0.354294	0.000009
11 11 2	-0.355285	0.000009
11 11 3	-0.356412	0.000007

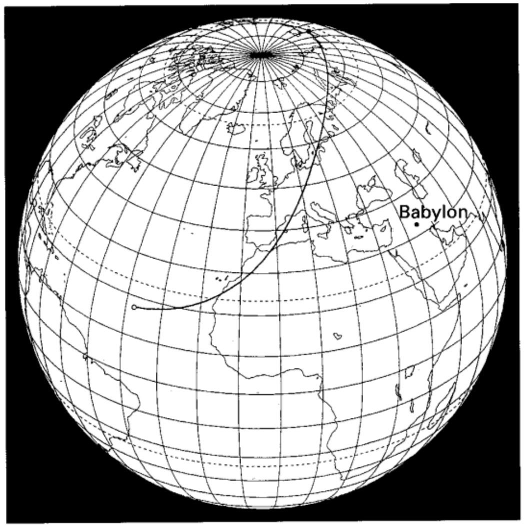
TAI - UTC = 34.0 s

Estimated accuracy of UT1 - UTC (s)

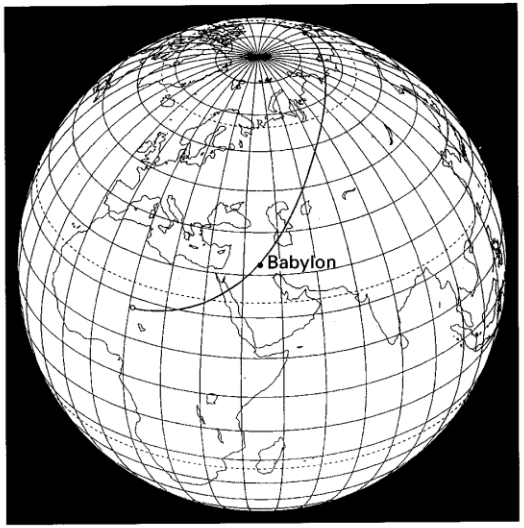
10 d	20 d	30 d	40 d
0.0014	0.0024	0.0032	0.0040

Rotation of the Earth

(a)



(b)

