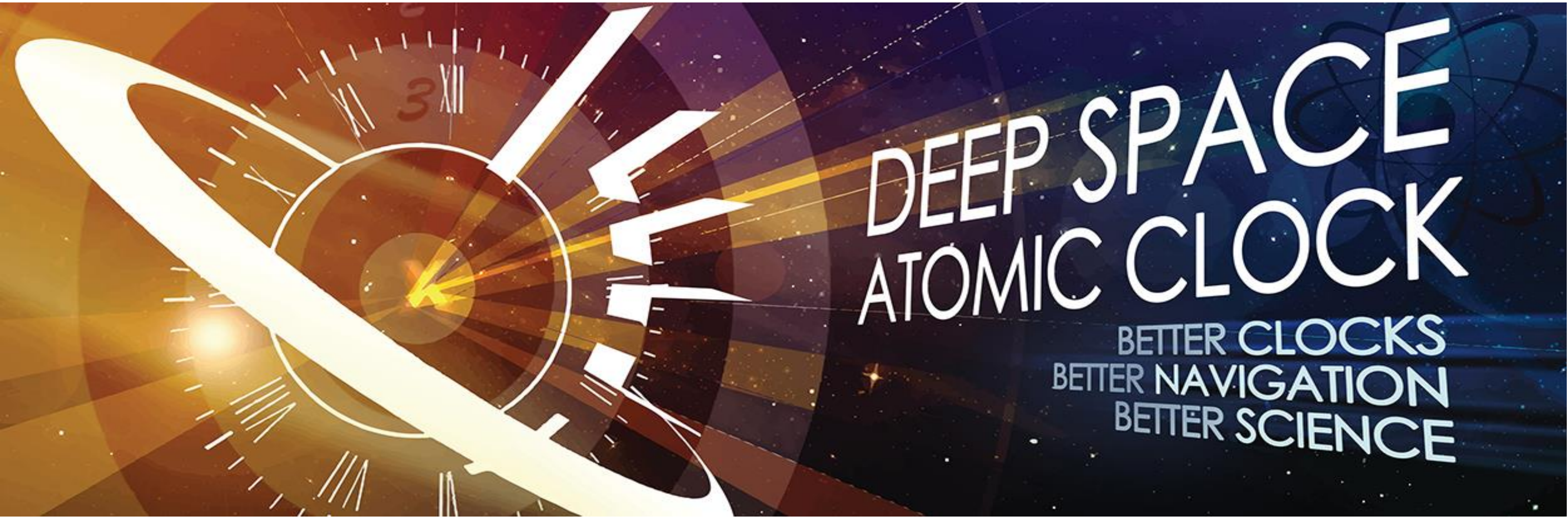


Navigation and Science with the Deep Space Atomic Clock

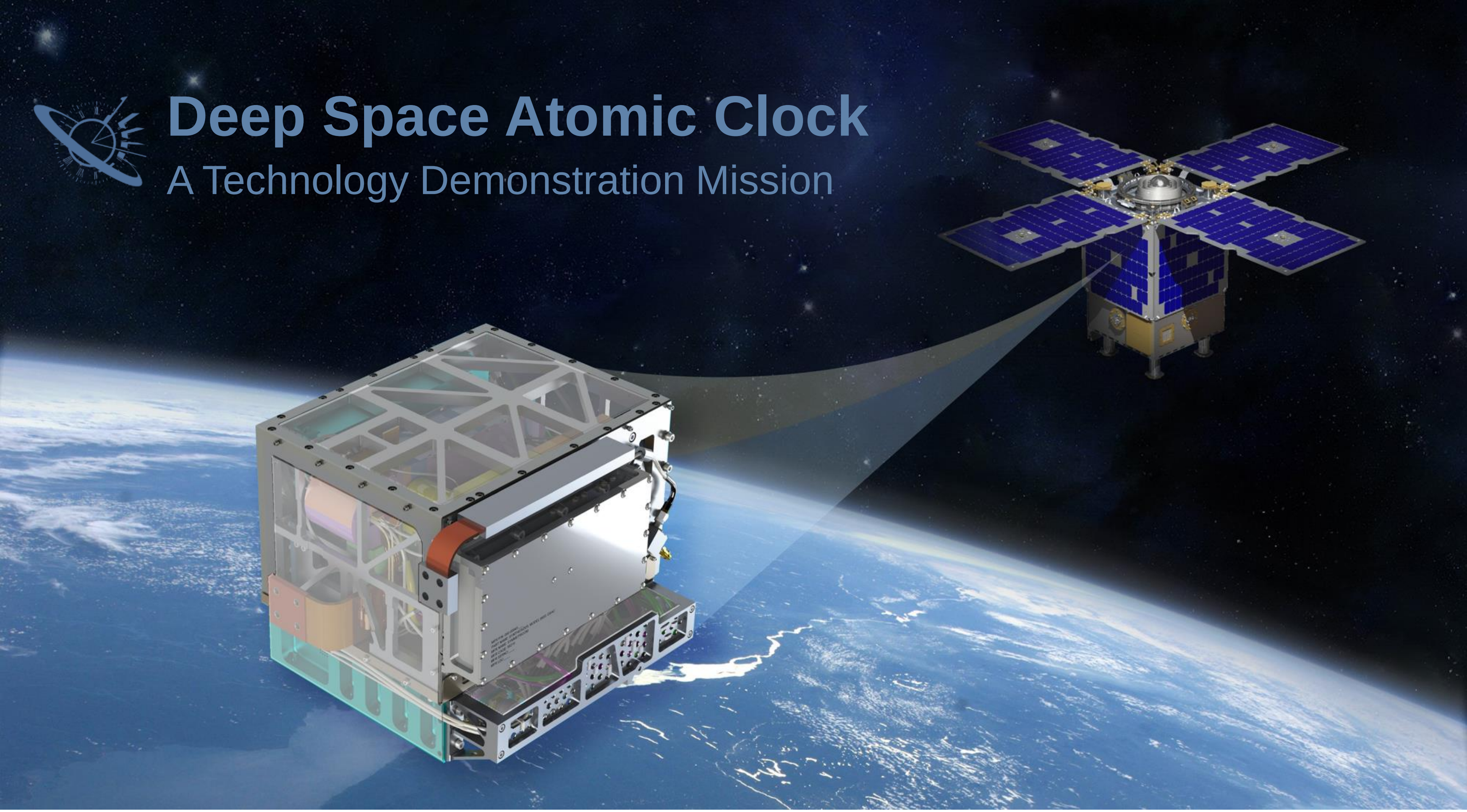
Todd Ely and Eric Burt

July 2017

Jet Propulsion Laboratory
California Institute of Technology

Deep Space Atomic Clock

A Technology Demonstration Mission



NASA

TDM

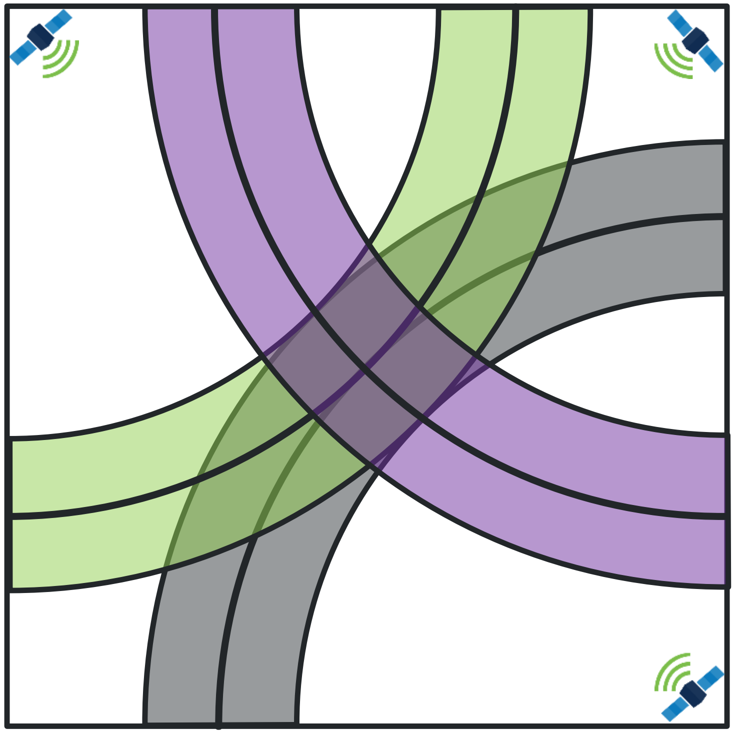
SPACE COMMUNICATIONS SCaN AND NAVIGATION

JPL
Jet Propulsion Laboratory
California Institute of Technology

SURREY
SATELLITE TECHNOLOGY US

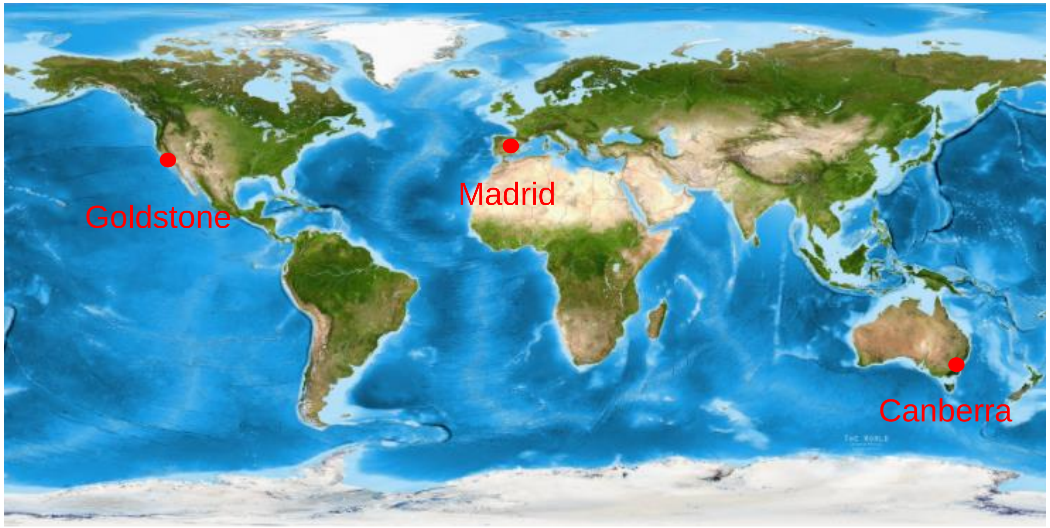
Deep Space Navigation

Deep Space Navigation is not like Localization with GPS: GPS Toy Example with Location and Time in a 2-d 'Flatland'



Deep Space Navigation starts with Observables (Range, Doppler, DDOR) from the Deep Space Network

DSN ground hydrogen maser atomic clock stability ~0.1 nanosecond/day

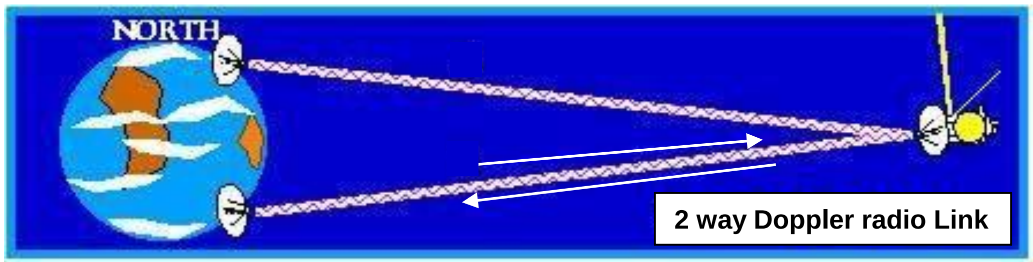


One station in view at all times

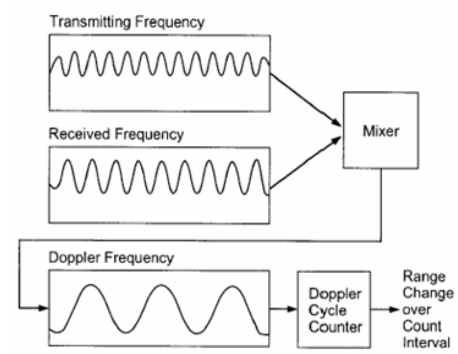
JPL trapped ion atomic clocks for operation in space

