GNSS Clocks: Challenges and Developments

Robert L. Tjoelker
Jet Propulsion Laboratory
Frequency and Timing Advanced Instrument Development Group

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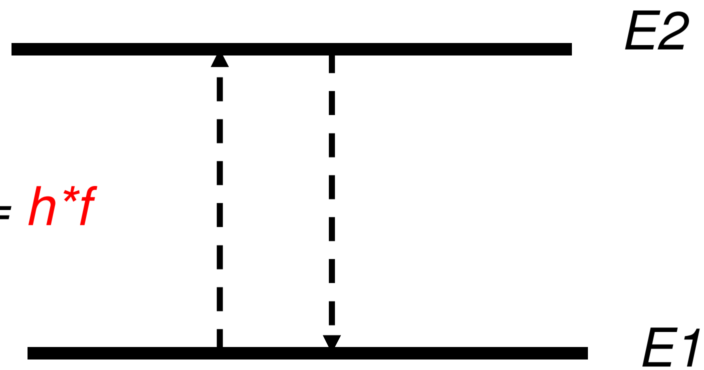
Atomic Frequency Standards

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."

*Energy Difference = h*f*



$f = (E2-E1) / h$

- Microwave (~GHz)
- Optical

Ideal World: Nearly a perfect clock!

Real World: Environmental perturbations, measurement noise, & relativity.

Different atomic transitions have different benefits and implementation challenges.

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

DSAC

Laser Cooled Standards – microwave (cold fountains, cold beams, cold ions)

- Laser cooled/trapped/interrogated atoms
- Key Apps: Accuracy metrology – definition of the second (Cs)

ACES, CAL

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

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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:

10^6-10^7 $^{199}Hg^+$ trapped ions

- No wall collisions, high Q microwave line
- buffer gas cooled to ~300K
- multi-pole ion trap – ***low T sensitivity***

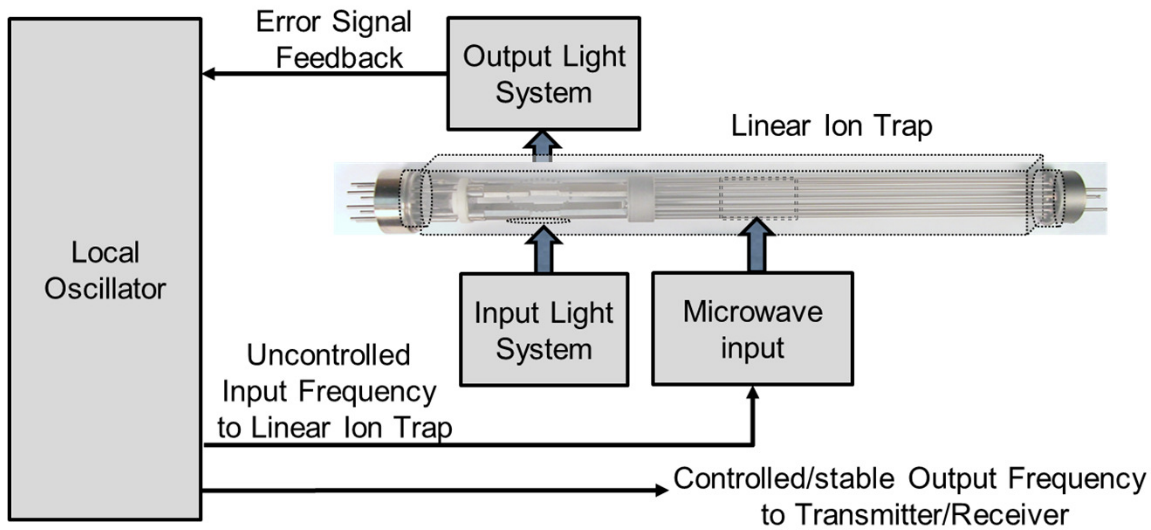
- **State selection:**
  - Optical Pumping from $^{202}Hg^+$ lamp
  - 1-2 UV photons per second scattered