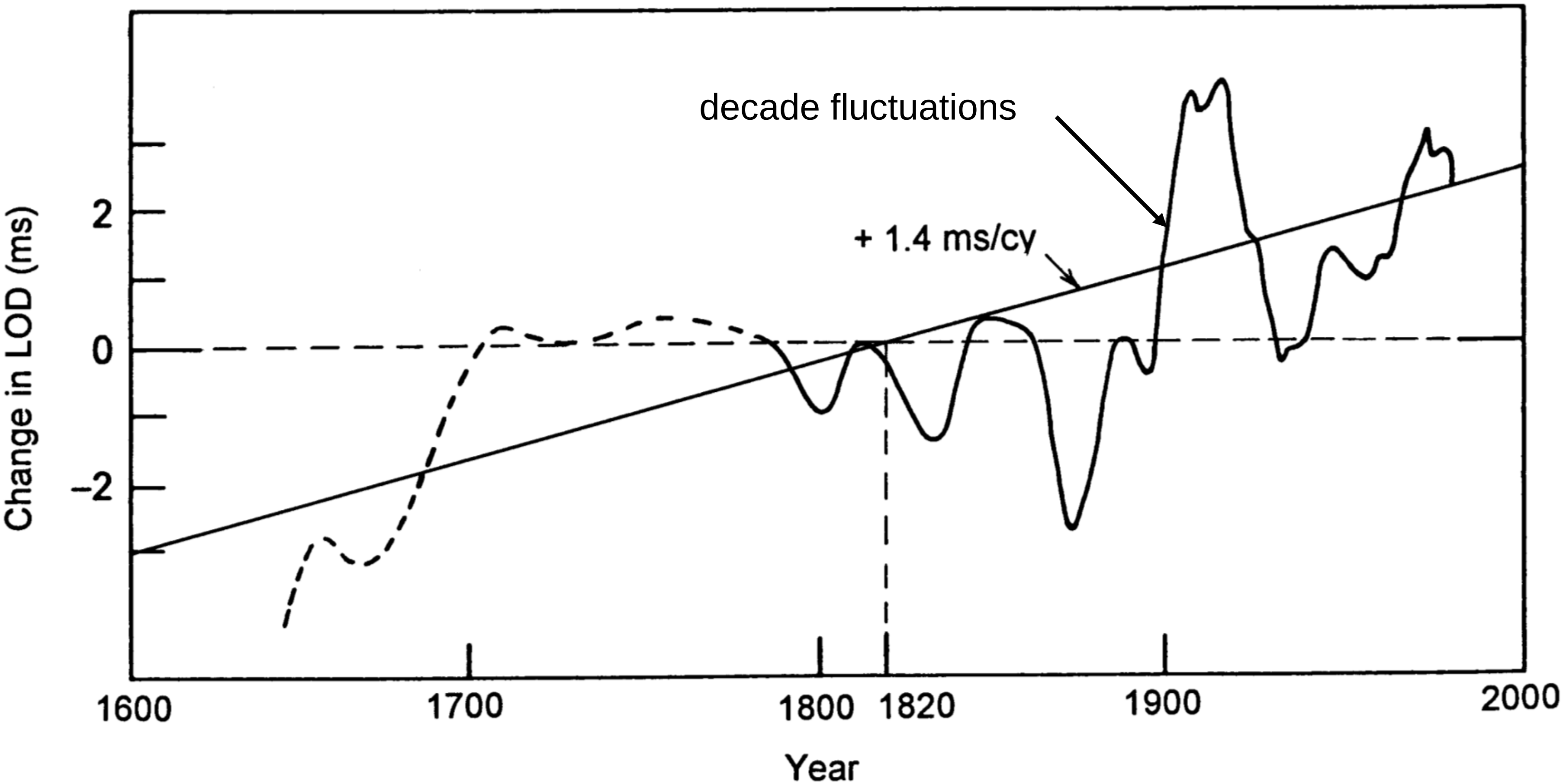


Effect of the slowing of the Earth's rotation over the past two thousand years on the path of the eclipse of 136 BC. The observed eclipse was total in Babylon.

