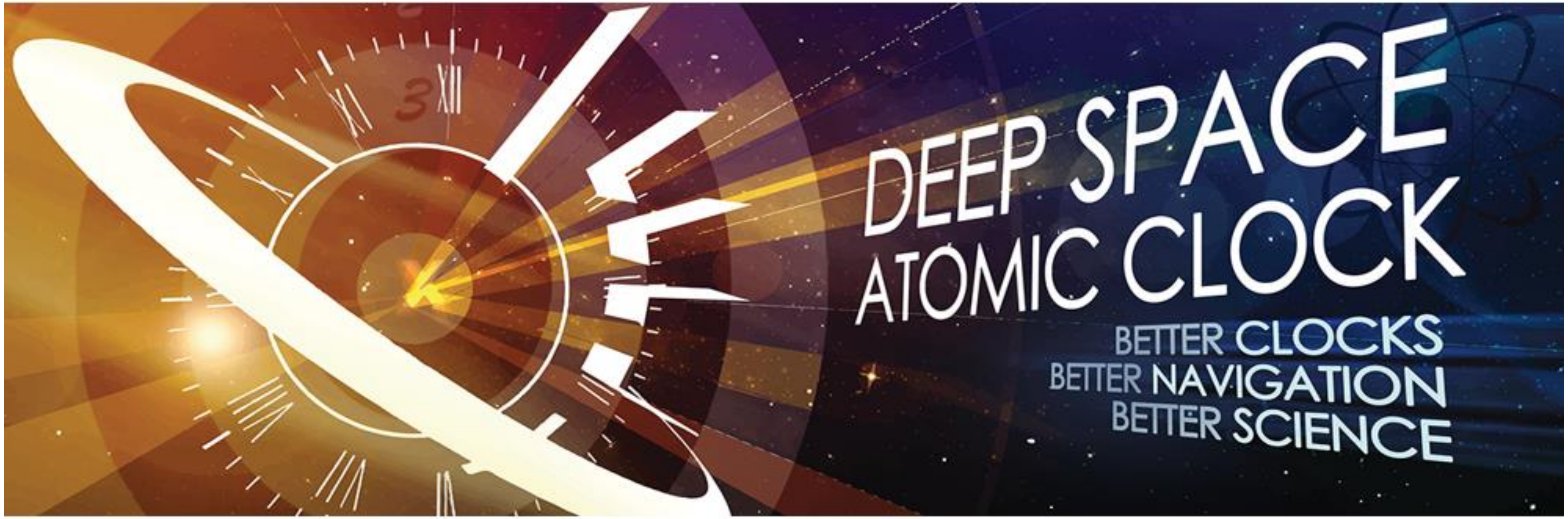

Deep Space Atomic Clock: A Technology Demonstration Mission

Robert L. Tjoelker

March 31, 2021

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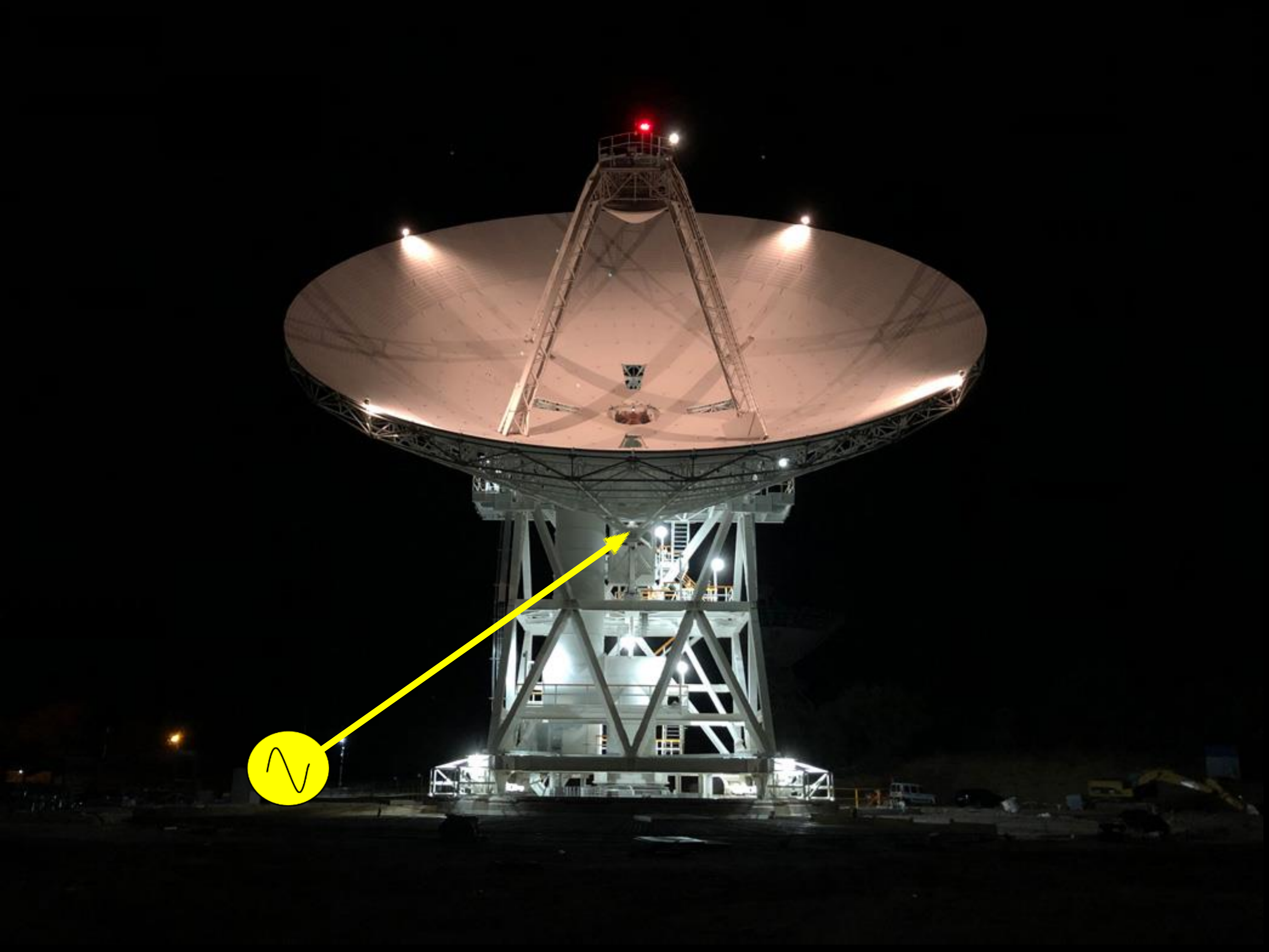
Outline