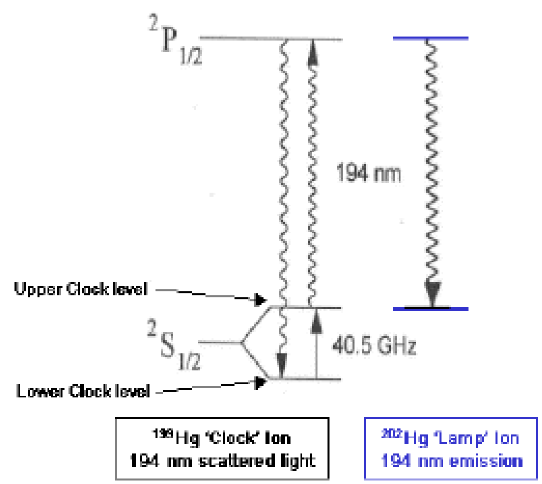
- **High Clock Transition:**
  - 40,507,347,996.8 Hz – ***low B sensitivity***

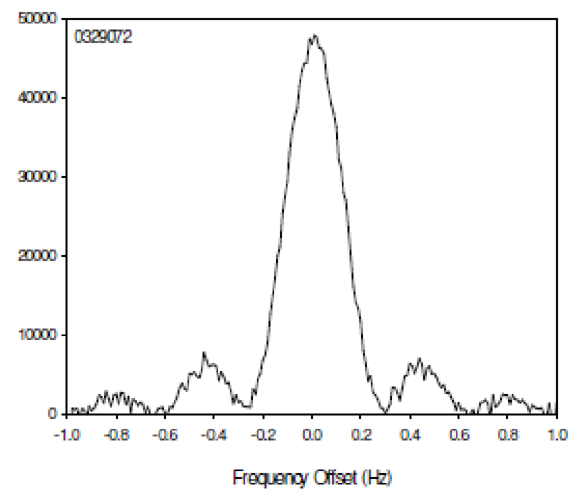
- **Adapts to variety of Local Oscillators - *flexible***

Key Reliability Features: - *practical*

- **No Lasers**
- **No Cryogenics**
- **No Microwave cavity**
- **No Light Shift**
- **Little/no Consumables**