(a) path of totality assuming uniform rotation of the Earth.

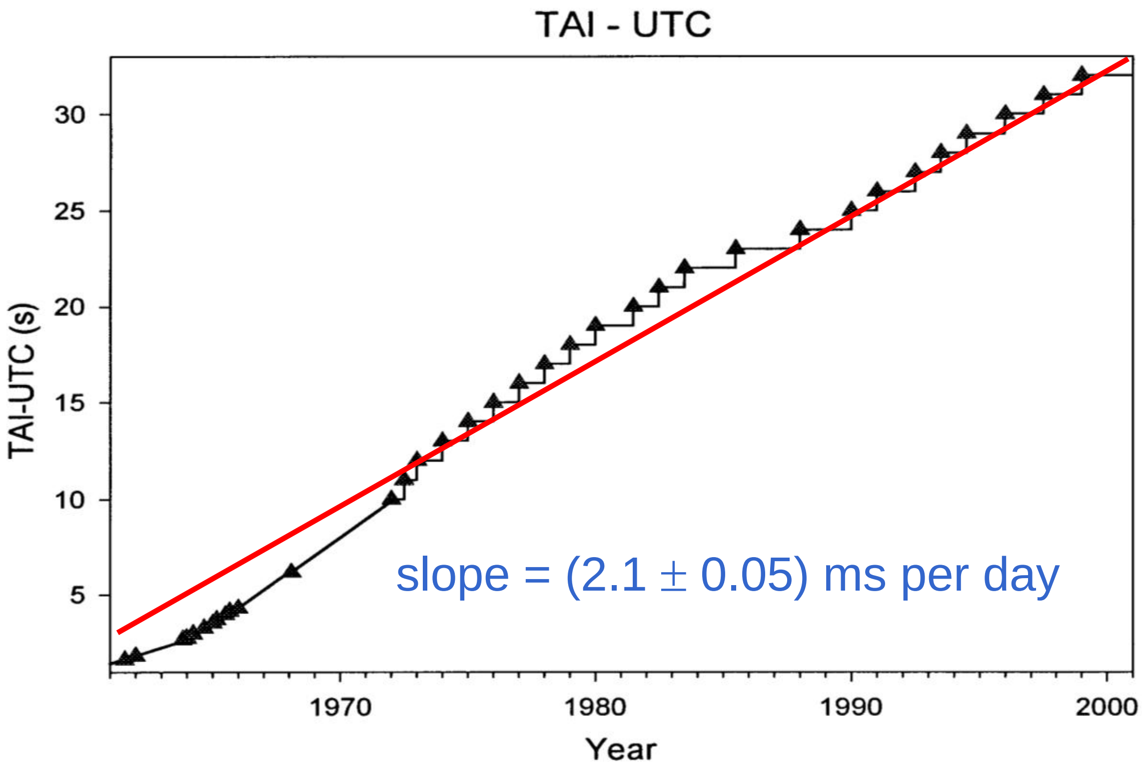
(b) totality taking into account the slowing of the Earth's rotation.