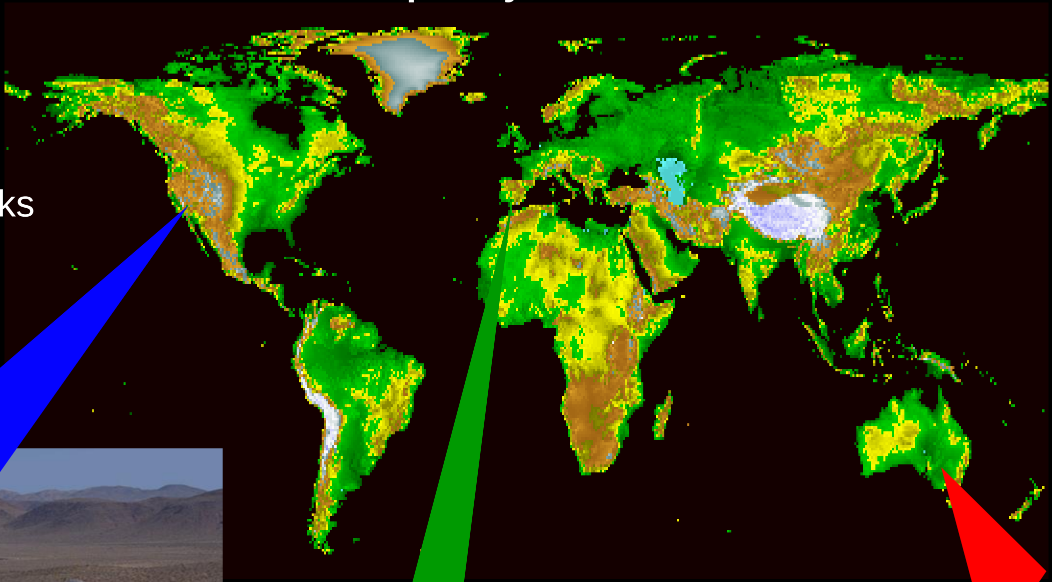
- Synchronization and Timing System Context: NASA Deep Space Exploration
  - Communications, Tracking and Navigation, and Radio Science
  - Deep Space Network (DSN) Frequency and Timing
- Mercury Ion Clocks
- Deep Space Atomic Clock (DSAC) Technology Demonstration Mission (TDM)
- What’s Next and Future Opportunities

Synchronization and Timing System Context: NASA Deep Space Exploration



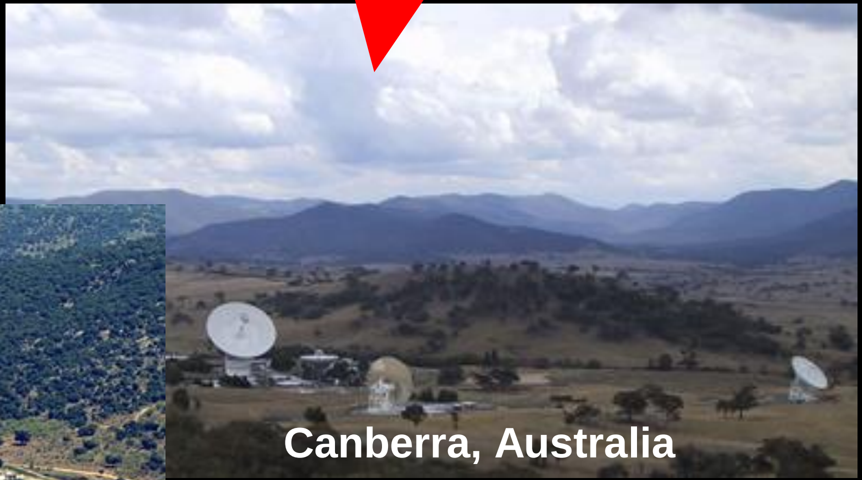
NASA's Deep Space Network (DSN)

Calibrated Time & Frequency Between each Site



Each DSN Site operates:

- Central frequency standard & clock
- Coherent references distributed via fiber links
- Calibration, performance measurements



DSN Frequency and Timing

Calibrated to *Universal Coordinated Time* (UTC)

Stability Performance:

- Communication & Telemetry (modest)
- Radiometric Tracking & Navigation (high)
- Radio Link Science (as good as you can get)