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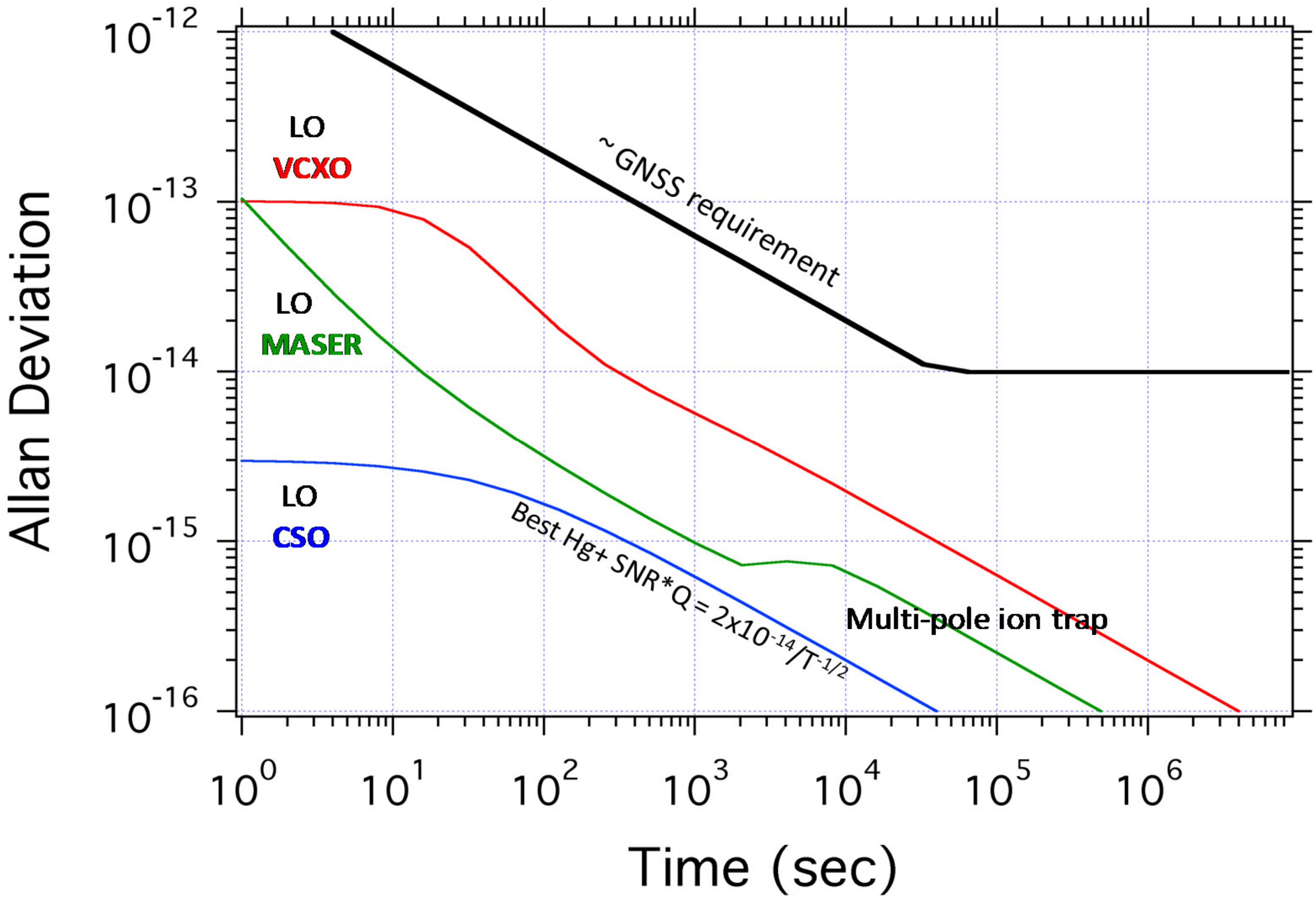
Hg+ Clock stability with differing Local Oscillators (LO)

- 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.

Trapped Mercury Ion Clocks at JPL

- **Long life & continuous high stability operation**

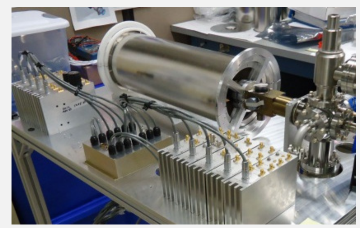
Killer App: Ultra-stable timekeeping and long term autonomy.
Killer App: Amenable to small, low power operation- space.

Original LITS

- **Mercury Ion Clock Paths and Applications (2014):**

Ultra-Stable Performance: UTC timescales.

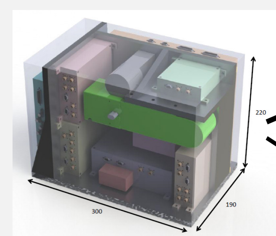
- "Compensated" Multi-pole ion trap.
- New References: drift ≤ 10^{-17}/day.
- 10^{-15} short term stability (~1 sec) via super LO's.



Ultra stable ion clock –Chassis Size

Space Operation: Reliable, long life. USO LO.

- DSAC Technology Demonstration Mission (TRL 5-7)
- Deep Space: 3×10^{-13} short term, 10^{-14} at 1 day
- GNSS: 1×10^{-13} short term , 10^{-15} at 1 to 10 days



DSAC

Deep Space Infusion

GNSS Infusion

Ultra-small, low power ion clock technologies:

- Few cm³ ion trap, Miniature light sources and LO's under development.