Navigation Observables

Station position, end of Doppler Track, 8 hours later



Station position, start of Doppler Track



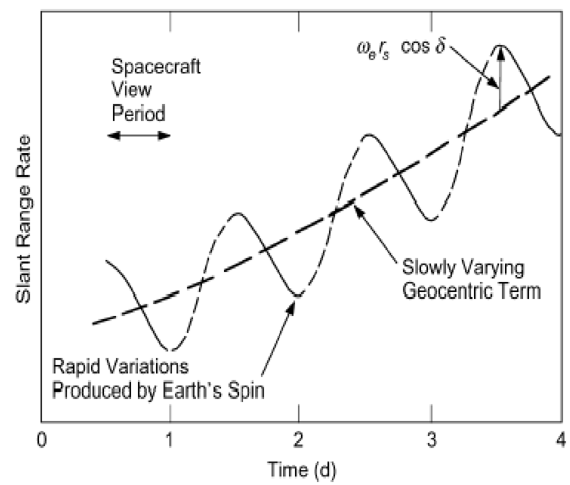
Ranging measurements
~ 1 meter precision

Velocity measurements (Doppler)
0.1 - 0.01 mm/s precision

~ 8 hour Doppler track measures
Angular position to ~ 50 nrad
(Mars angular size ~ *30 μrad*)

Two station VLBI measurements (DDOR)
few nrad precision, eg., 374 m at Mars

1) Motional Considerations



Idealized Doppler observable

Earth's Rotation

$$\frac{\omega r_s}{c} \approx 10^{-6}$$

Earth Orbit

$$\frac{\dot{r}}{c} \approx 10^{-4}$$

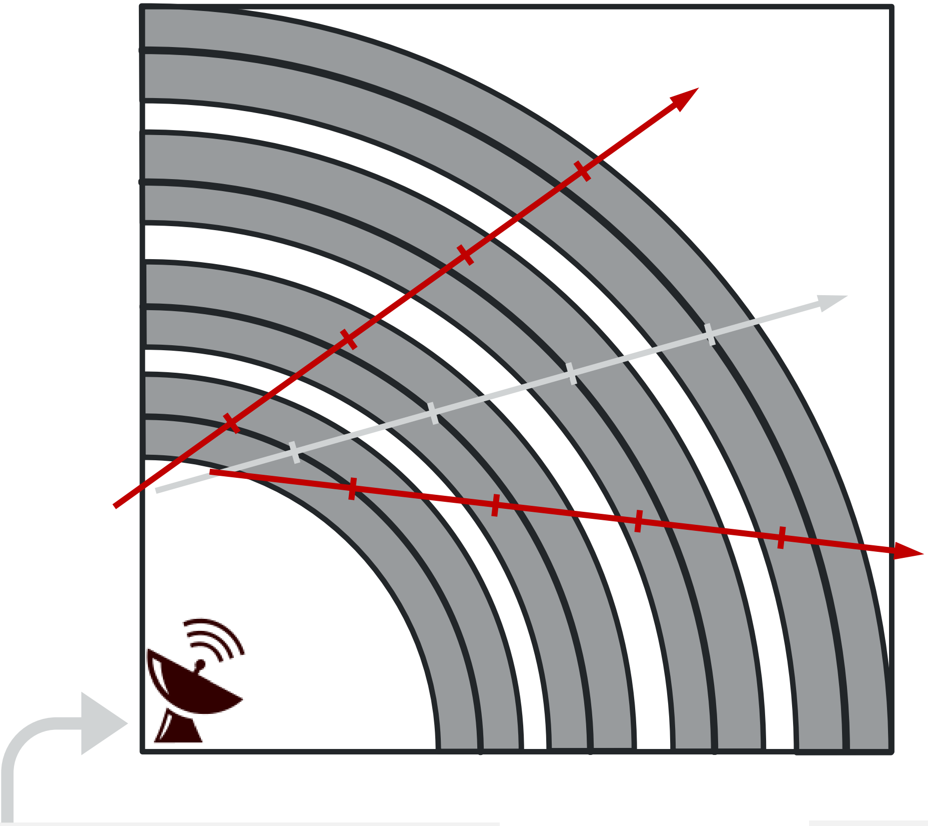
2) Tropospheric Path delays & Link Instabilities

Deep Space Navigation Modelling

- Frame of reference,
- Solar system model,
- F = mA
- Relativity

Fit model predictions to observables to get position, velocity 6-vector

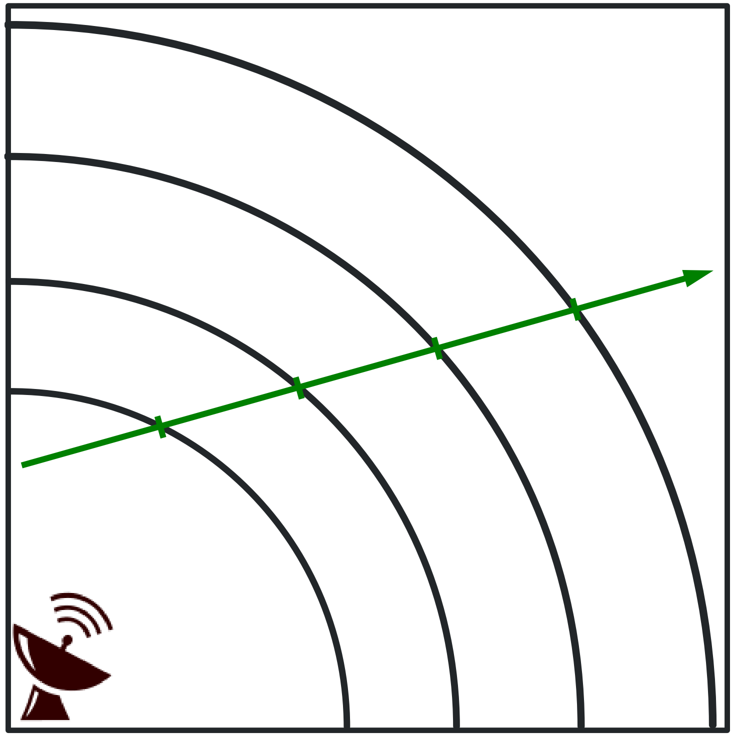
Deep Space Nav using 1-Way Range and a 'Bad' Spacecraft Clock



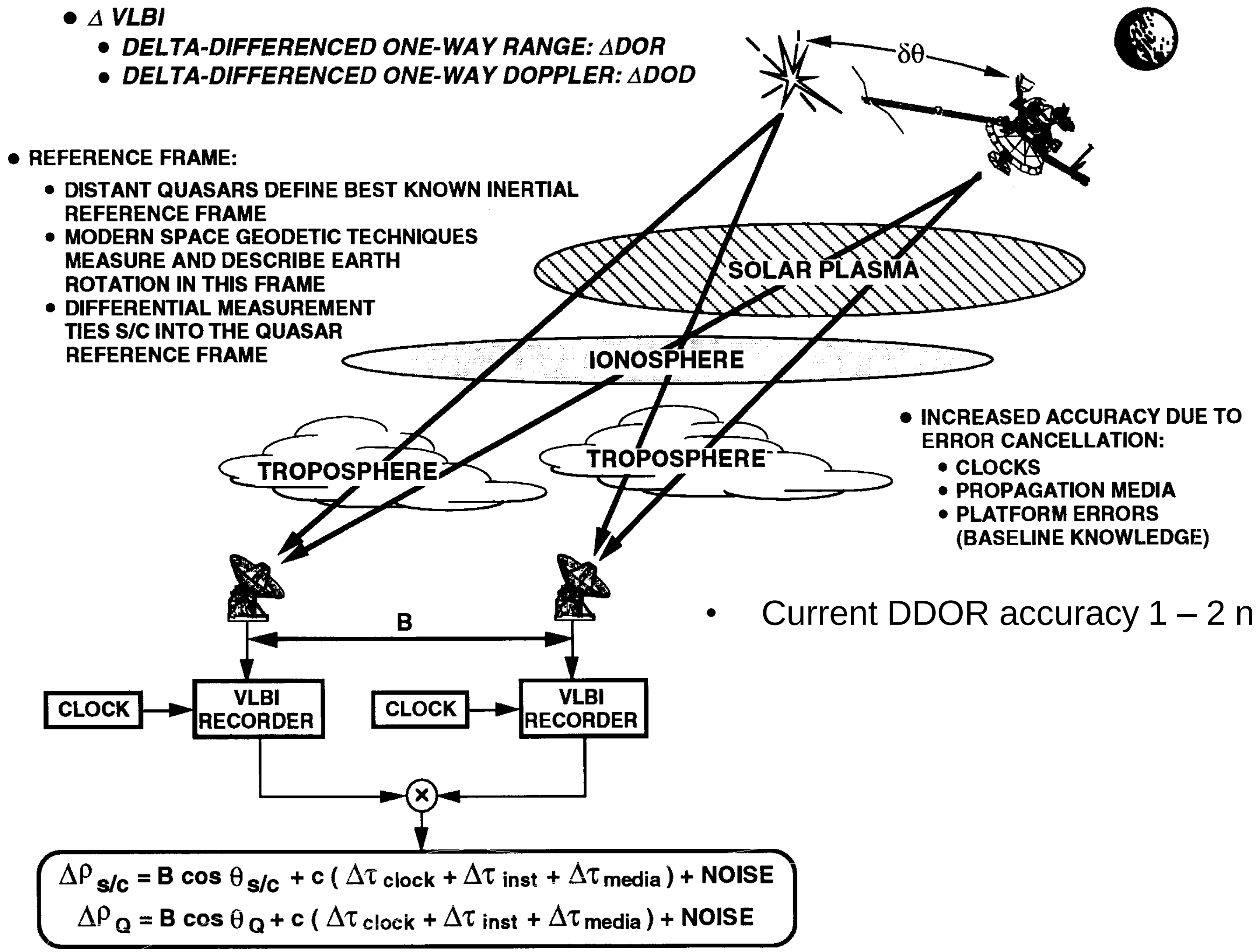
Only one DSN station at a time vs multiple/simultaneous GPS satellites

Model Assumption:
F = **0** → **v** = constant

Deep Space Nav using Either 2-Way Data or 1-Way Data with DSAC



DDOR Provides 'Plane-of-Sky' Information



- Current DDOR accuracy 1 – 2 nrad

NASA Clock Technology Enabling Navigation

NASA/JPL Context: Mercury Trapped Ion Clocks

- **Long life, continuous, high stability operation**
- **Mercury Linear Ion Clock Paths and Applications:**

Ultra stable ion clock

1. Ultra-Stable Performance: UTC timescales

"Compensated" Multi-pole ion clock technologies:

- 10^{-16} at 1 to 10 days, drift ≤ 10^{-17}/day.
- 10^{-15} short term stability (~1 sec) via super LO's.

