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

Ninth Meeting
November 9 – 10, 2011
Crown Plaza Hotel
Alexandria, VA

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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

\[ \text{UT1} - \text{UTC} \leq 0.9 \text{ s} \]
IERS Bulletin – A

Rapid Service/Prediction of Earth Orientation

3 November 2011    Vol. XXIV    No. 044

IERS Rapid Service

<table>
<thead>
<tr>
<th>MJD</th>
<th>UT1 - UTC</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 10 28</td>
<td>-0.350807</td>
<td>0.000008</td>
</tr>
<tr>
<td>11 10 29</td>
<td>-0.351772</td>
<td>0.000009</td>
</tr>
<tr>
<td>11 10 30</td>
<td>-0.352606</td>
<td>0.000010</td>
</tr>
<tr>
<td>11 10 31</td>
<td>-0.353414</td>
<td>0.000009</td>
</tr>
<tr>
<td>11 11 1</td>
<td>-0.354294</td>
<td>0.000009</td>
</tr>
<tr>
<td>11 11 2</td>
<td>-0.355285</td>
<td>0.000009</td>
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<tr>
<td>11 11 3</td>
<td>-0.356412</td>
<td>0.000007</td>
</tr>
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</table>

TAI - UTC = 34.0 s

Estimated accuracy of UT1 - UTC (s)

<table>
<thead>
<tr>
<th>10 d</th>
<th>20 d</th>
<th>30 d</th>
<th>40 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0014</td>
<td>0.0024</td>
<td>0.0032</td>
<td>0.0040</td>
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</tbody>
</table>
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

UTC since 1961

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

<table>
<thead>
<tr>
<th>Year</th>
<th>TAI – UTC</th>
<th>GPS – UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>32 s</td>
<td>13 s</td>
</tr>
<tr>
<td>2005</td>
<td>33 s</td>
<td>14 s</td>
</tr>
<tr>
<td>2008</td>
<td>34 s</td>
<td>15 s</td>
</tr>
</tbody>
</table>

slope = (2.1 ± 0.05) ms per day
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
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

*Space-Based Atomic Clocks (LEO/MEO)*

- **JPL DSAC Ion Clock**
- **GPS Cs**
- **GLONASS Cs**
- **GPS Rb** (10^{-13}/day drift)
- **Galileo Passive H-Maser** (sub-orbital)
- **GPA H-Maser** (sub-orbital)
- **ACES H-Maser**
- **NASA/ESA H-Masers**
- **ACES ISS Cold Cs Atom**

**Best Stability**

- **Mass of Atomic Clock (kg)**

**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
Deep Space Atomic Clock

**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

**Technology Overview**

![Diagram of Deep Space Atomic Clock](image)
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 cm³ 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

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.

\[
PR = D + c (\Delta T - \Delta t_{sv} + \Delta t_{iono} + \Delta t_{tropo})
\]

\[
\Delta t_{sv} = \Delta t_{sv}^* + \Delta t_{rel}
\]
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

\[ \Delta t_{\text{eccentricity}} = \frac{2}{c^2} \sqrt{GM} \ a \ e \ \sin E = \frac{2}{c^2} \ v \cdot r \]

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: \(-7.2 \ \mu s \ \text{per day}\)
- Gravitational redshift: \(+45.8 \ \mu s \ \text{per day}\)
- Net secular effect: \(+38.6 \ \mu s \ \text{per day}\)
- Residual periodic effect: \(46 \ \text{ns amplitude for } e = 0.02\)
- Sagnac effect: \(133 \ \text{ns maximum}\)
Time transfer between clock on Mars and on the Earth

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

\[
TCB - TT \approx (L_C + L_G) \text{TCB} + P + \frac{1}{c^2} \mathbf{v}_E \cdot \mathbf{R} \bigg|_{t_0}
\]

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

\[
TCB - TM \approx (L_{CM} + L_M) \text{TCB} + P + \frac{1}{c^2} \mathbf{v}_M \cdot \mathbf{R} \bigg|_{t_0}
\]

\[
MT - TT = (TCB - TT) - (TCB - TM)
\]

The drift rate is \((1.28 \text{ ms/d} + 0.06 \text{ ms/d}) - (0.84 \text{ ms/d} + 0.01 \text{ ms/d}) = 0.49 \text{ ms/d}.

The amplitudes of the periodic variations are \((a) 1.7 \text{ ms} \text{ at the Earth orbital period (365.2422 d)} \text{ 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.