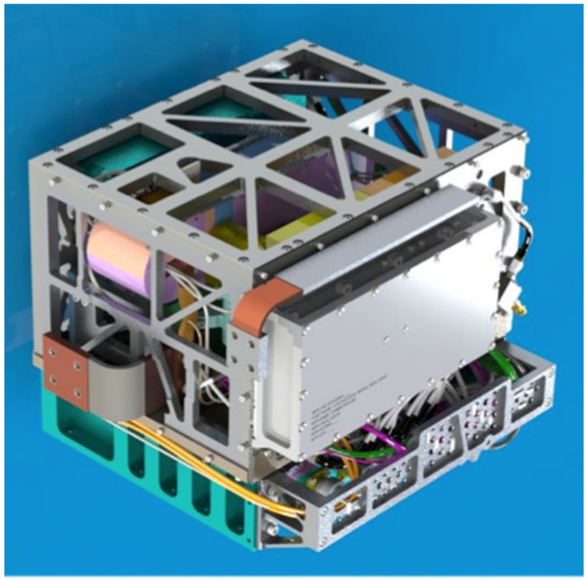
<10 cm³

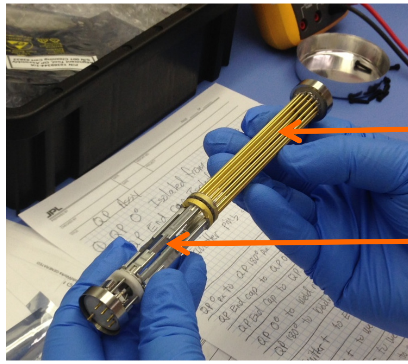
DSAC Technology Demonstration Mission (NASA TDM):

- First space demonstration of ion clock technology
- Establishes cross cutting path to Deep Space, GNSS, and Science Applications

NASA's DSAC Technology Demonstration Mission

DSAC Demonstration Unit (CAD)