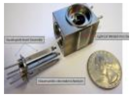
2. Space: DSAC Technology Demonstration Mission (TRL 5-7)

- NASA Deep Space: ~ 20W and 5 kg goal
- GNSS (MAFS) : ~ 1×10^{-13} short term, 10^{-15} at 1 to 10 days
- Science and other apps….

DSAC

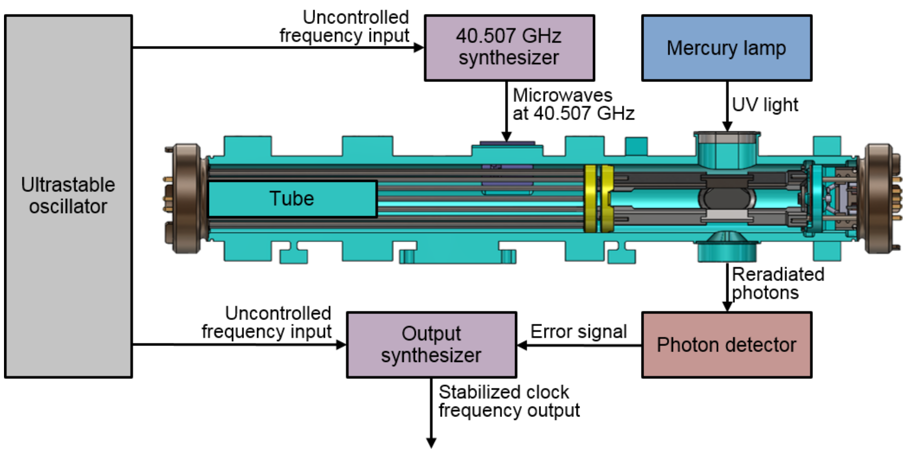
3. Miniature, low power

- cm^3 scale ion trap
- Miniature UV light sources and LO's
- Alternative ions



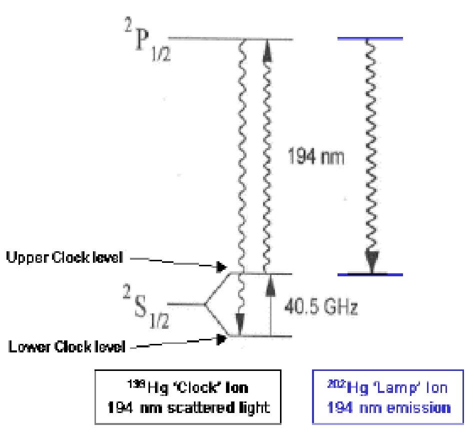
<3 cm^3

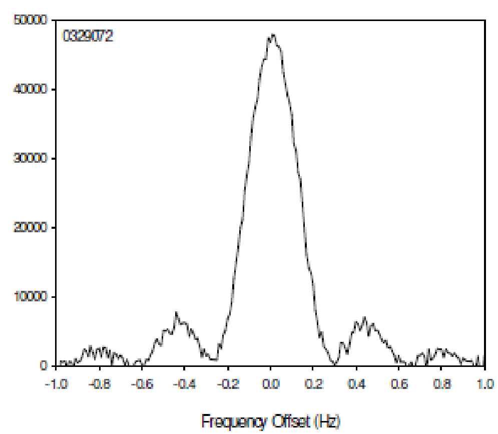
NASA/JPL Trapped Ion Technology & Operation



- Ions moved between quadrupole and multipole traps.
- State selection via optical pumping.
- No wall collisions, high Q microwave line.
- Clock transition: 40.507,347,9968 GHz
- No lasers, cryogenics, or microwave cavity.
- No light shift as opposed to gas cells used in GPS.
- Radiation tolerance similar to GPS Rb clocks

Ion trapping, state selection, & measurement of the clock transition

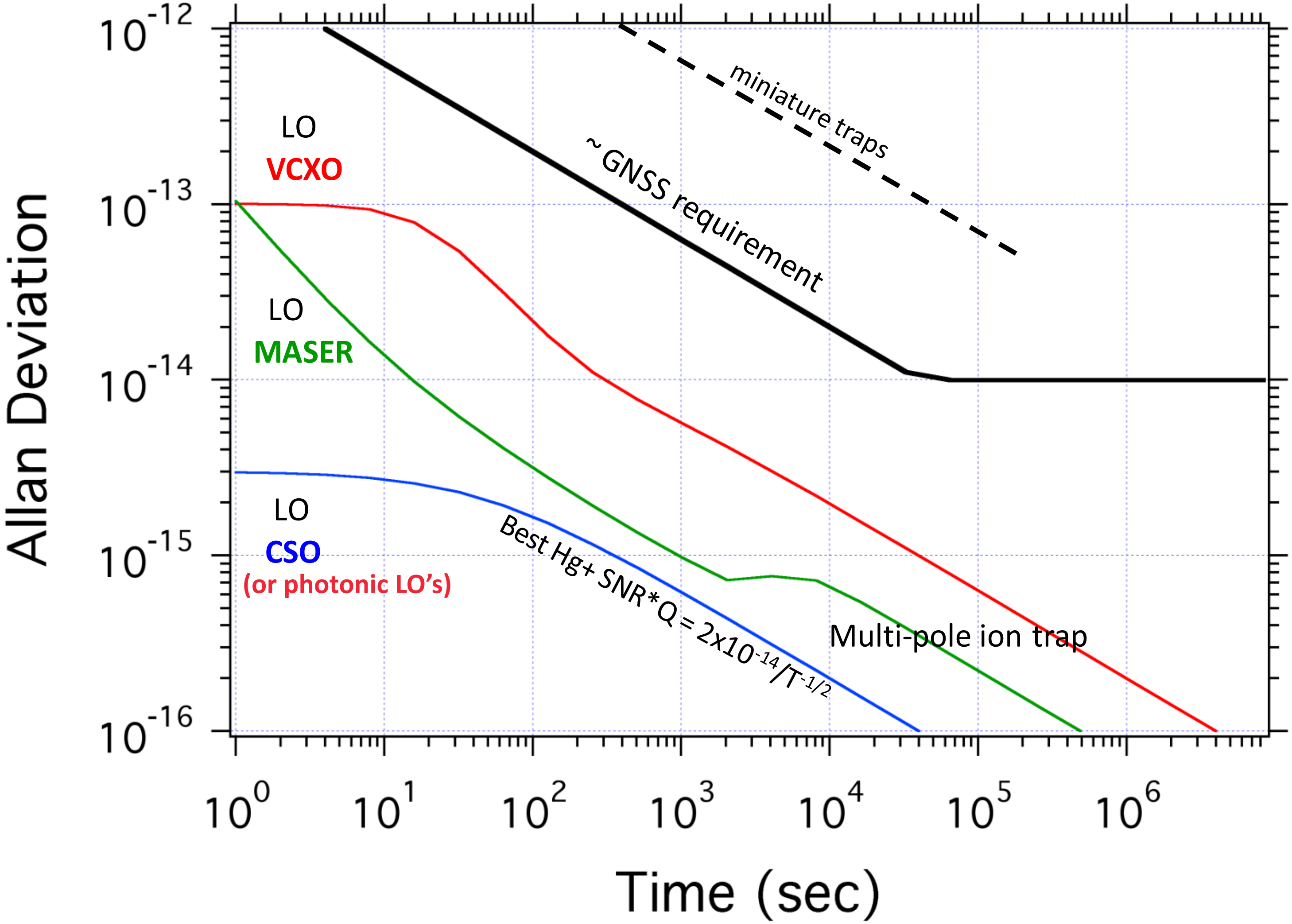




$$SNR \times Q < 3\times10^{-13}/\sqrt{\tau}$$

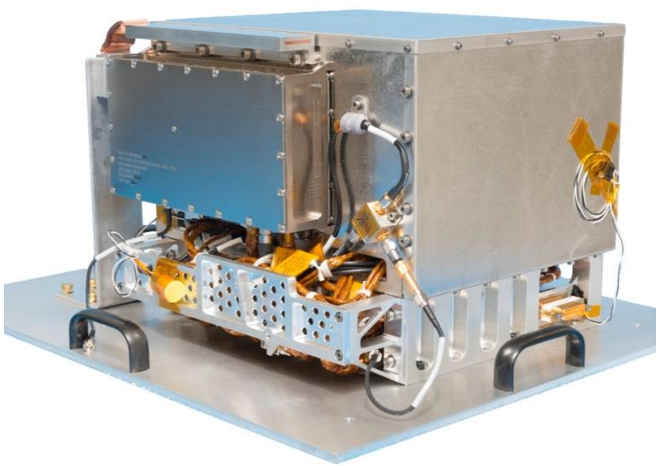
$$Adev < 3\times10^{-15}$$

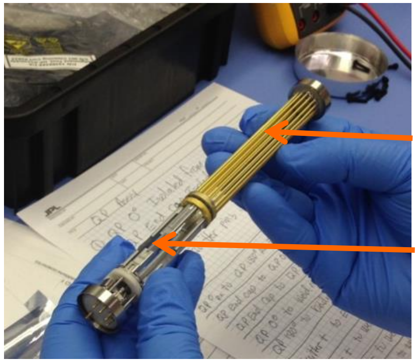
Hg+ Standards with various Local Oscillators