Two-way Range Measurement

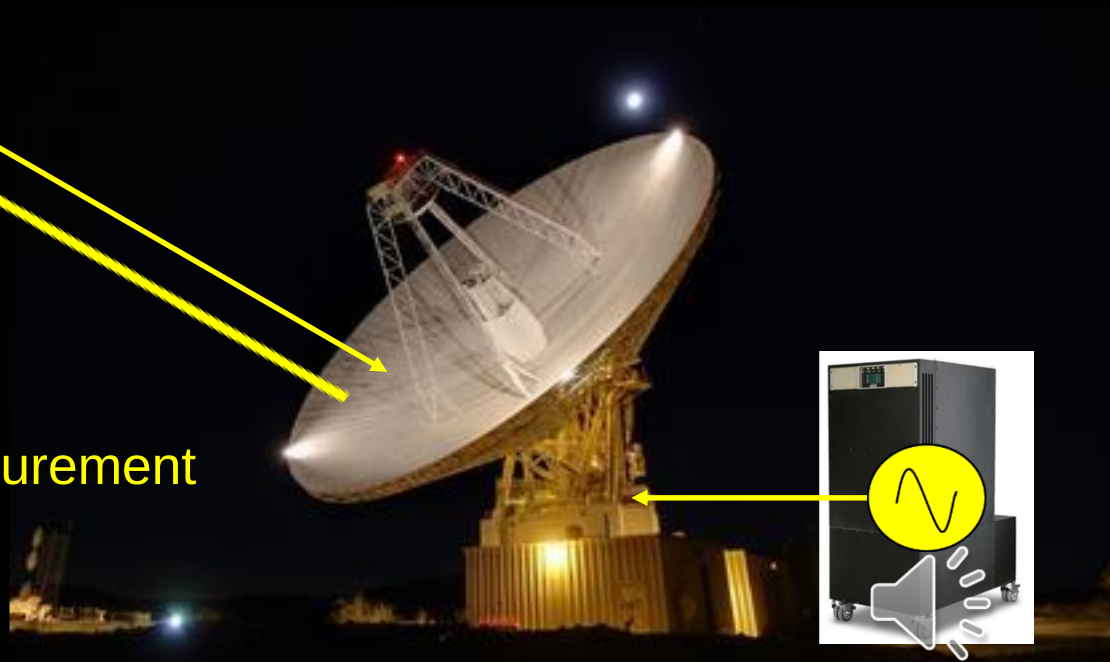
Round Trip Delay in Line-of-Sight Position

Two-way Doppler Measurement

Range Rate, Relative Motion of S/C in Line-of-Sight Position

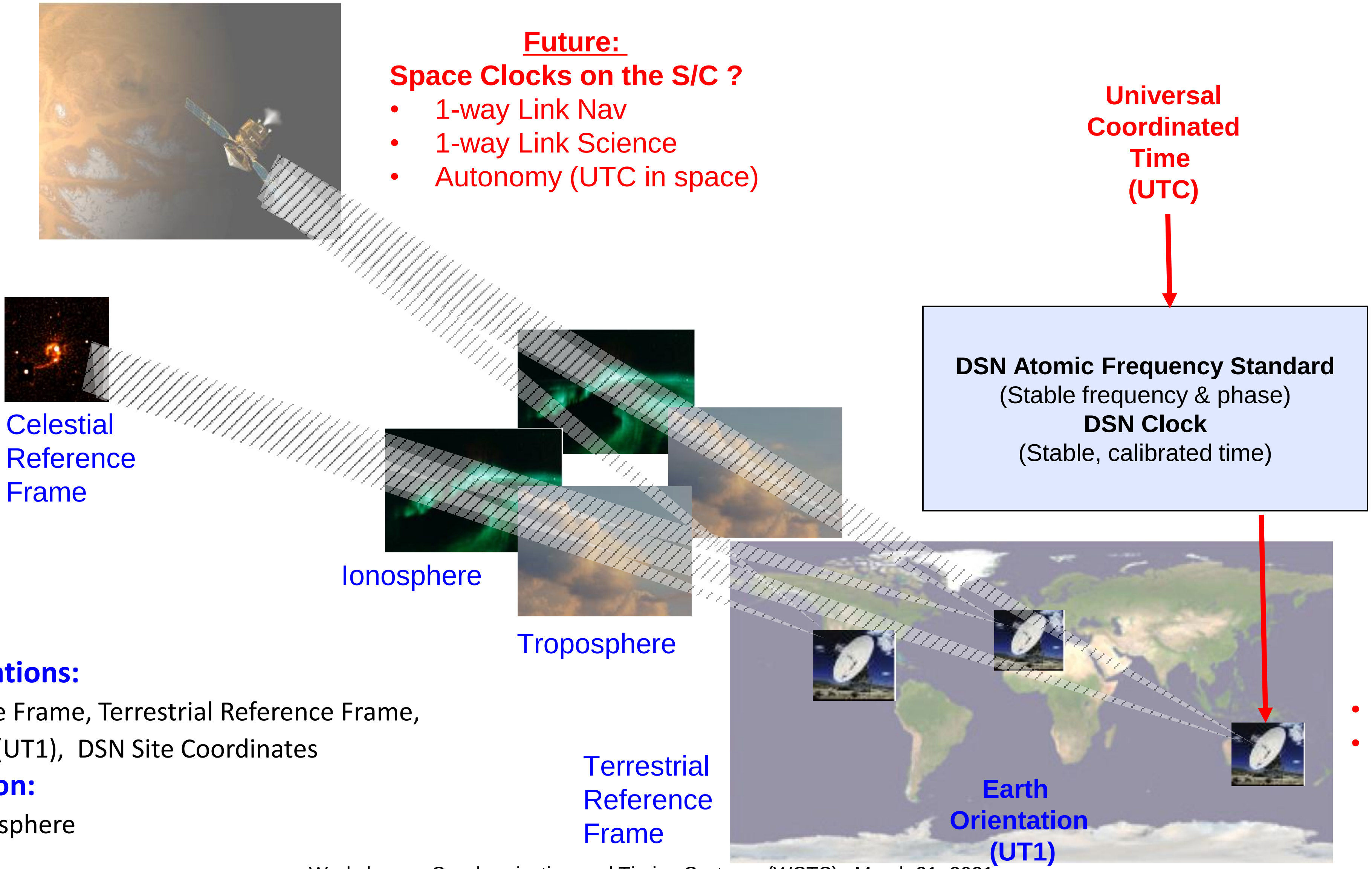
One-way (DDOR) Delta Differential One-Way Range Measurement

S/C Angular Position in Plane-of-Sky Position



Spacecraft Tracking and Navigation with the DSN

Atomic oscillators are ***identical*** everywhere in the universe.