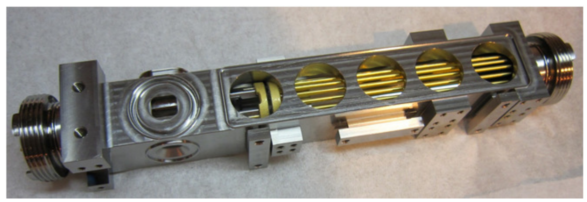




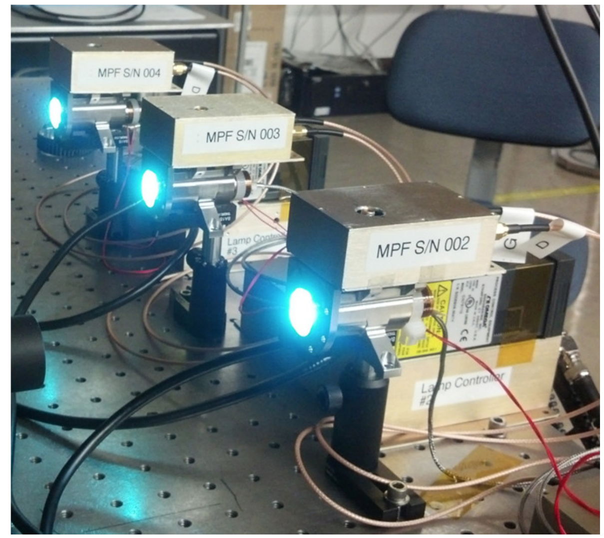
Multi-pole Trap

Quadrupole Trap

Vacuum Tube



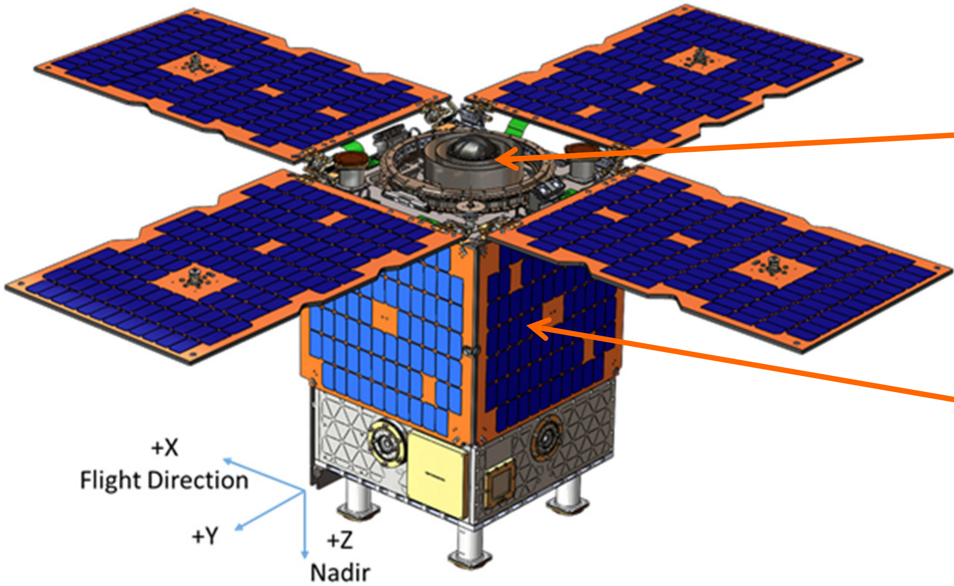
Mercury UV Lamp Testing



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



DSAC Payload Elements

- Zenith-oriented choke ring GPS antenna
- USO
- DSAC Ion Clock
- TriG GPS receiver

- 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

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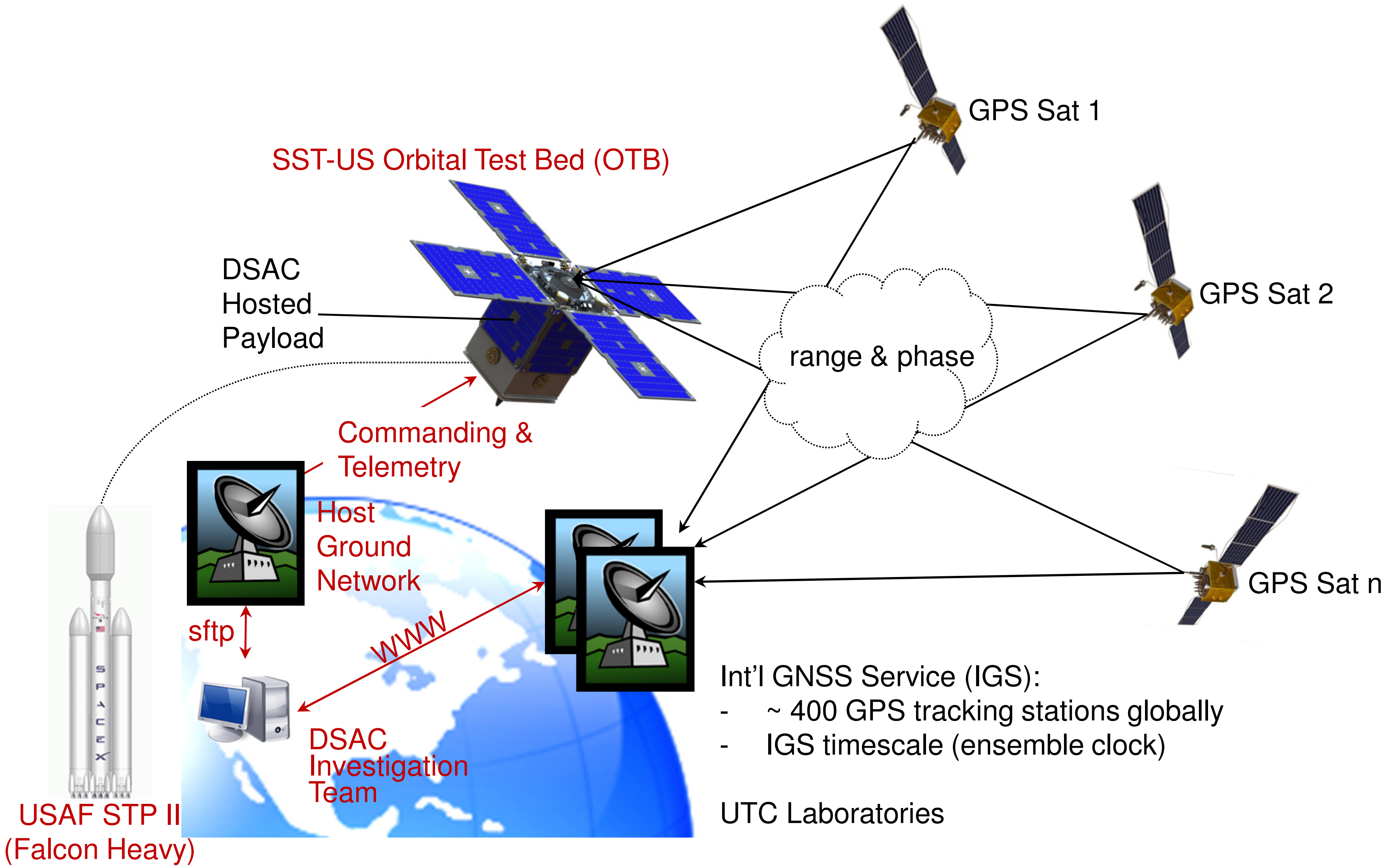
DSAC Mission Architecture