The DSAC Technology Demonstration Mission

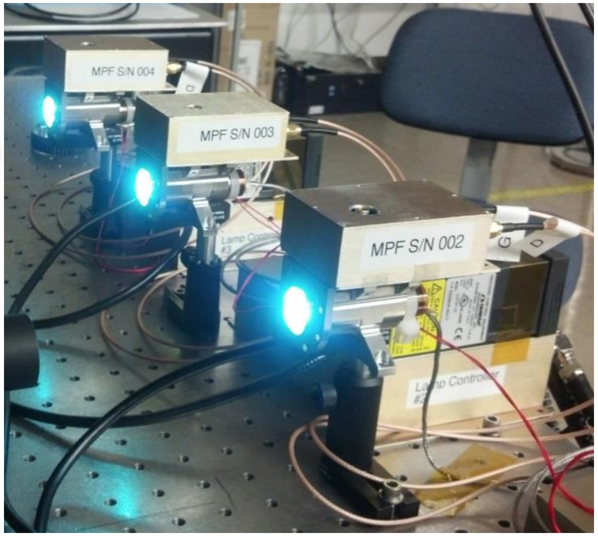
DSAC Demonstration Unit





Titanium Vacuum Tube

Mercury UV Lamp Testing

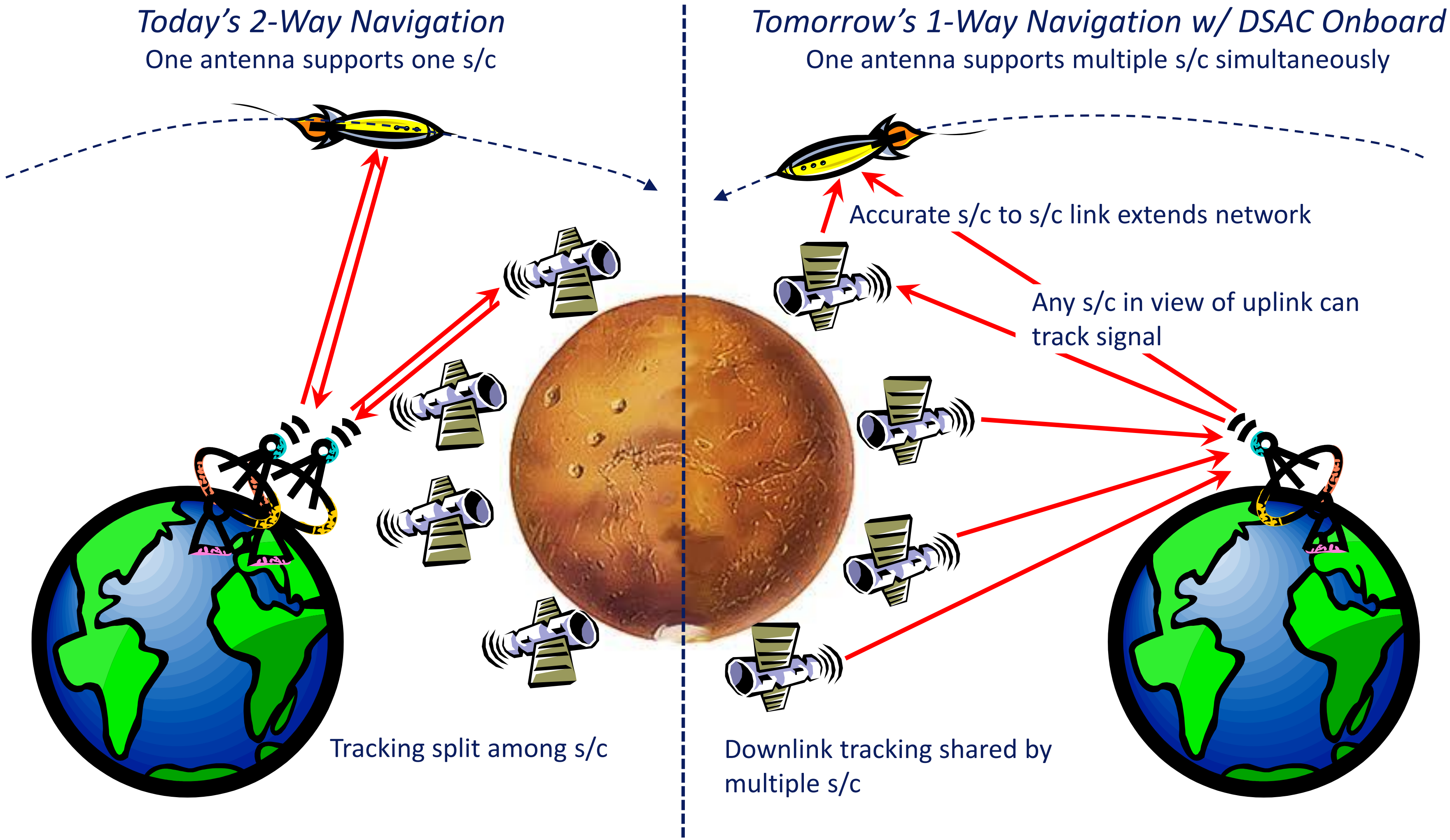


Develop advanced prototype mercury-ion atomic clock for operation in space

- Year-long demonstration in space beginning Dec 2017+ – advancing to TRL 7
- Mature the new technology
  - Ion trap and optical systems
  - SWaP
- Identify pathways for future operational units (TRL 7 → 9)

DSAC Enables a Scalable DSN Tracking Architecture

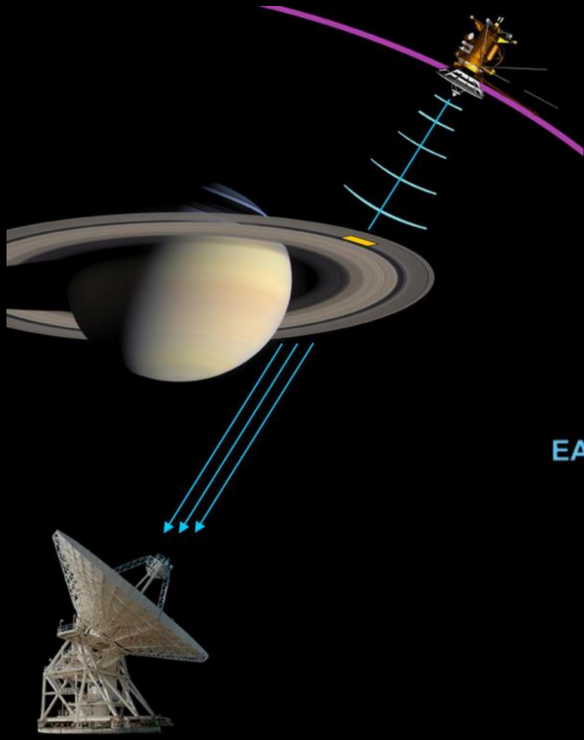
DSN antennas: send/receive to one SC vs. send to multiple SC

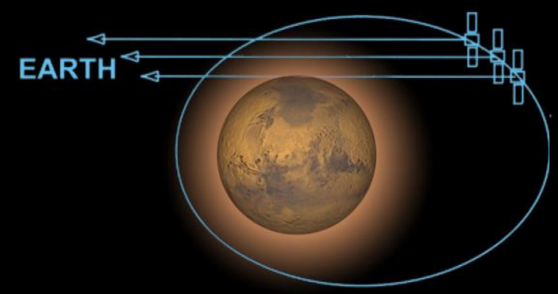


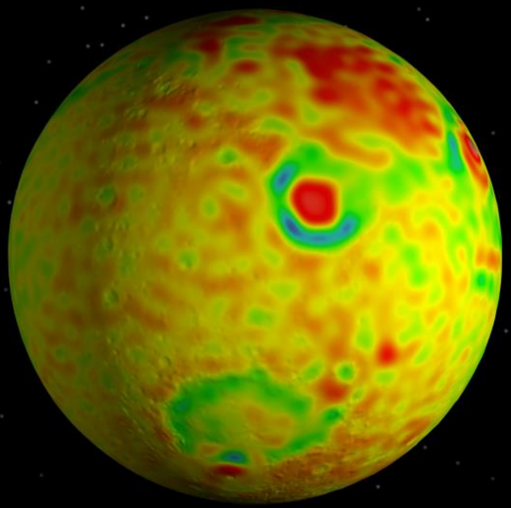
Advantages of a DSAC clock in space

Occultation Science

DSAC + Ka-band crosslink/downlink = up to 100X precision & 2X tracking



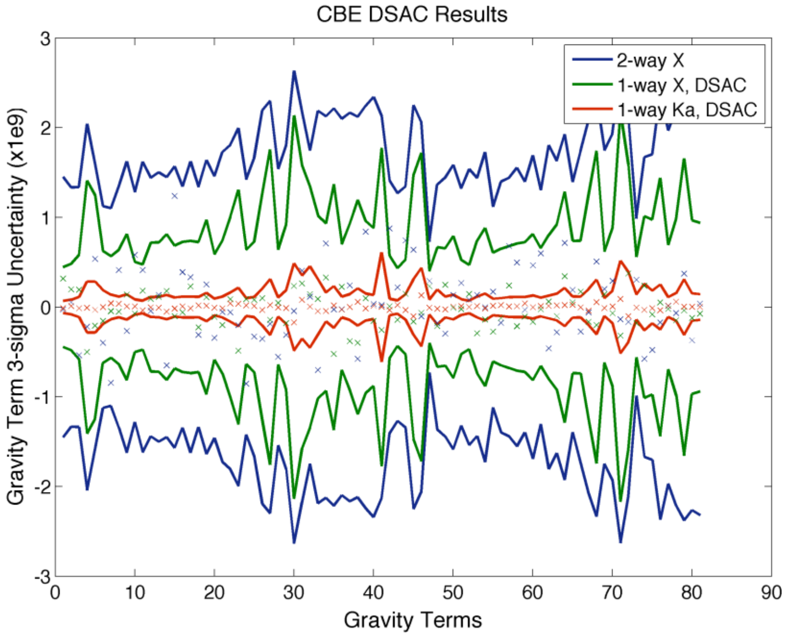




Example: Mars Orbiter Gravity Field Estimation

- **Low altitude mars orbiter with:**
  - DSAC clock on board using 1-way nav.
  - Ka-band tracking
  - Multiple Spacecraft Per Aperture (MSPA)
  - gravity science info increases at 12 x rate (relative to 2-Way X-band)
  - approaches GRACE quality with a *single* orbiter.

- **DSAC's long-term frequency characteristics well suited for gravity experiments to measure:**
  - Long wavelength gravity variations
  - Mars orientation parameters
    - seasonal rotation
    - precession
  - Mars tide (k_2)
  - Polar Motion
  - Temporal gravity to determine seasonal ice-cap seasonal mass exchange

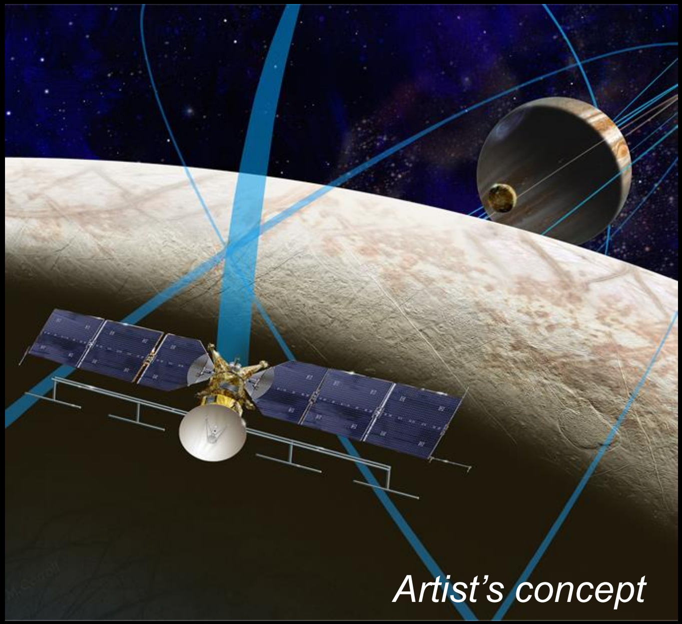


Average overall improvement of DSAC enabled 1-Way solution over 2-way:

- X-band: 2x (MSPA and/or uplink tracking)
- Ka-band: 12x (MSPA and 10x better data)

Increased Time for Science Observations…

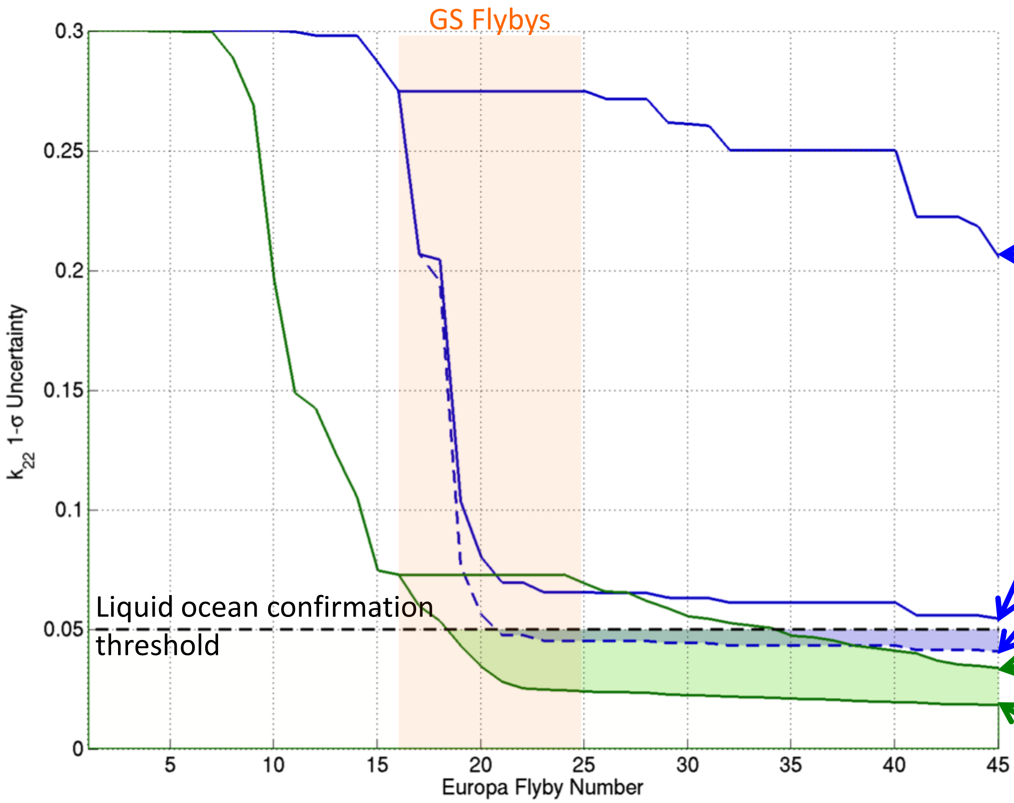
DSAC + Uplink/LGA + Radio =
Agile 'Attitude Free' Nav & Science