Today:
- Clocks in the DSN
- 2-way Links

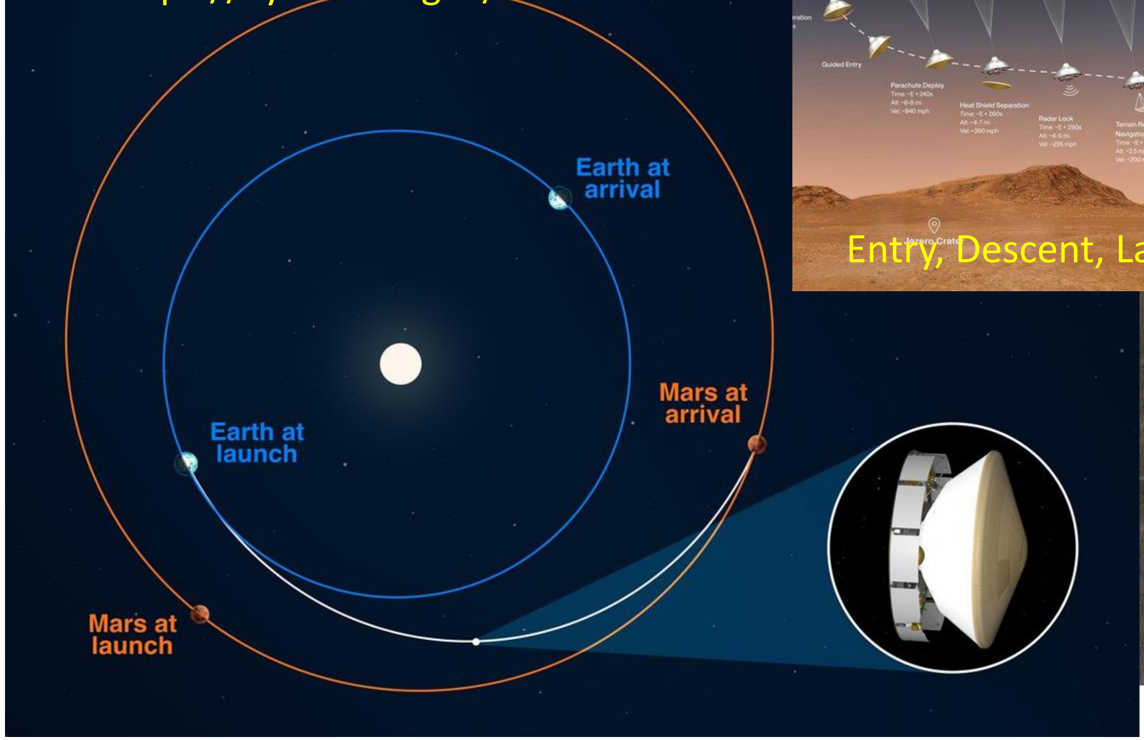
Platform Calibrations:

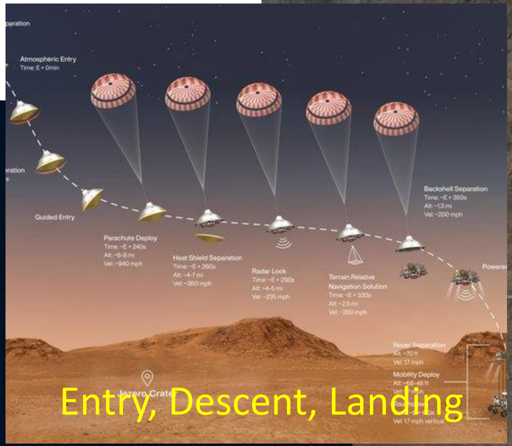
Celestial Reference Frame, Terrestrial Reference Frame, Earth Orientation (UT1), DSN Site Coordinates