Length of Day (LOD) since 1600



After F.R. Stephenson and L.V. Morrison, *Phil. Trans. R. Soc. London* **A313**, 47 – 70 (1984)

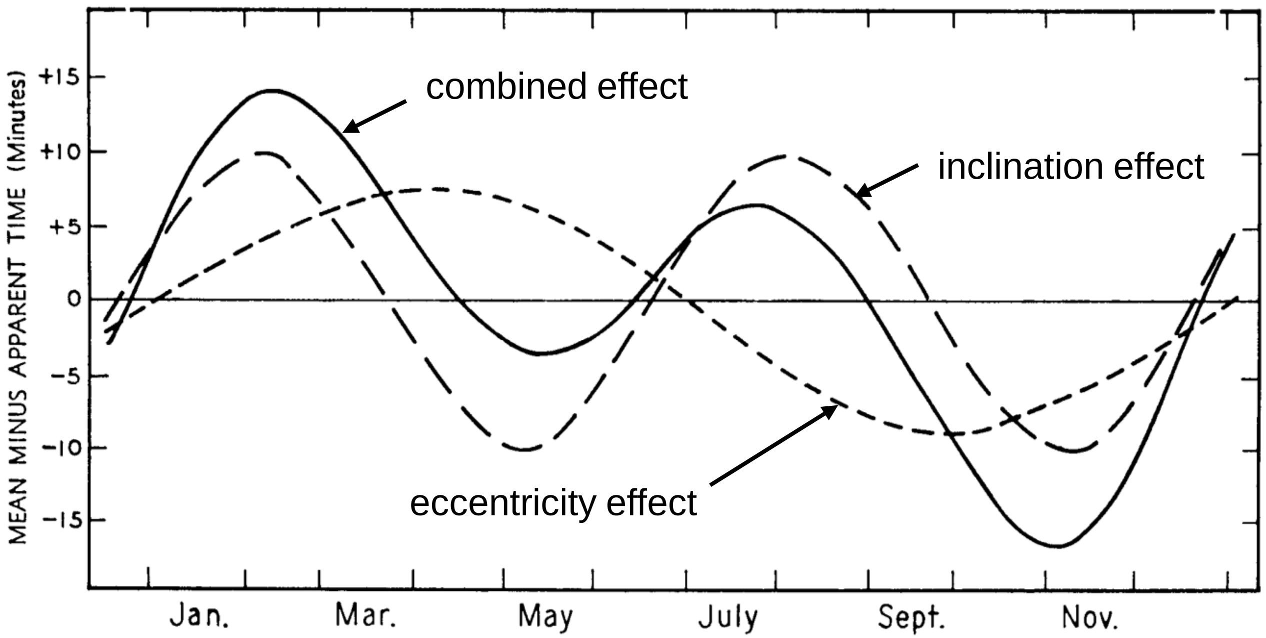
UTC since 1961



In 1972 TAI – UTC set = 10 s
24 leap seconds have been added since 1972

Year	TAI – UTC	GPS – UTC
1998	32 s	13 s
2005	33 s	14 s
2008	34 s	15 s

Apparent Solar Time

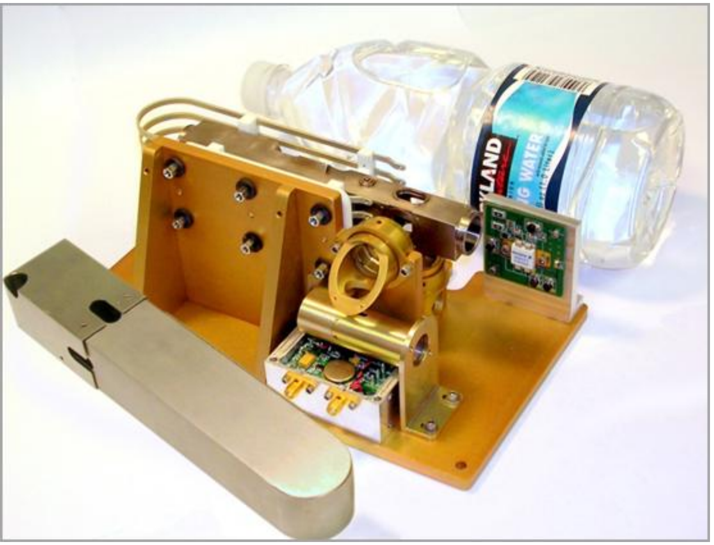


After B.M. Oliver, “The Shape of the Analemma,” *Sky and Telescope*, July, 1972, 20 - 22

Difference between mean time and apparent time is called the “equation of time”

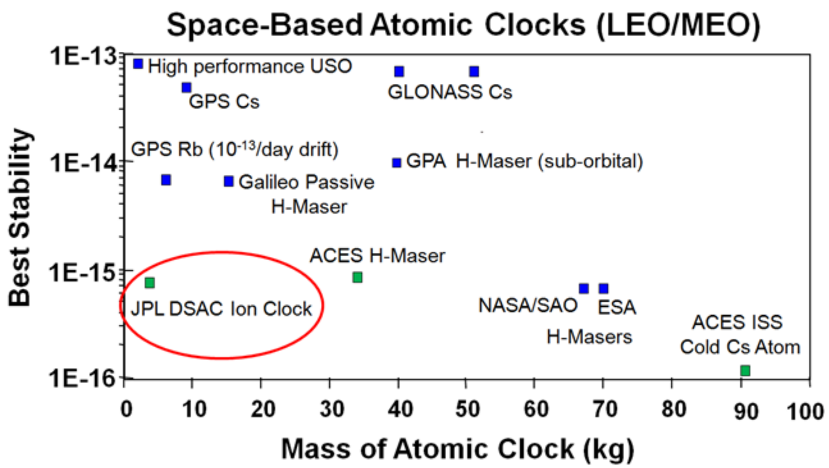
- Mean noon precedes apparent noon by 14.5 minutes on February 12
- Apparent noon precedes mean noon by 16.5 minutes on November 3