Artist's concept


Artist's concept

- DSAC enables 1-way uplink
- Receive only => low gain antenna (LGA) sufficient
- LGA's have wide aperture => work no matter what SC orientation
- Don't have to waste fly-by's on orientation to accommodate downlink

Example: Low-SNR, Attitude Free Tracking Enables Efficient Europa Gravitational Tide Recovery



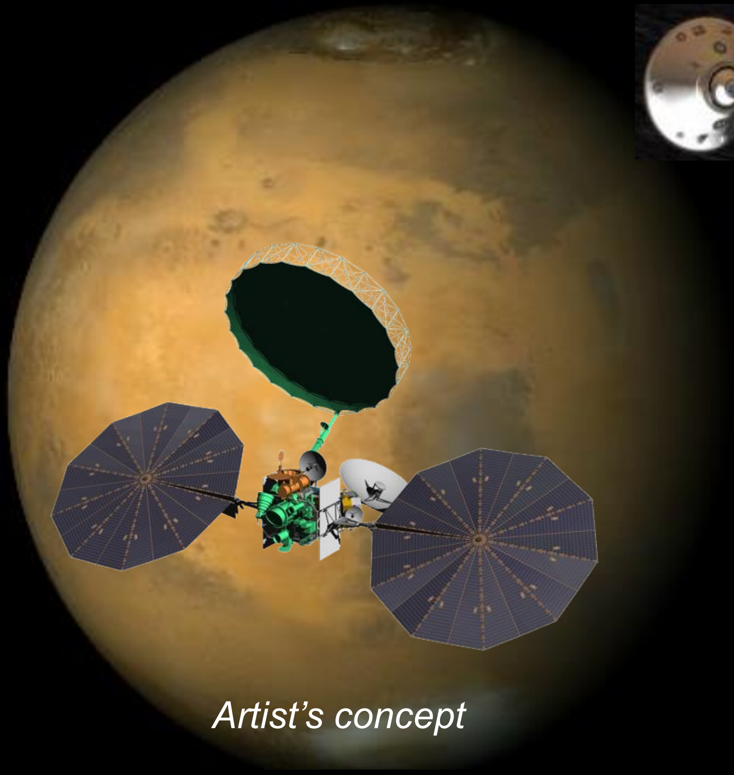
Solutions obtained using solar powered spacecraft configuration with current trajectory (as of June 2015) with following results:

- 2-Way, DSN, No GS Flybys
  ✗ No confirmation
- 2-Way, DSN, All GS Flybys
  ✗ No confirmation
- 2-Way, DSN+ESA, All GS Flybys
  ✓ Confirmed, no flyby margin
- 1-Way w/ DSAC, DSN, No GS Flybys
  ✓ Confirmed w/ flyby margin
- 1-Way w/ DSAC, DSN, All GS Flybys
  ✓ Confirmed w/ flyby margin

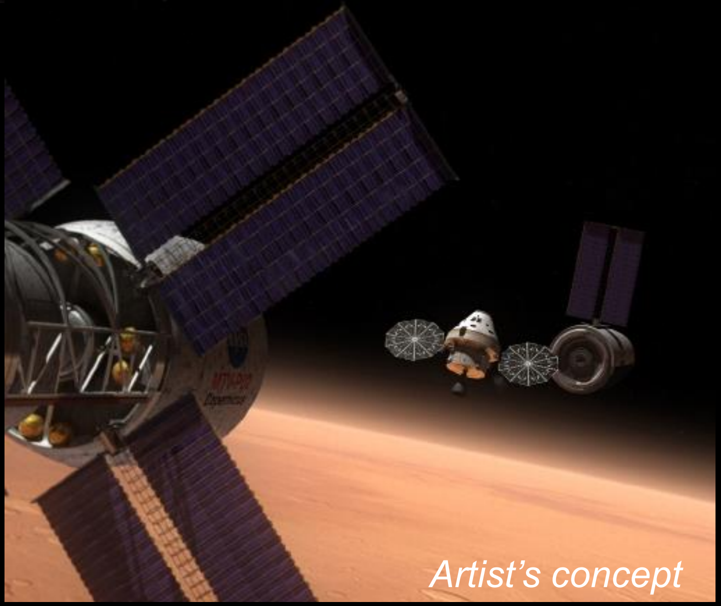
1-Way with DSAC using low gain antennas yields solutions with margin with or without GS

Precision landing and real-time navigation

DSAC + uplink/LGA + radio + nav computer =
robust on-board nav



Artist's concept

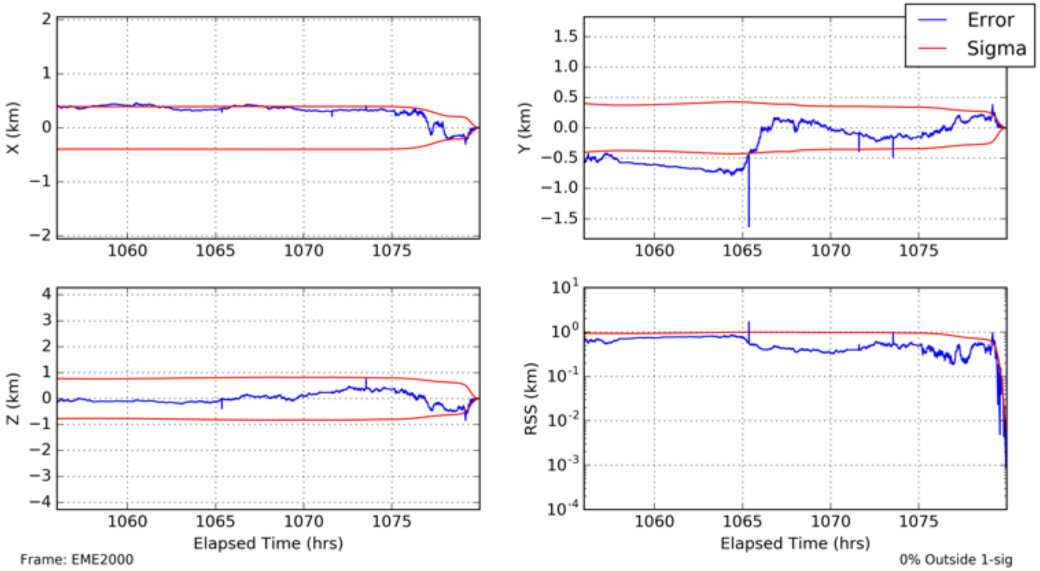


Artist's concept

Next Generation of Autonomous Navigation

Demonstration on next Mars orbiter of DSAC with tracking by LGAs, optical, and on-board navigation would yield:

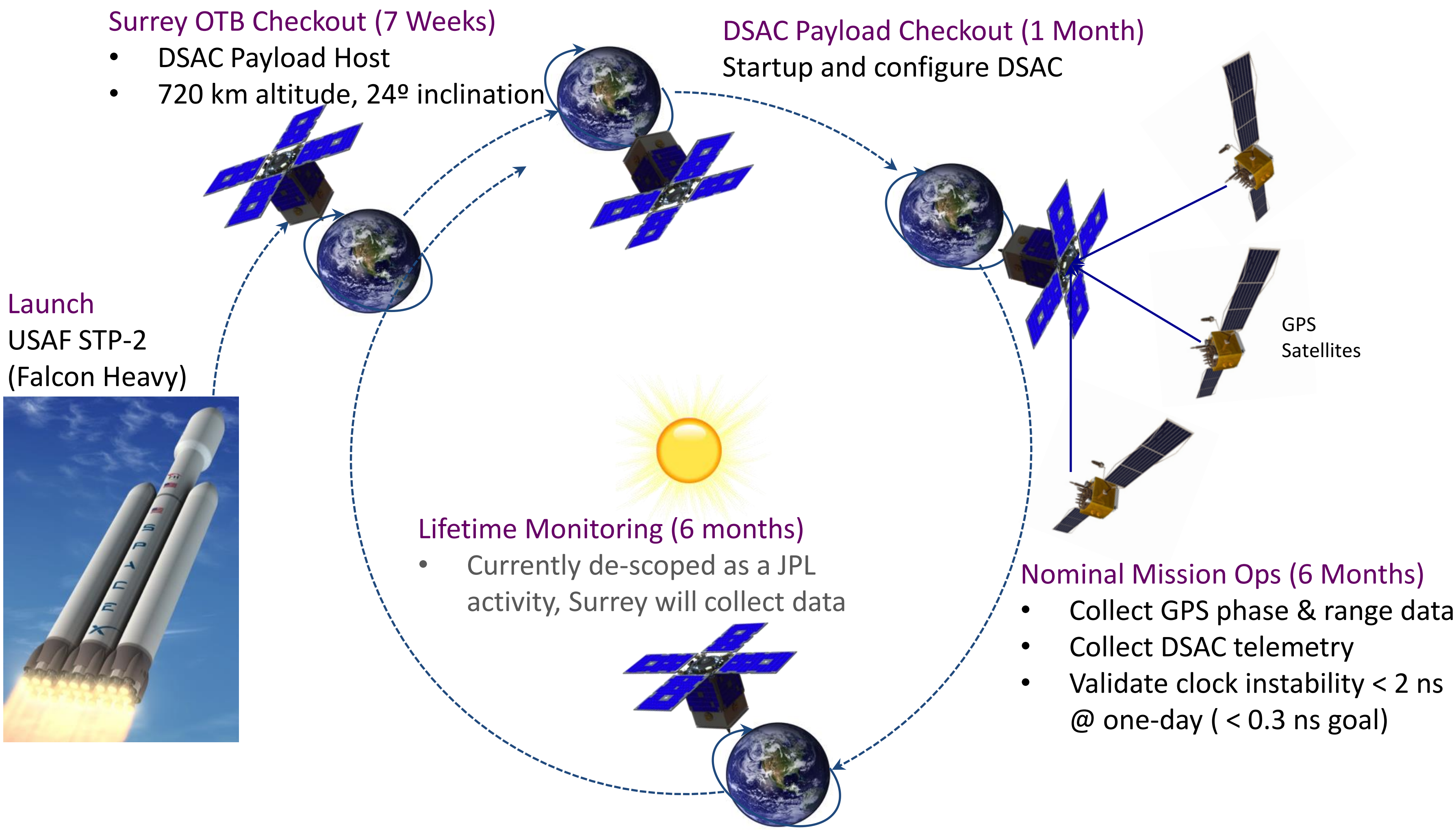
- *Real-time nav:*
  - Near continuous navigation data using an ever-present uplink signal from the Earth to Mars – One-way broadcast system (like GPS) at Mars
- *Autonomous nav:*
  - Proof of concept demonstration robust, fault tolerant autonomous navigation processing of optical and one-way uplink data during Mars approach and SEP spiraling into a low Mars orbit
  - Potential to significantly offload ground operations support
  - Pathfinder that retires significant risk for future human exploration
- *Added value:*
  - Once there DSAC adds value to Mars exploration with enhanced radio science, geo-tagging for science observations, and improved navigation



