GNSS Clocks: Challenges and Developments

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Atomic Frequency Standards

Atomic clocks are based on an electron transitions, assumed identical everywhere.

“Since 1967 the unit of the second is defined to be “the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium atom.”

\[ f = \frac{(E_2 - E_1)}{h} \]

Energy Difference = \( h \times f \)

Ideal World: Nearly a perfect clock!
Real World: Environmental perturbations, measurement noise, & relativity.

Different atomic transitions have different benefits and implementation challenges.

- Microwave (~GHz)
- Optical
GNSS Clock Technologies: Challenges and Developments

- Many atomic clock technologies, specialized to specific applications
  - Inherent atomic sensitivity
  - Localization method (cells, beams, RF traps, optical traps)
  - State selection method (magnetic selection, optical pumping)
  - Engineered isolation (if needed)

- Only a few meet the criteria for space operation: Rb (6.8 GHz), Cs (9.2 GHz), H (1.4 GHz)
  - Size, mass, and power constraints
  - Continuous, reliable, and long life operation
  - High immunity (or engineered isolation) to changing environments

- Current GNSS clocks
  - GPS: Rb, Cs
  - GLONASS: Cs
  - GALILEO: H, Rb
  - BEIDOU: Rb
  - IRNSS: Rb
  - QZSS: Rb
Current GNSS Space Clock Technology

Industrialized Clocks (ground & space): Rb, Cs, H
- Continuous, reliable, long life operation
- **Key Apps:** Telecommunications, timescale flywheels, space navigation.

Future GNSS Space Clock Technology?

Trapped Ion Frequency Standards (room temp)
- Practical operation with very good long term stability
- Amenable to lower SWaP
- **Key Apps:** Autonomous operation, Ultra stable timescales, space navigation

Laser Cooled Standards – microwave (cold fountains, cold beams, cold ions)
- Laser cooled/trapped/interrogated atoms
- **Key Apps:** Accuracy metrology – definition of the second (Cs)

Laser Cooled Standards – optical (trapped ion or neutrals, optical lattices)
- Laser cooled/trapped/interrogated atoms
- Laser (optical) local oscillator. Count optical frequencies through femtosecond combs
- **Key Apps:** Accuracy metrology - future definition of the second

Chip Scale Atomic Clocks (CSAC): Rb, Cs
- MEMS fabrication and low power
- Large performance compromises
- **Key Apps:** Battery powered, requiring accuracy not achievable with quartz resonators.
Trapped Mercury Ion Clocks at JPL

Key Performance Features:
- $10^5$-$10^7$ $^{199}$Hg$^+$ trapped ions
  - No wall collisions, high Q microwave line
  - Buffer gas cooled to ~300K
  - Multi-pole ion trap – low T sensitivity
- State selection:
  - Optical Pumping from $^{202}$Hg$^+$ lamp
  - 1-2 UV photons per second scattered
- High Clock Transition:
  - 40,507,347,996.8 Hz – low B sensitivity
- Adapts to variety of Local Oscillators - flexible

Key Reliability Features: - practical
- No Lasers
- No Cryogenics
- No Microwave cavity
- No Light Shift
- Little/no Consumables
Hg+ Clock stability with differing Local Oscillators (LO)

- Short term stability depends on the LO
- Long term stability determined by the Hg+ systematics

- Space clocks (e.g. GNSS) would be configured with a USO LO
- Optical-microwave LO being considered for advanced science missions.
• Long life & continuous high stability operation

Killer App: Amenable to small, low power operation - space.

• Mercury Ion Clock Paths and Applications (2014):

Ultra-Stable Performance: UTC timescales.
  • “Compensated” Multi-pole ion trap.
  • New References: drift \( \leq 10^{-17} \) /day.
  • \( 10^{-15} \) short term stability (~1 sec) via super LO’s.

Space Operation: Reliable, long life. USO LO.
  • DSAC Technology Demonstration Mission (TRL 5-7)
  • Deep Space: \( 3 \times 10^{-13} \) short term, \( 10^{-14} \) at 1 day
  • GNSS: \( 1 \times 10^{-13} \) short term, \( 10^{-15} \) at 1 to 10 days

Ultra-small, low power ion clock technologies:
  • Few \( \text{cm}^3 \) ion trap, Miniature light sources and LO’s under development.
DSAC Technology Demonstration Mission (NASA TDM):

- First space demonstration of ion clock technology
- Establishes cross cutting path to Deep Space, GNSS, and Science Applications
Develop “Demonstration Unit” mercury ion clock for navigation/science in deep space

- Advance technology to TRL 7 and perform 1 year demonstration in space.
- Use commercial USO LO. Monitor long term stability through GPS Time Transfer
- Future operational unit (TRL 7 → 9) to be smaller, more power efficient.
DSAC Demonstration Payload and Hosting

- Flight experiment of the ion clock as a hosted payload on Surrey Satellite Technology US Orbital Test Bed II (OTB II) spacecraft
  - OTB II is a 180 kg ESPA-compatible spacecraft – fixed arrays, no active maneuvering, nadir fixed attitude maintained/controlled via reaction wheels/magnetorquers.
  - OTB II hosting other payloads including several US Air Force experiments
  - Launched as part of USAF STP II (a Space X Falcon 9 Heavy). Scheduled for May 2016
Int’l GNSS Service (IGS):
- ~ 400 GPS tracking stations globally
- IGS timescale (ensemble clock)

UTC Laboratories
DSAC Mission Schedule

- Mission Definition & System Reqmts Review: February 2012 ✔
- Preliminary Design Review: May 2013 ✔
- NASA Commitment Review (KDP-C): November 2013 ✔
- Clock Critical Design Review: July 2014
- Mission CDR & System Integration Review: September 2014
- Pre-Ship Review: March 2015
- Flight Readiness Review: February 2016
- Launch & Mission Operations: May 2016 + 1 Year
DSAC Compared to Existing GNSS Frequency Standards

- Required AD (including drift) of < 3e-15 at one-day (current estimate at 1.5e-15)
- 2nd Generation DSAC will focus on packaging and lifetime.
- Satisfies future GPS IIIB URE requirement (includes clock and ephemeris)

Further ion clock stability already demonstrated on ground if needed in space.

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<tr>
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<th>AFS</th>
<th>Average Power</th>
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<tbody>
<tr>
<td>DSAC Demo Unit (1st Gen)</td>
<td>1st Demo</td>
<td>&lt; 50 W</td>
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<tr>
<td></td>
<td>Unit</td>
<td>&lt;16 kg</td>
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<tr>
<td>DSAC Future Unit (2nd Gen)</td>
<td>2nd Gen</td>
<td>&lt; 30 W</td>
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<td>GPS IIF Rb (w/o drift)</td>
<td>5th Gen</td>
<td>&lt; 40 W</td>
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<td>Galileo H-Maser</td>
<td>2nd Gen</td>
<td>&lt; 60 W</td>
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Mercury Ion Clock Timekeeping

Time Uncertainty after Unattended Operation versus Time

- **Ground Clock Stability**: < 0.1 ns at 10 days \(10^{-16}\)
- **Space Clock Stability**: < 1 ns at 10 days \(10^{-15}\)

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“**Mercury Atomic Frequency Standards for Space Based Navigation and Timekeeping**”, Proc. of PTTI (2011)