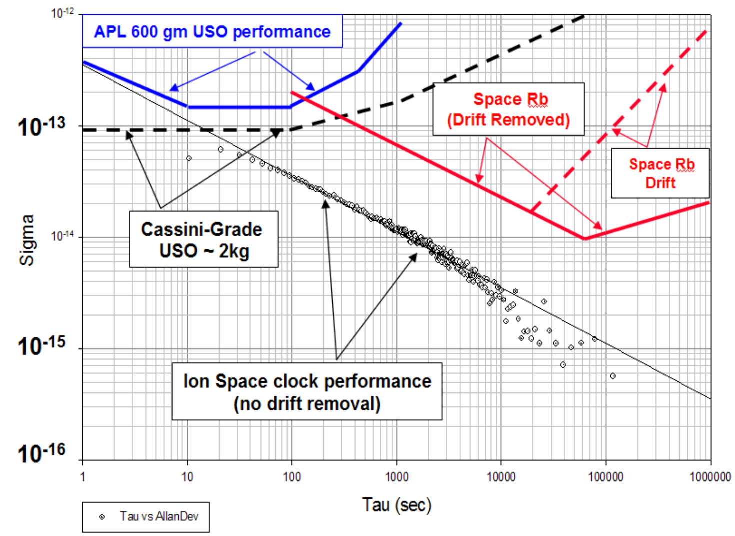
Mercury Ion Deep Space Atomic Clock (DSAC)
Jet Propulsion Laboratory

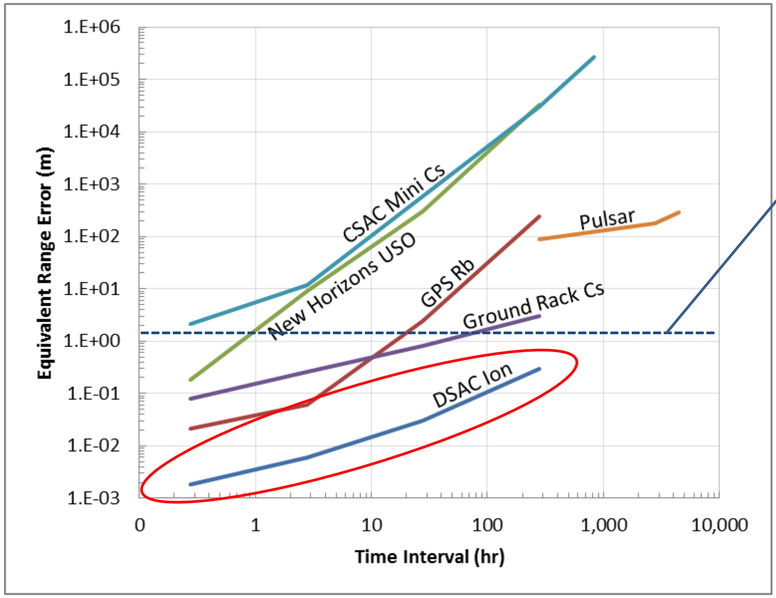


Develop a small, low-mass atomic clock based on mercury-ion trap technology and demonstrate it in space, providing unprecedented stability needed for the next-generation of deep space navigation and radio science.

DSAC Compared to Other Space Based Clocks







Current 2-Way Deep Space Range Error Levels (1 – 2 m)

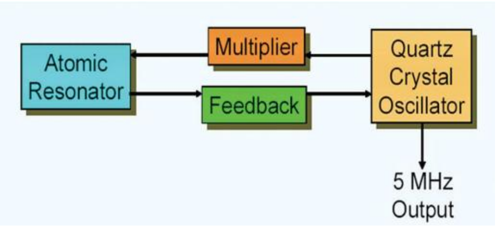
DSAC is ideal for deep space use

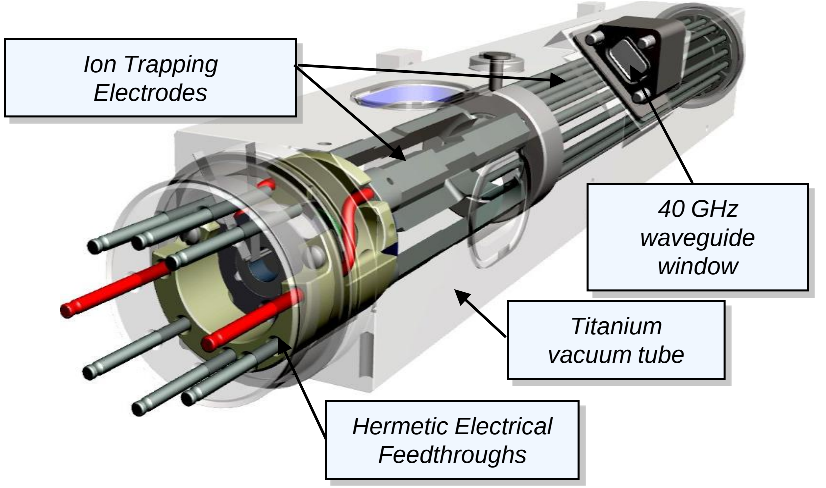
- Long lifetimes via no consumables
- Low sensitivity to temperature changes, magnetic fields, radiation, zero-g