Approach nav simulation using one-way uplink tracking and optical tracking for an Insight-like trajectory in the last 24 hours prior to entry

The DSAC TDM

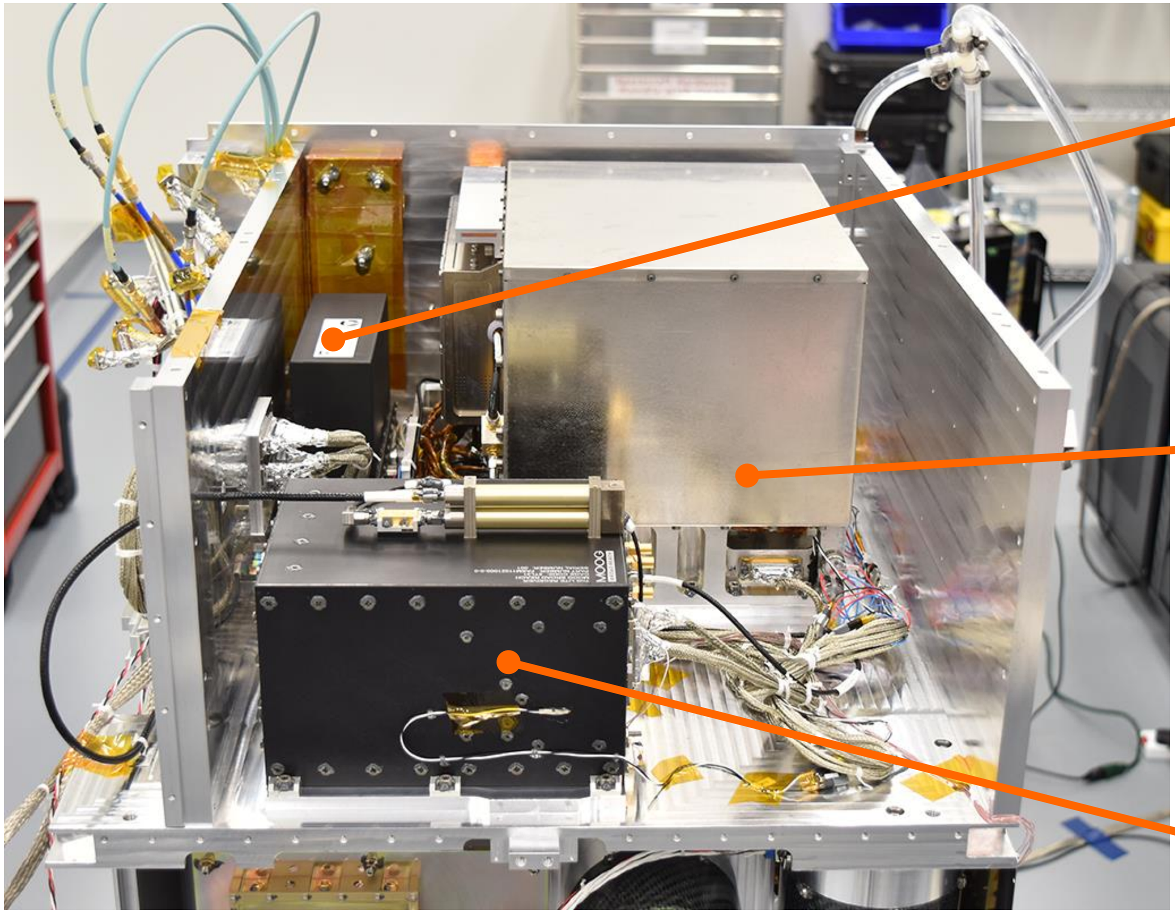
DSAC Mission Architecture and Timeline



DSAC integrated with OTB. Launch Dec 2017+ for one-year demonstration

DSAC Payload Integrated on Orbital Test Bed Spacecraft

- passed payload vibe and enviornmental testing
- awaiting launch!



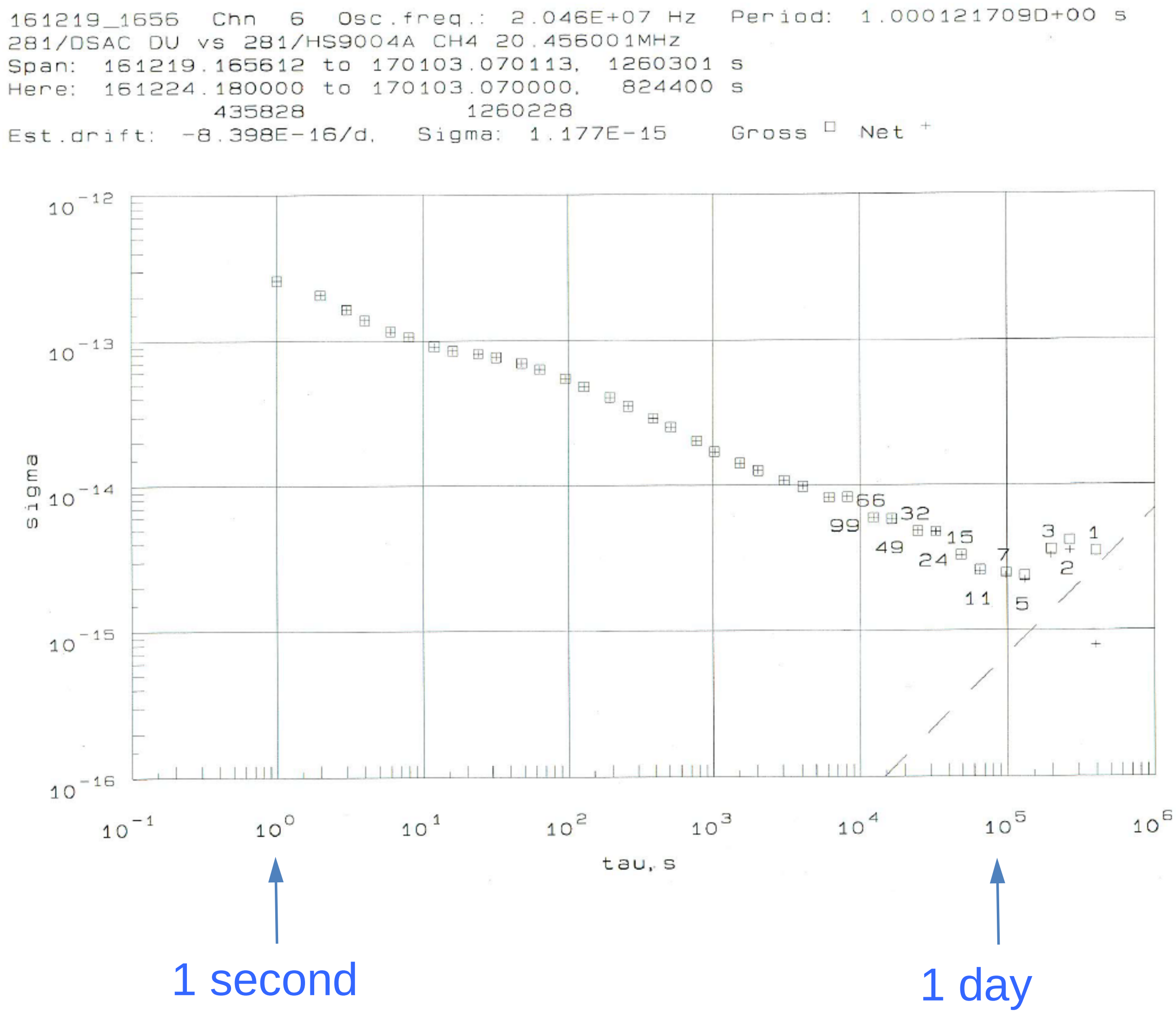
Ultra-Stable Oscillator (USO)
Local Oscillator (FEI)

DSAC Demo Unit (DU)
Atomic Resonator (JPL)
V: 285 x 265 x 228 mm
M: 16 kg, Physics Pkg – 6.6 kg
P: 45 W, Physics Pkg – 17 W

GPS Receiver
Validation System (JPL-Moog)

Demo Unit designed for prototyping flexibility – pathways to < 10kg and < 30 W possible for operational version

Demo Unit Ground-Based Measured Stability



- Results show DU with Maser input at constant temperature operating in QP-only mode
- DU/USO configuration tested with similar results (some transients present due to post-vibe testing effects)
- Stability ~ 3e-15 @ 1-day

DSAC TDM Summary

New clock technology

- First demonstration of trapped ion clock technology in space
- unprecedented performance, low SWaP mercury ion atomic clock in the low Earth orbit
    - Expected Allan Deviation < 3.e-15 at 1 day with no drift removal
    - Similar to DSN ground clock performance and better than any existing space clocks

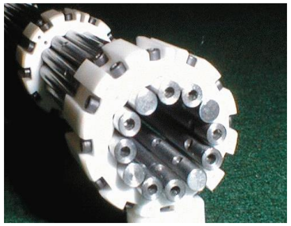
Candidate nav applications enabled by DSAC

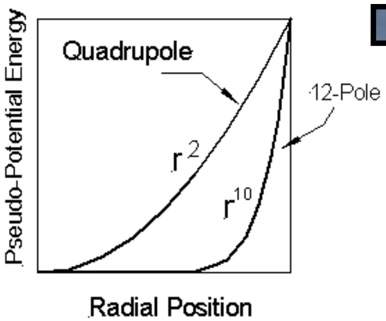
- high-quality one-way signals for deep space navigation and radio science can
    - Enhanced occultation science
- Reduced dependence on HGA's
    - Attitude free science data streams - Improve data quantity and quality
- Real time precision nav
    - Enhance tracking architecture flexibility and robustness
    - Enable fully-autonomous onboard absolute radio navigation