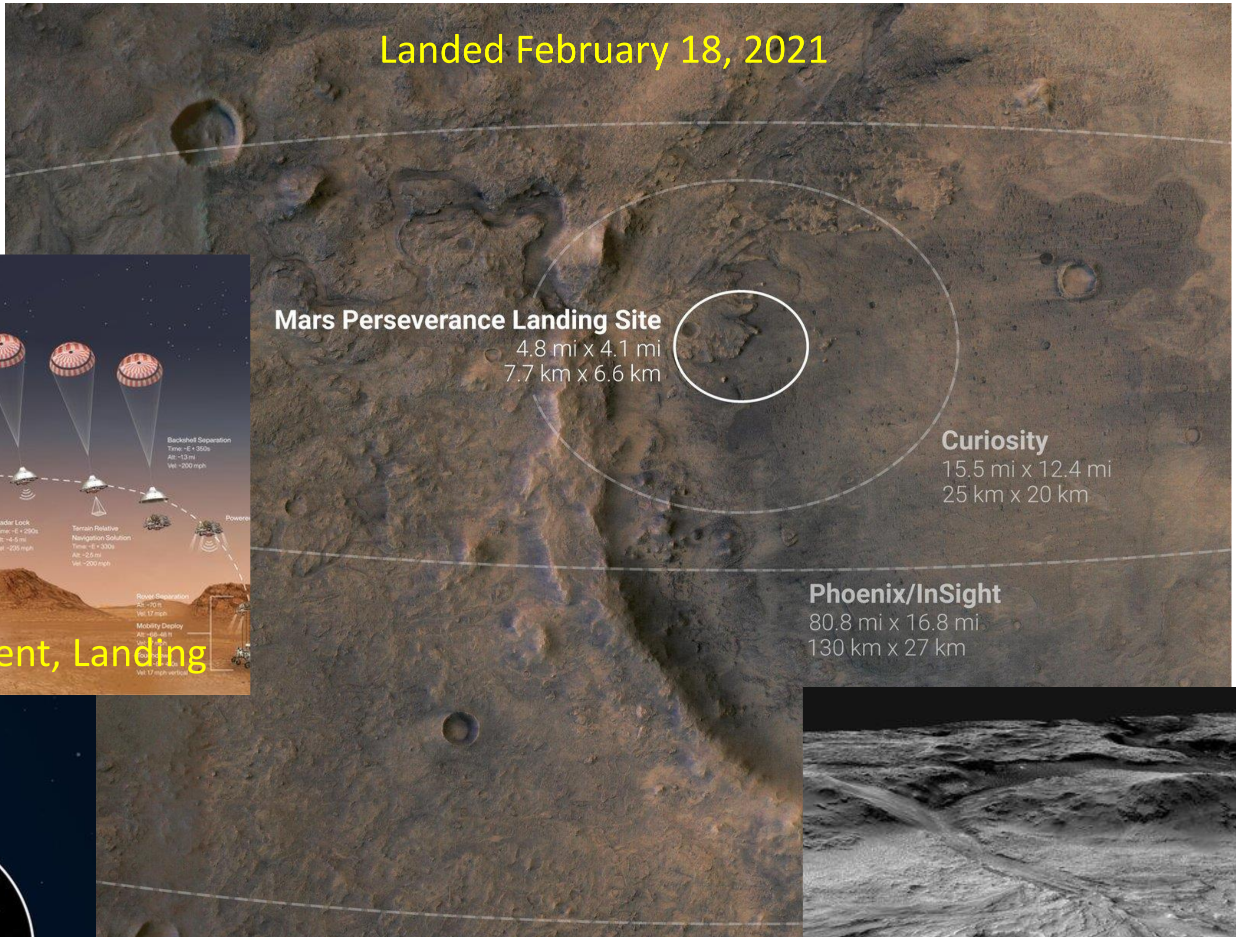
Media Calibration:

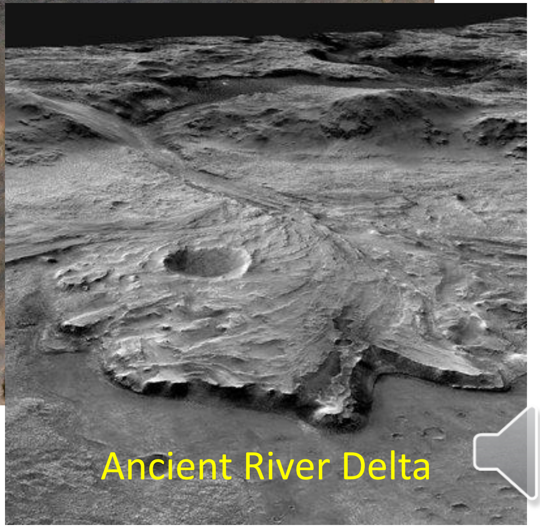
Troposphere, Ionosphere

Things you can do with good timing!
Mars 2020









Mars 2020: Perseverance Rover

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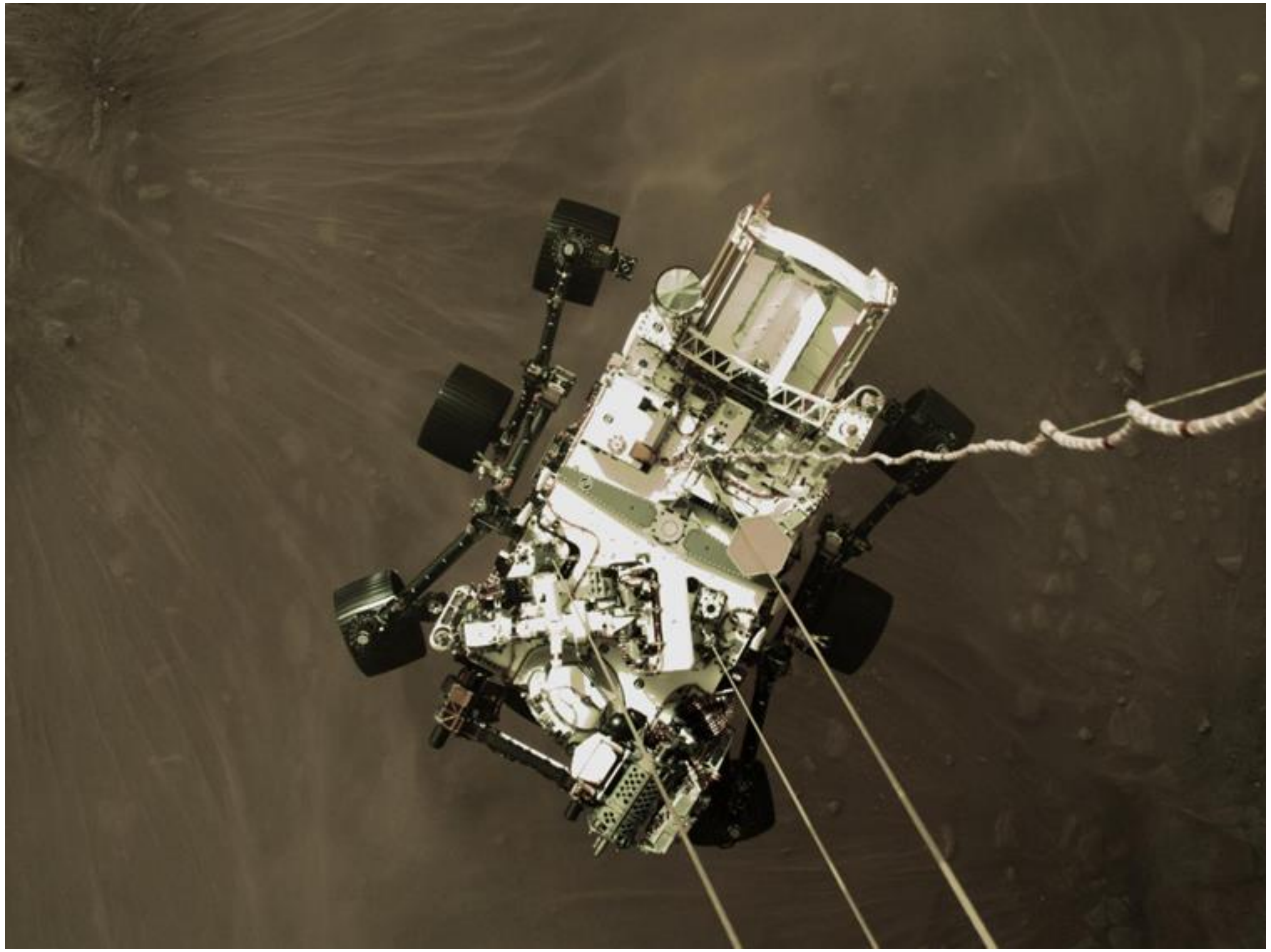


Being set down in Jezero Crater, Mars
February 18, 2021

On the move!

Mercury Ion Clocks

Operable Atomic Clocks

- Many atomic clock technologies, specialized to differing applications
  - Inherent atomic sensitivity
  - Localization method - vapor cells, beams, **trapped Ions**, trapped atoms
  - Atomic state selection and interrogation method
  - Environmental isolation, if needed

- Challenge: Few technologies meet the criteria for space operation:
  - Reliable, long life, and remotely operable
  - Low Size, Weight, and Power (SWaP)
  - High immunity to changing environments
    - Magnetic, temperature, radiation

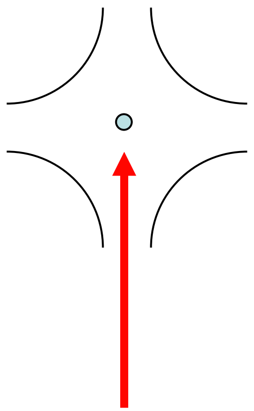
- Industrial and space clocks: Rb (6.8 GHz),Cs (9.2 GHz), H(1.4 GHz)

DSAC: First trapped ion clock in space, Hg+ (40.5 GHz)

Quadrupole and Multi-pole Linear Ion Traps

Spherical Quadrupole RF Trap

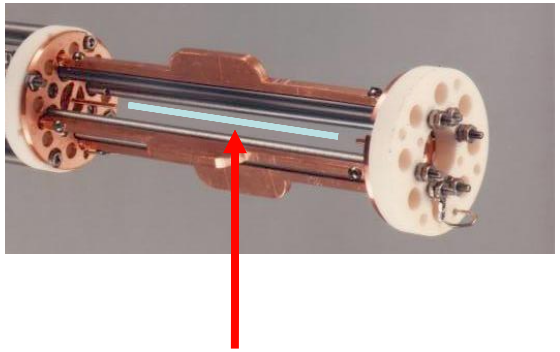
Bull. Am. Phys. Soc. 18, 1521 (1973)



Field-free region
at one point in center of trap

Linear Quadrupole (QP) RF Trap

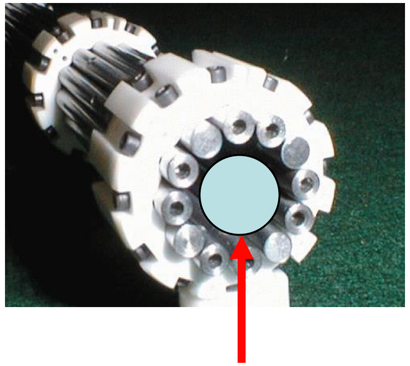
J. Appl. Phys. 66, 1013 (1989)