Technology Overview

KEY FEATURES:

- No Lasers,
- No Cryogenics,
- No Microwave cavities
- No Light Shift,
- No Consumables

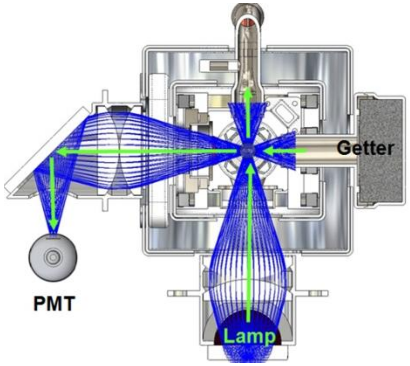




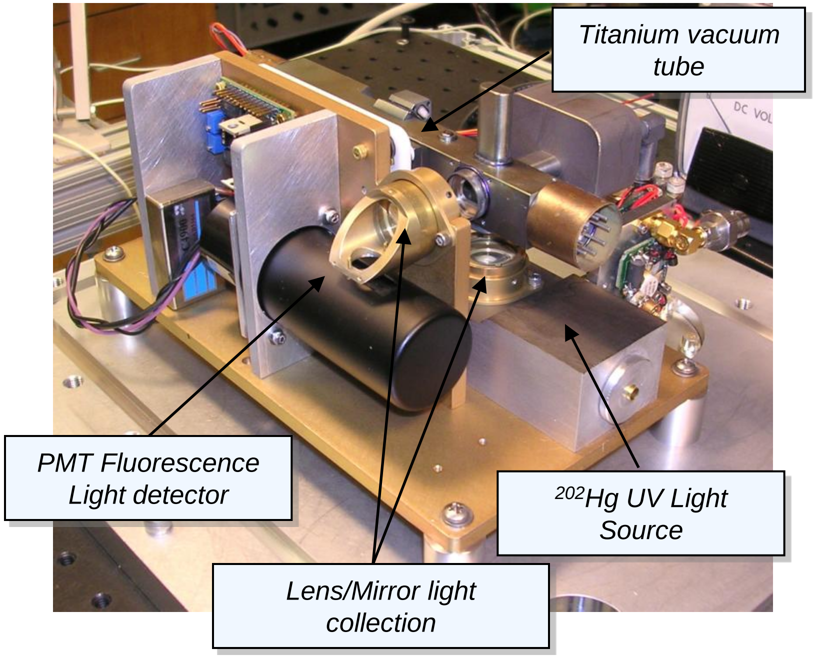
- Based on other space vacuum tubes
  - Must use non-magnetic materials
  - 5,000-fold improvement in vacuum
  - 10-fold reliability improvement

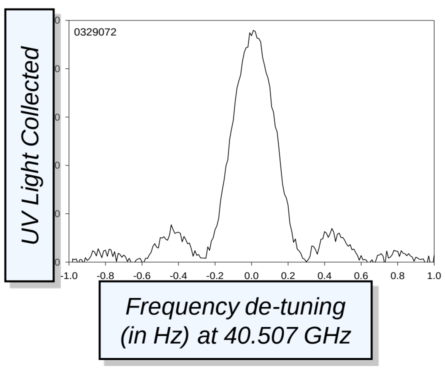
- 10^6-10^7 $^{199}Hg^+$ trapped ions
- Clock Transition: 40,507,347,996.8 Hz
- No wall collisions, high Q microwave line