NASA trapped ion clock technology in support of ACES

LITS-9: Single clock representation of UTC

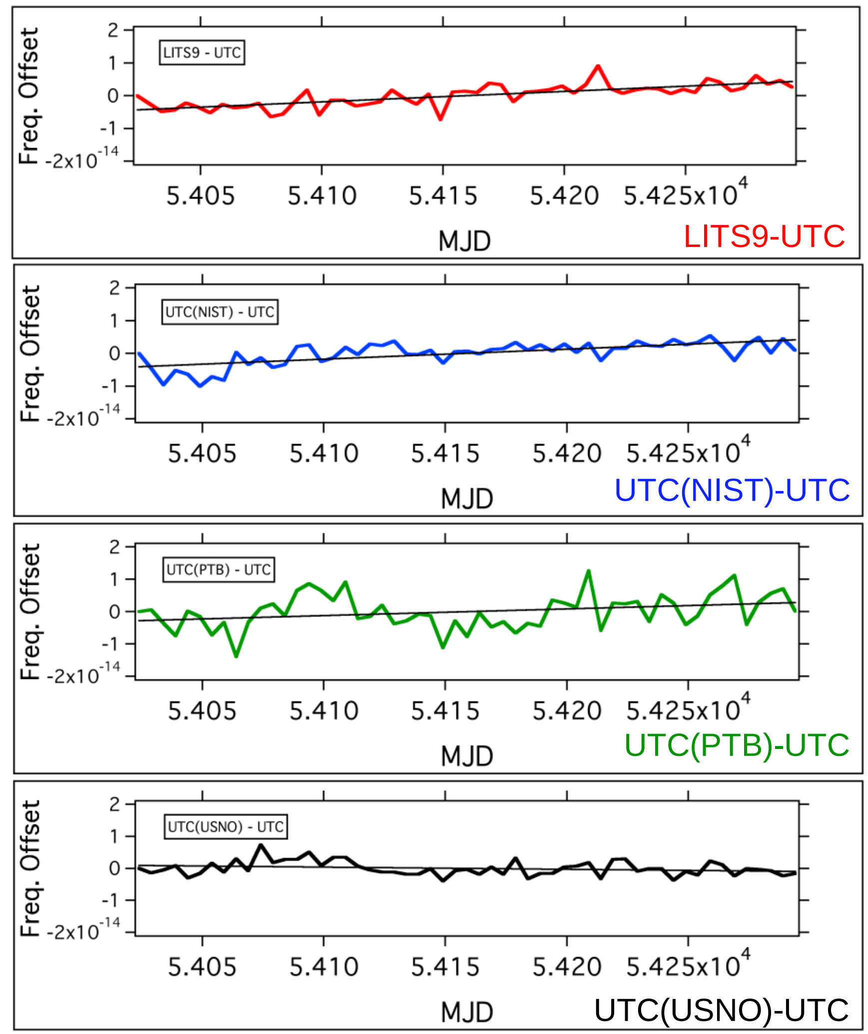
*E.A. Burt, W.A. Diener and R.L. Tjoelker, IEEE TUFFC **55**, 2586 (2008).*





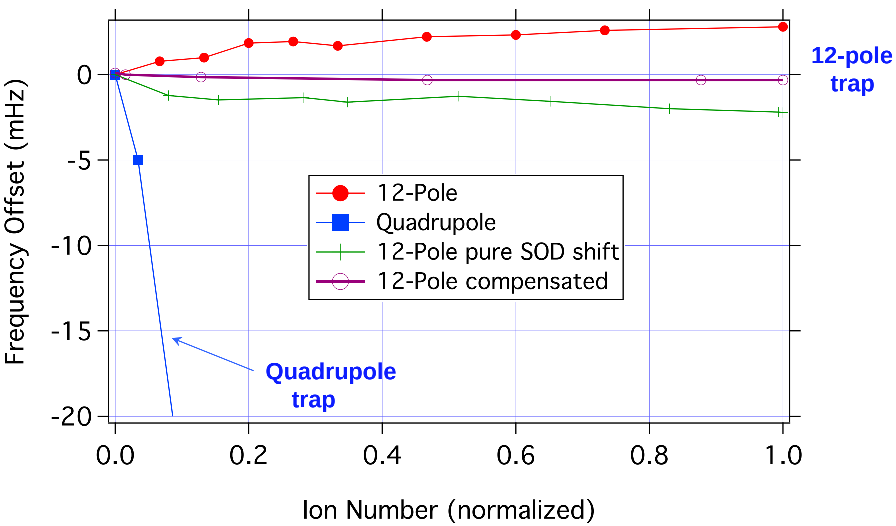
LITS-9

2.7 x 10^{-17}/day vs. TT(BIPM)



Magnetic Compensation of residual Doppler

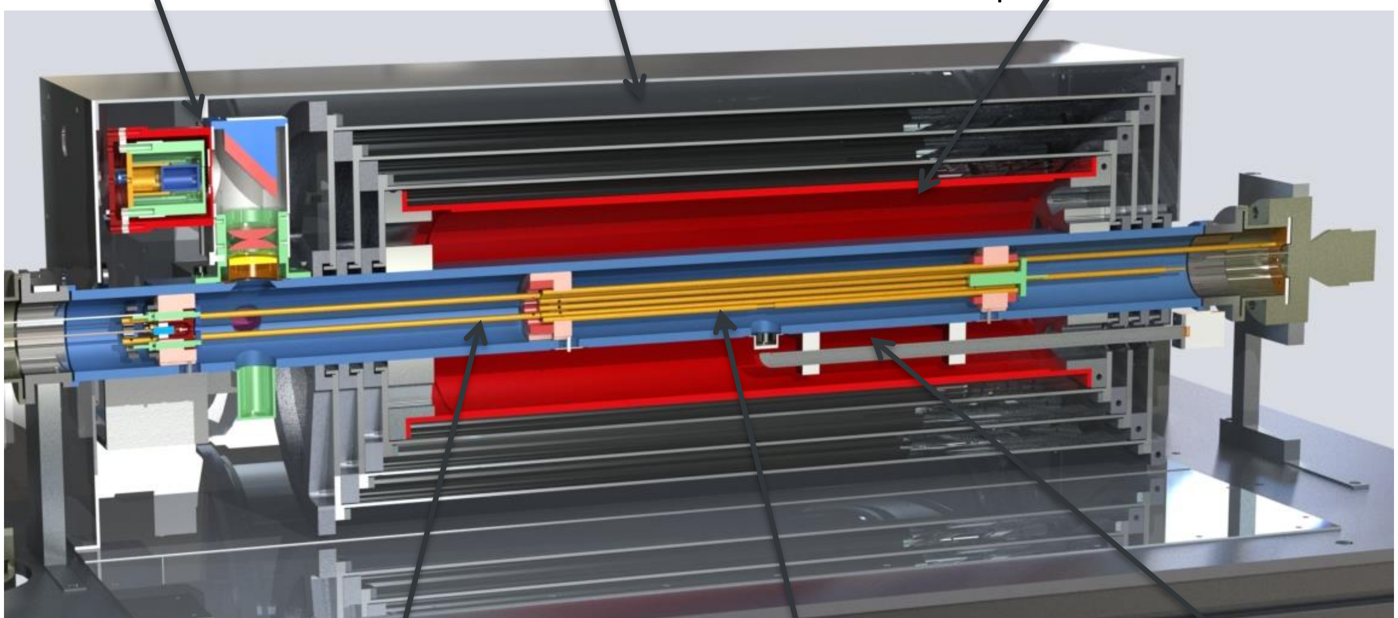
Sensitivity to ion number changes < 5E-17



Ultra-stable ion clock development

E.A. Burt, L. Yi., B. Tucker, R. Hamell, and R.L. Tjoelker;
"JPL Ultra-Stable Trapped Ion Atomic Frequency Standards"; accepted for special issue IEEE TUFFC (2016).

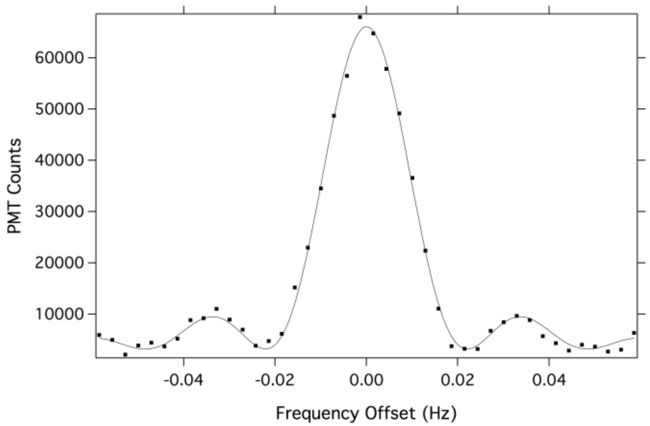
Fundamental shifts on the 40.5 GHz hyperfine transition in ^{199}Hg+	***sensitivity minimized via***
1. *Magnetic Shifts*	*choice of ion*
2. *Doppler Shifts (Thermal and Motional Doppler effects)*	*compensated multipole linear ion traps*
3. *Collision Shifts (residual gases)*	*high bakeout UHV approach*



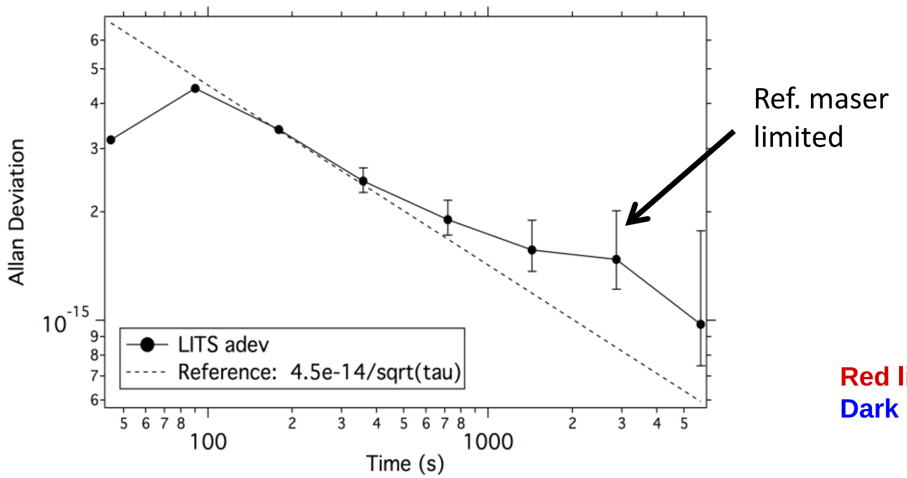
Ultra-stable ion clock performance

High Q operation with maser LO

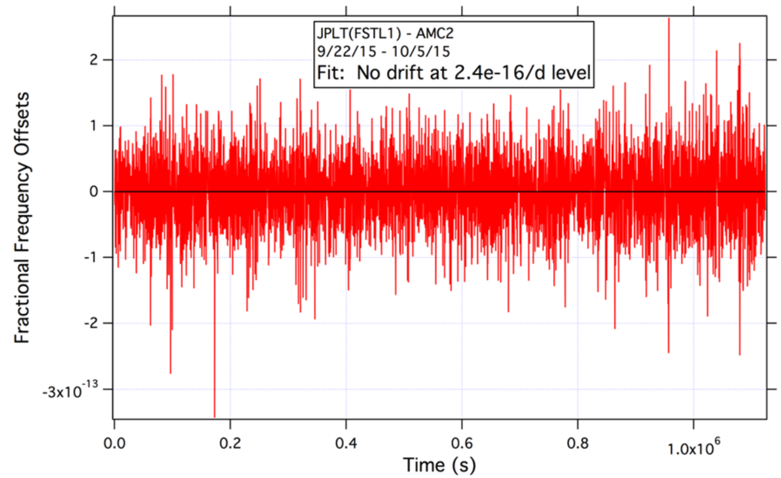
Local Characterizations vs H-maser

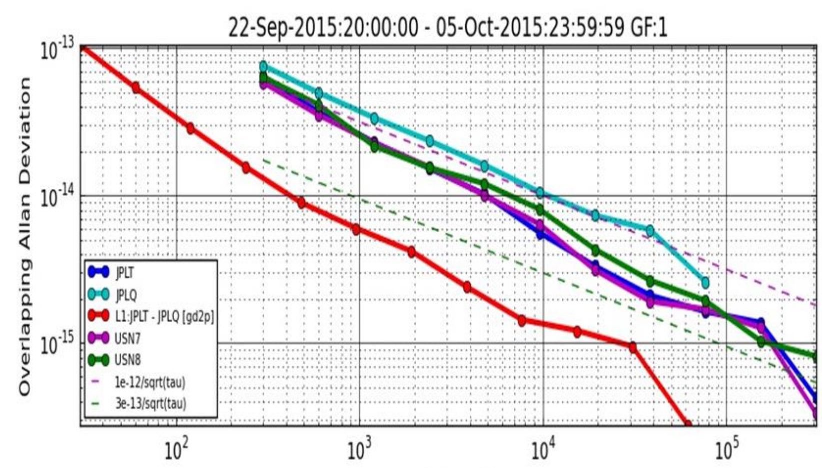


- **40 second Rabi Interrogation**
- **Q ~ 1.6E+12**
- **SNR*Q ~ 4.5E-14/sqrt(tau)**