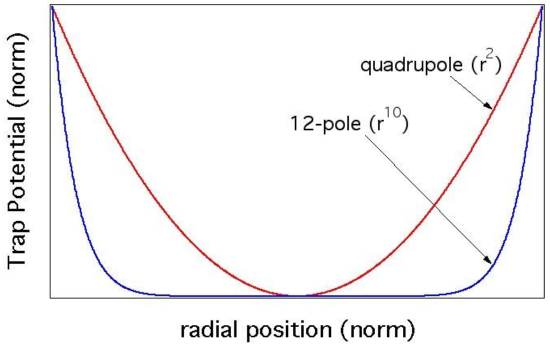
Field-free
region on a line

Multi-pole (MP) RF Trap

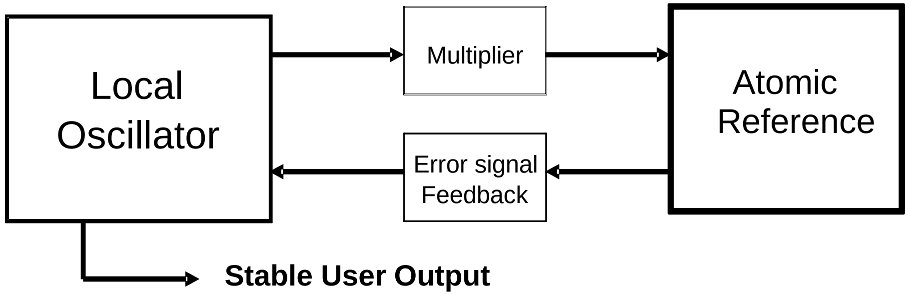
Proc. of the Joint EFTF-FCS (1999)



Field-"free"
region in a volume



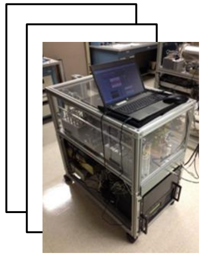
JPL Hg+ Linear Ion Trap Standards (LITS)



Quadrupole LITS 1-7

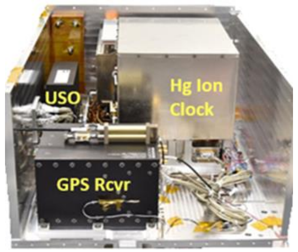
SNR*Q ~ 2E-14/ sqrt(tau)
Proc. IEEE IFCS (1996)

Multipole LITS 8-12

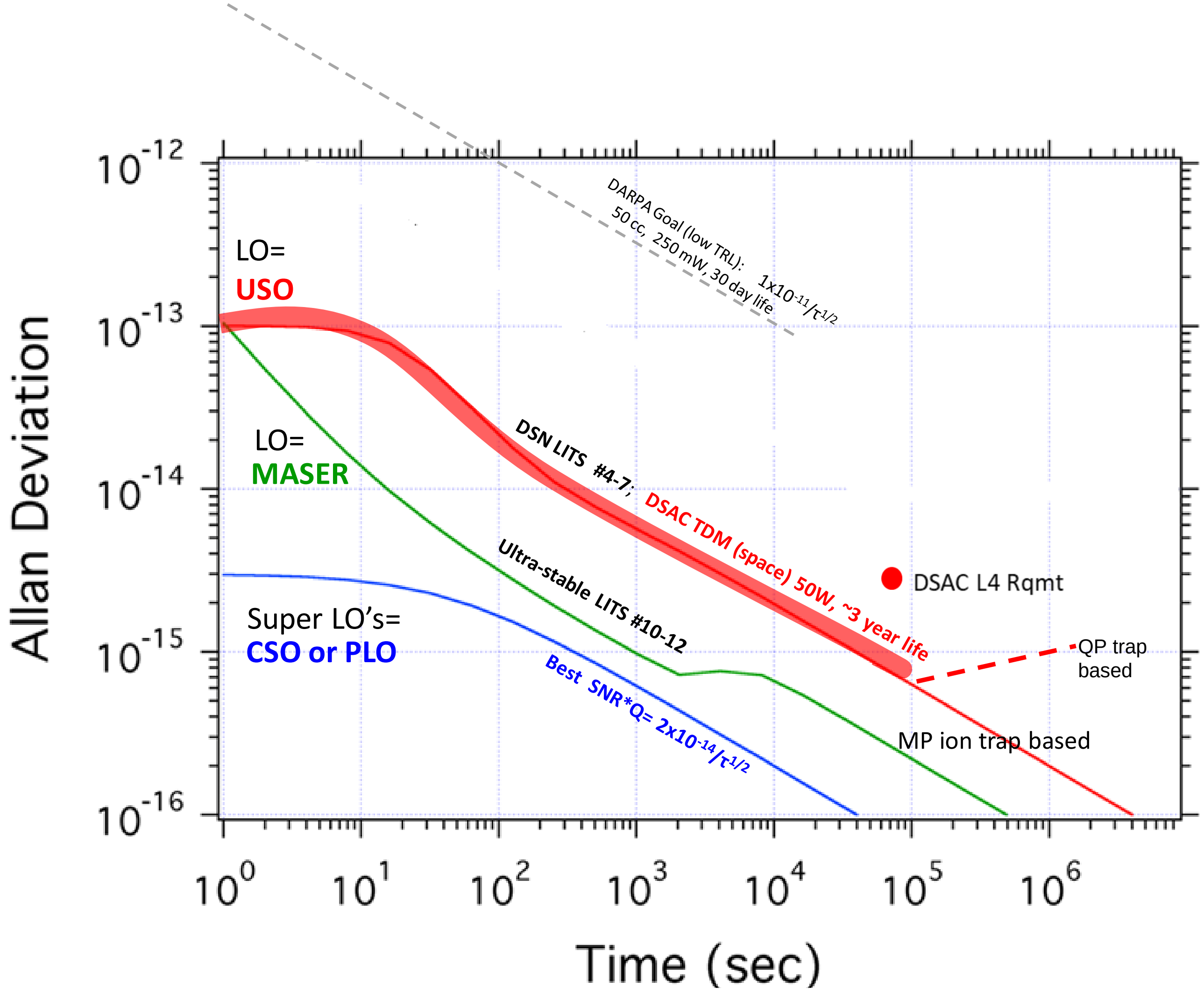


< 3E-17/day drift
IEEE UFFC Trans. (2008)