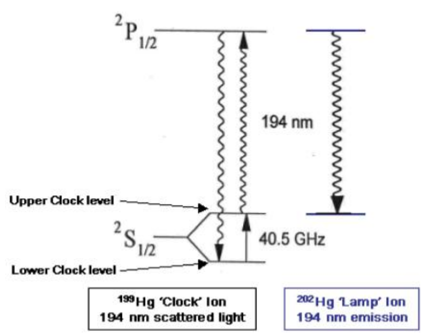
- State selection via optical pumping from $^{202}Hg^+$;
- 1-2 UV photons per second scattered
- Ions are buffer-gas (Ne) cooled to ~300K
- Ion Shuttling from Quadrupole to Multipole trap where best isolation from disturbances is achieved



- Frequency de-tunings and drift of USO are detected via UV light scattering from trapped ions





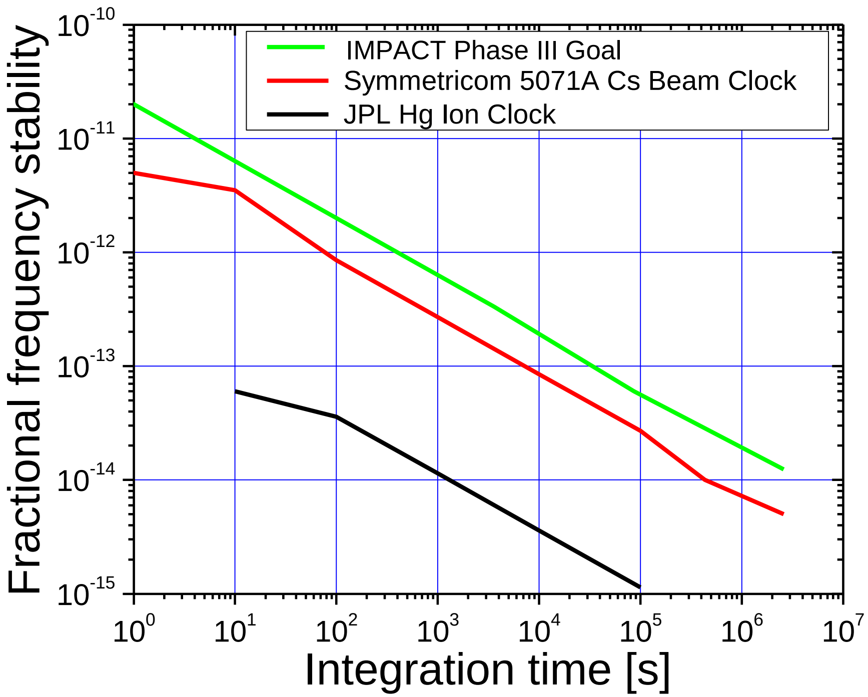


Chip Scale Atomic Clock Technology

Integrated Micro Primary Atomic Clock Technology (IMPACT)

Realize a primary atomic clock with drastically reduced size, weight, and power over state-of-the-art primary clocks

Achieve Cs Beam Clock Performance in an extremely small size and low power package (5 cm^3 and 50 mW)



Applications--Excellent timing for:

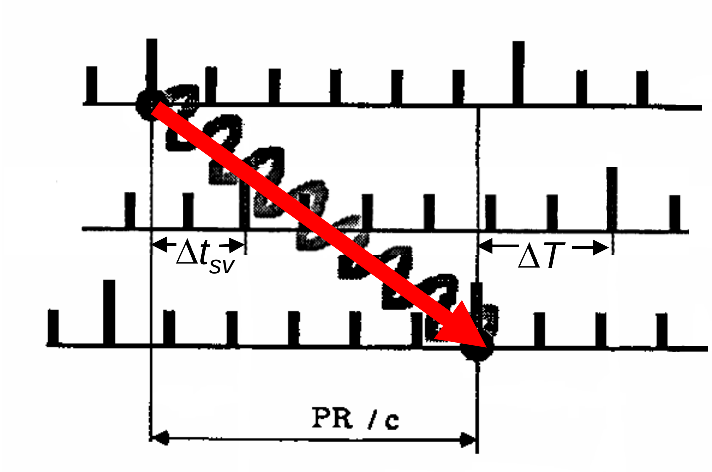
- **Nano/pico satellites**
- **Rapid acquisition of GPS signal**
- **Pulsed radio and spread spectrum communications**