GPS TT characterizations vs UTC

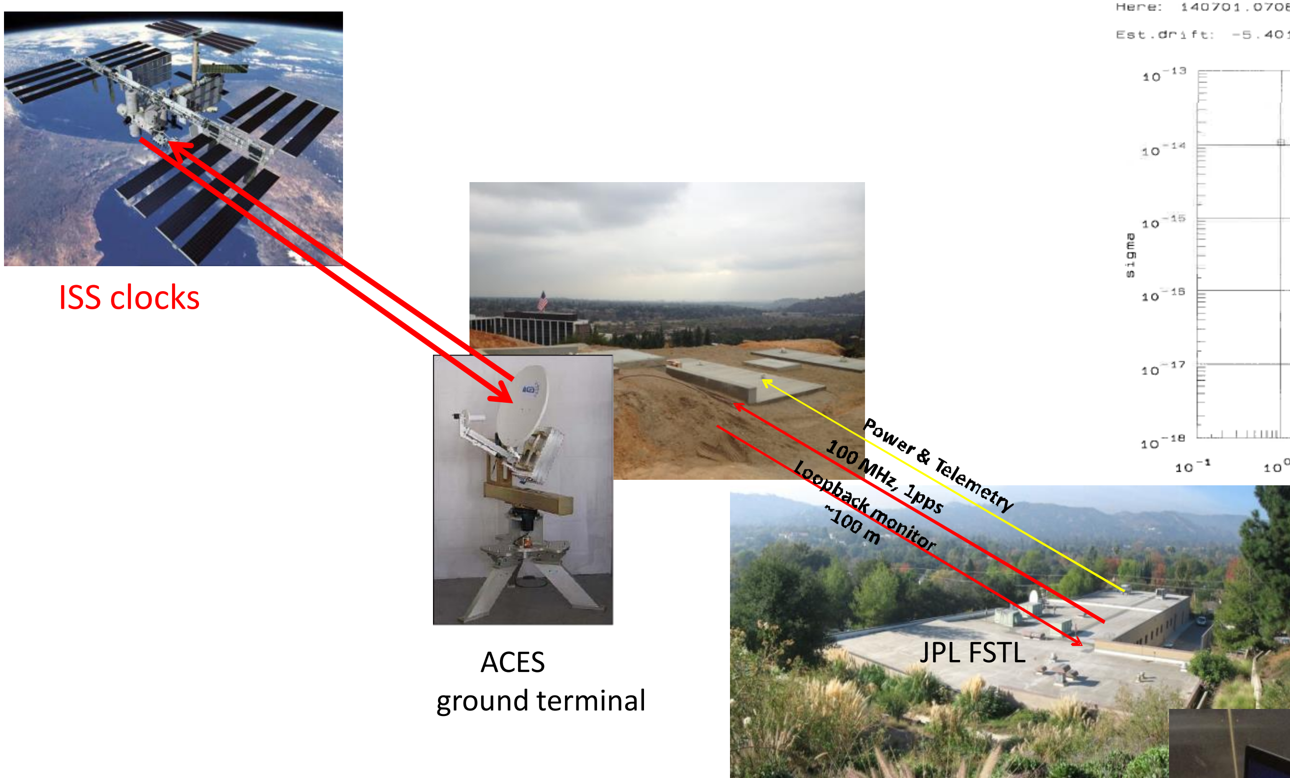


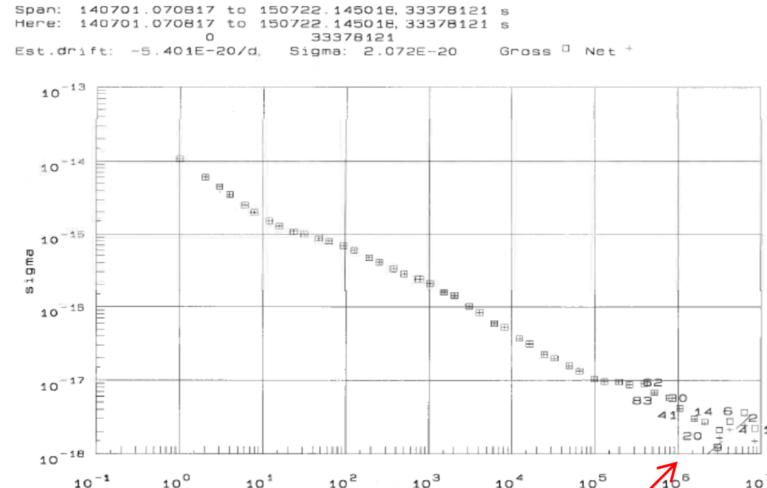


Red line: GPS TT zero baseline floor between two rcvrs, common reference.

Dark Blue: FSTL Hg1/SAO reference vs USNO AMC2 (i.e. GPS time)
$<10^5$ s dominated by GPS time transfer noise.
$>10^5$ s representative of the Hg standard stability over 14 day interval.

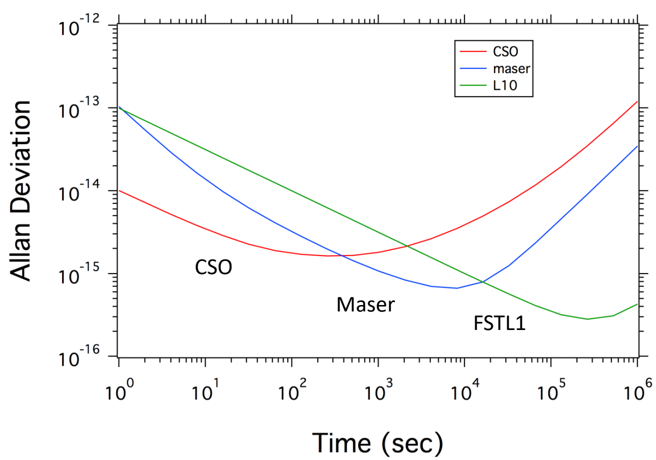
Atomic Clock Ensemble in Space Mission (ACES)- JPL reference

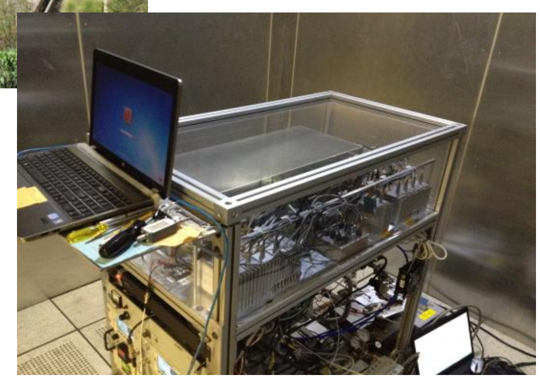




JPL link noise:

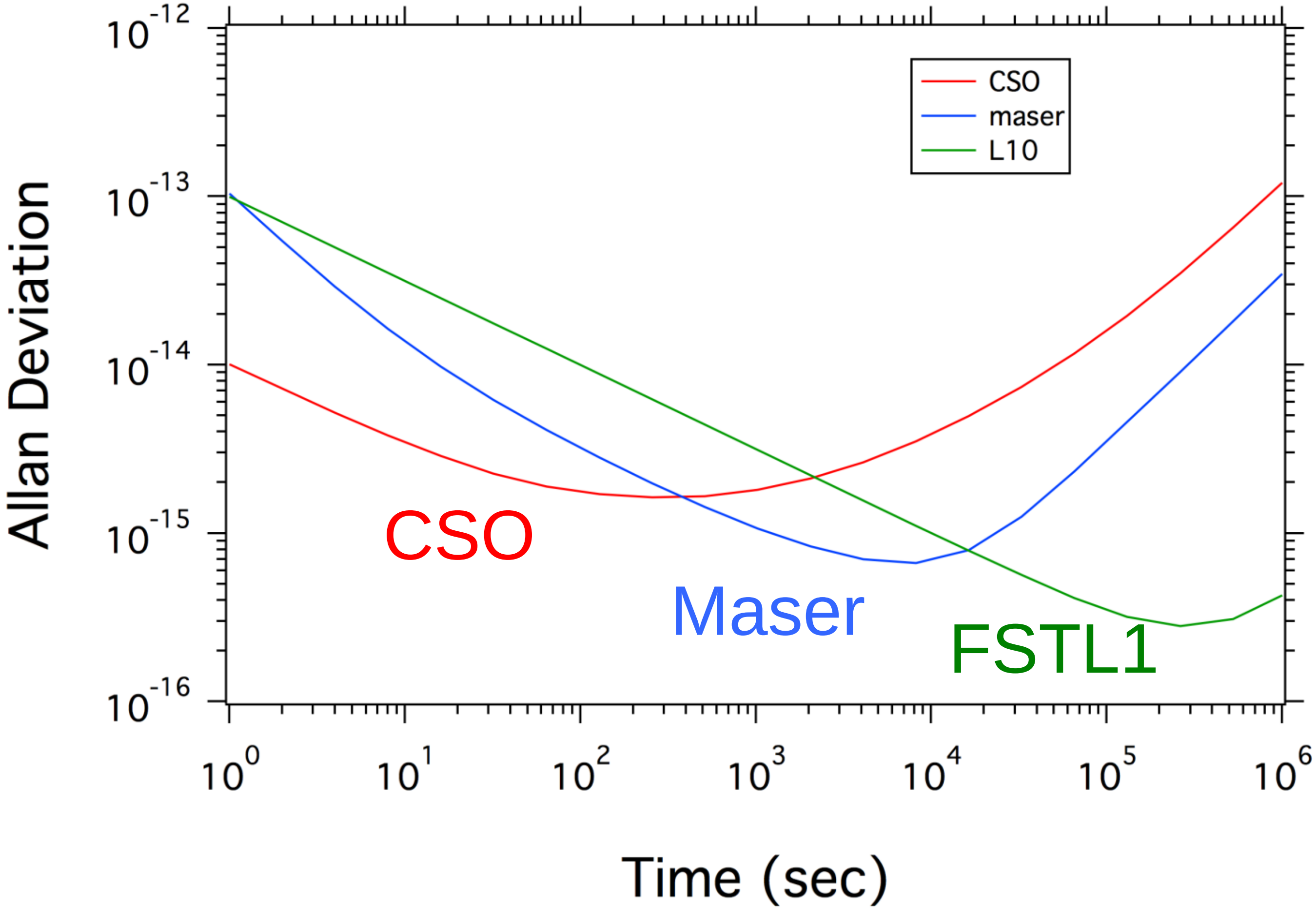
- 1e-14 at 1 s
- 3×10^{-18} noise floor at 1 yr





H-maser LO – Hg+ reference

ACES Ground Terminal Reference: Clock Ensemble



JPL ACES Reference Summary

- ACES GT pad ready for GT installation

- GT pad to FSTL link noise
  - 1e-14 at 1 second
  - 1e-17 at 1 day

- Two next-generation ultra-stable clocks serve as ACES GT reference

- Continuous operation – no expected down time

- JPL FSTL clock ensemble to provide:
  - < 5e-14 at 1 second
  - < 2e-16 at 1 day