Int'l GNSS Service (IGS):
- ~ 400 GPS tracking stations globally
- IGS timescale (ensemble clock)

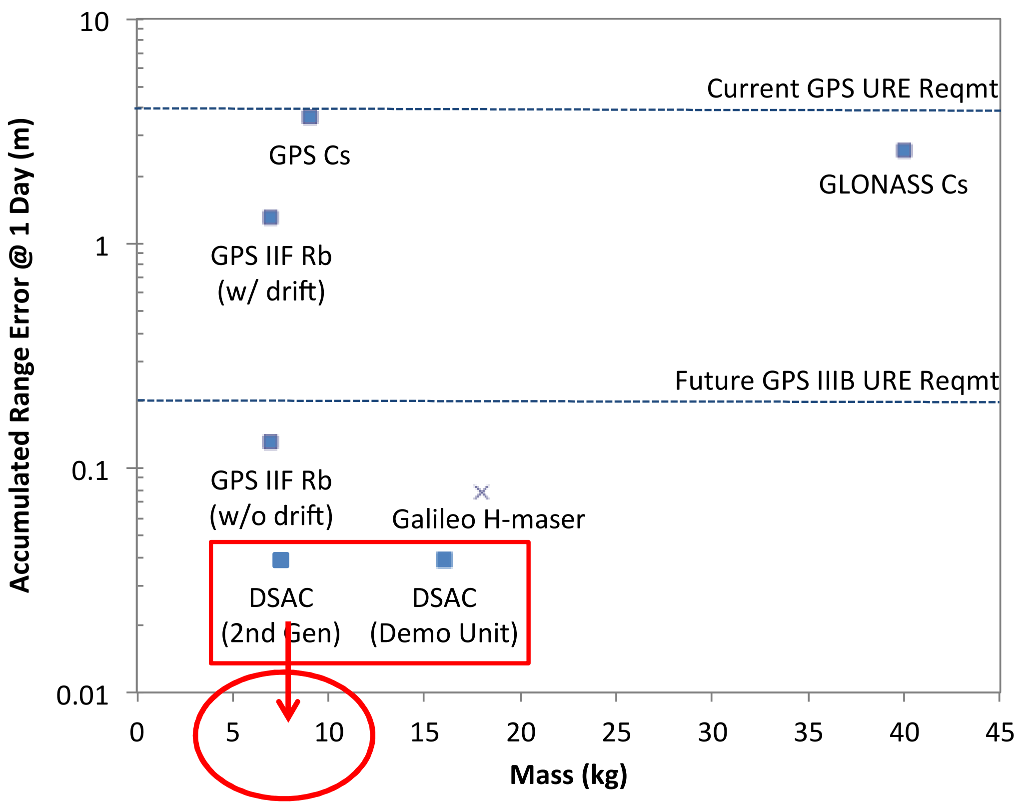
UTC Laboratories

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)