GPS Time

Internal time scale used by the GPS as realized by operating clocks in the GPS satellites and at the Master Control Station in Colorado Springs. The difference between GPS Time and UTC(USNO) is broadcast in the GPS navigation message.

- 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)
  - TAI – GPS Time = 19 s = constant
  - TAI – UTC = 34 s presently
  - GPS Time – UTC = 15 s presently

GPS measurement of pseudorange



PRN sequence transmitted by satellite

GPS Time maintained by MCS

Replica PRN sequence generated in receiver

$$\mathrm{PR} = D + c\,(\Delta T - \Delta t_{sv} + \Delta t_{iono} + \Delta t_{tropo}) \qquad \Delta t_{sv} = \Delta t^{*}_{sv} + \Delta t_{rel}$$

Satellite broadcasts its own ephemeris in navigation message.

Receiver measures propagation time of signal (pseudorange) by autocorrelation between transmitted and replica pseudorandom noise (PRN) codes.

Four pseudorange measurements plus corrections yield receiver position and time.

Relativistic effects in the GPS

Satellite clock

$$\Delta\tau' = \int_A^B \left\{ 1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{1}{c^2}(U - W_0) \right\} d\tau$$

time dilation

redshift

$$\Delta t_{\text{eccentricity}} = \frac{2}{c^2}\sqrt{GM\,a}\;e\sin E = \frac{2}{c^2}\,\mathbf{v}\cdot\mathbf{r}$$

Light signal

$$\Delta t = \frac{D}{c} + \frac{2\,\omega\,A}{c^2}$$

Sagnac effect

Relativistic effects incorporated in the GPS (satellite clock – geoid clock)

Time dilation:	− 7.2 μs per day
Gravitational redshift:	+ 45.8 μs per day
Net secular effect:	+ 38.6 μs per day
Residual periodic effect:	46 ns amplitude for e = 0.02
Sagnac effect:	133 ns maximum

Time transfer between clock on Mars and on the Earth

- Transformation between Terrestrial Time (TT) and Barycentric Coordinate Time (TCB)

$$\mathrm{TCB} - \mathrm{TT} \approx (L_C + L_G)\,\mathrm{TCB} + P + \left.\frac{1}{c^2}\,\mathbf{v}_E \cdot \mathbf{R}\right|_{t_0}^{t}$$

- Transformation between Mars Time (TM) and Barycentric Coordinate Time (TCB)

$$\mathrm{TCB} - \mathrm{TM} \approx (L_{CM} + L_M)\,\mathrm{TCB} + P + \left.\frac{1}{c^2}\,\mathbf{v}_M \cdot \mathbf{R}\right|_{t_0}^{t}$$

$$\mathrm{MT} - \mathrm{TT} = (\mathrm{TCB} - \mathrm{TT}) - (\mathrm{TCB} - \mathrm{TM})$$

Orbital semimajor axis
1.524 AU = 2.280 $\times$ 10^8 km

The drift rate is (1.28 ms/d + 0.06 ms/d) – (0.84 ms/d + 0.01 ms/d) = 0.49 ms/d.

The amplitudes of the periodic variations are (*a*) 1.7 ms at the Earth orbital period (365.2422 d) and (*b*) 11.4 ms at the Mars orbital period (687 d).

Summary

- As clock technology and theory have progressed, time scales and methods of time measurement have evolved to achieve greater self-consistency

- Astronomical measures of time have been replaced by atomic measures of time

- Atomic clocks requiring small size and low power are under development

- High precision time measurement and dissemination requires application of the principles of the general theory of relativity

- For future missions, it would be desirable for UTC to be uniform without steps