AFS	Average Power
DSAC Demo Unit (1st Generation)	< 50 W <16 kg
DSAC Future Unit (2nd Generation)	< 30 W
GPS IIF Rb (5th Generation)	< 40 W
Galileo H-Maser (2nd Generation)	< 60 W

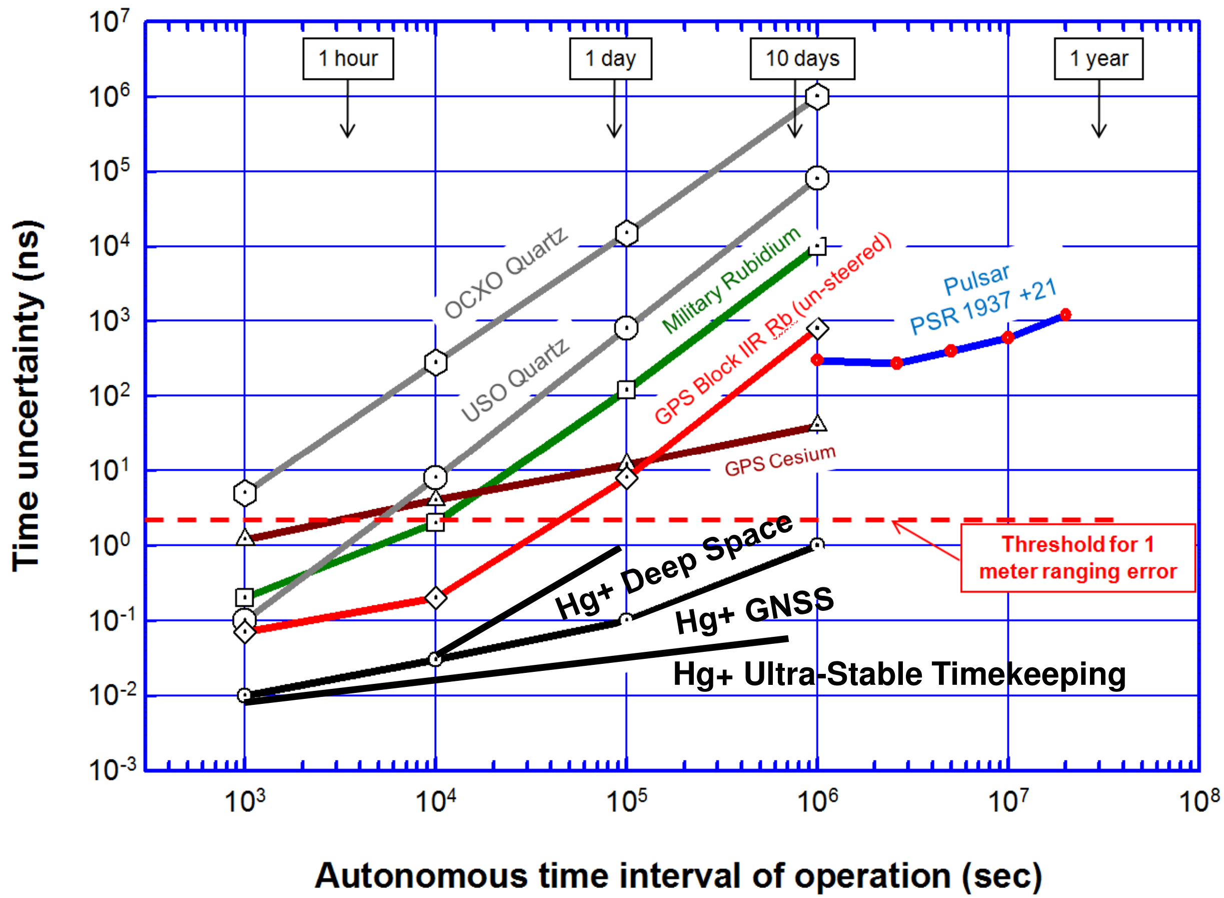
Further ion clock stability already demonstrated on ground if needed in space.

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})**



"A Compensated Linear Ion Trap Mercury Frequency Standard for Ultra-Stable Timekeeping", IEEE Trans of UFFC, 55, No. 12, (2008).

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