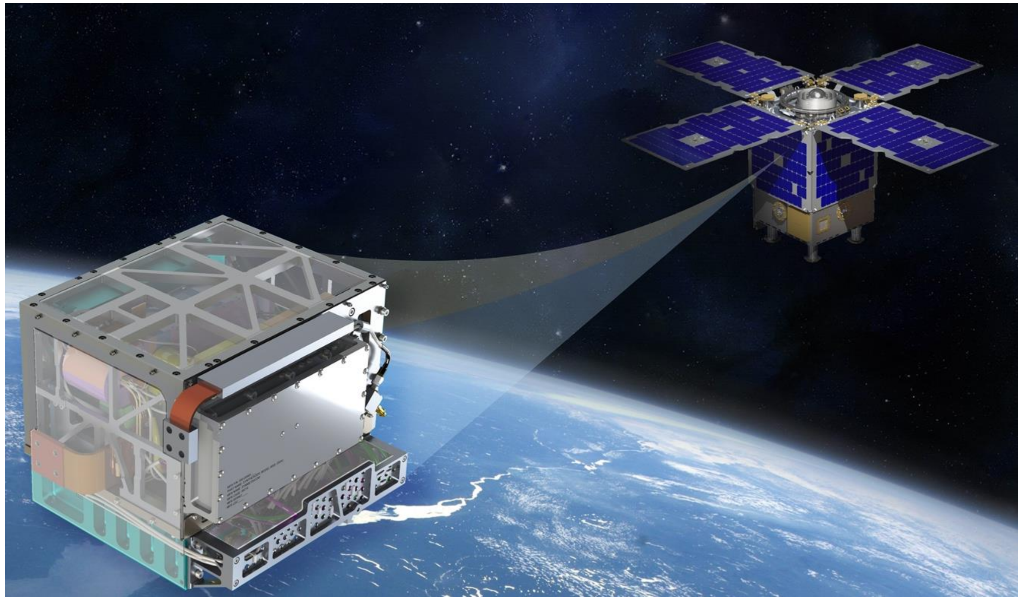
DSAC TDM

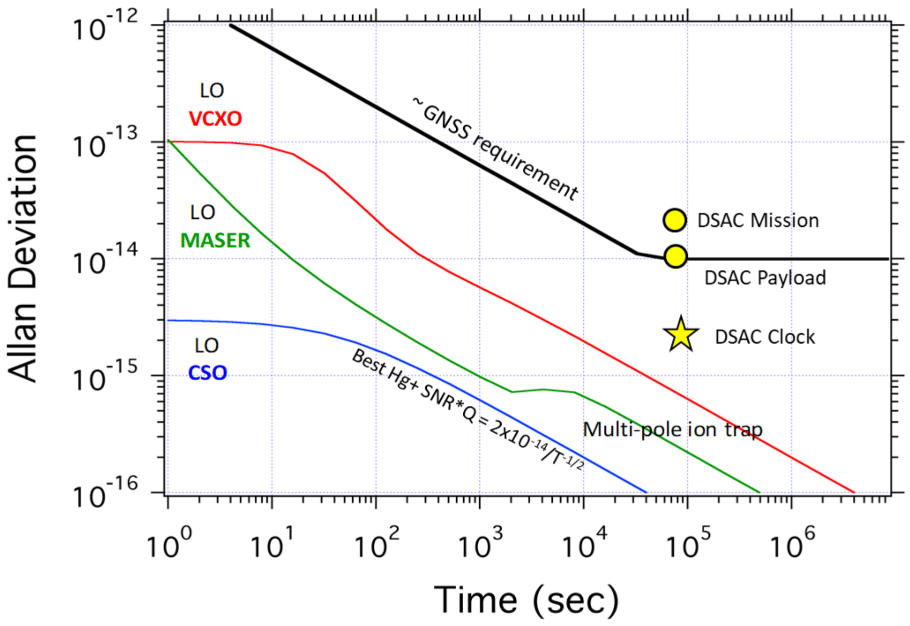


IEEE UFFC Trans. (2016)
IEEE UFFC Trans. (2018)



Deep Space Atomic Clock (DSAC)
Technology Demonstration Mission (TDM)





Objective

- Develop a mercury-ion clock and characterize operation and performance in space for 1 year.
- Identify design trades and steps towards a future operational version for infusion.

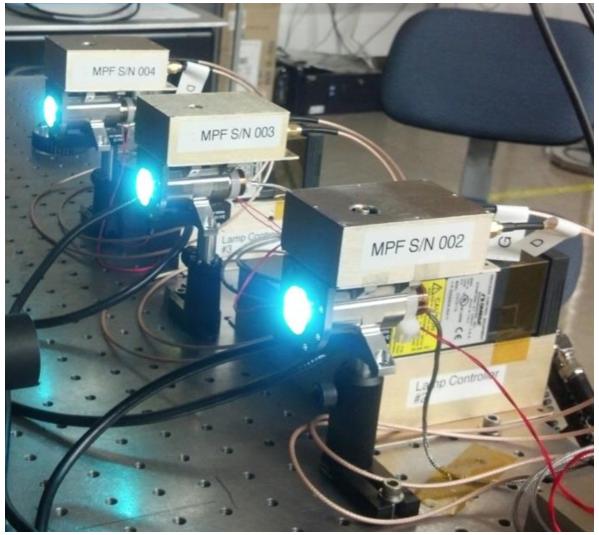
Approach: Hosted Payload Paradigm:

- Class D, Type II *hosted payload* on General Atomics' (GA) Orbital Test Bed (OTB), accept risk consistent with a technology demo.
  - GA owns/operates platform and controls processes for spacecraft operation
  - JPL owns/operates the DSAC payload and controls process for operation of the payload

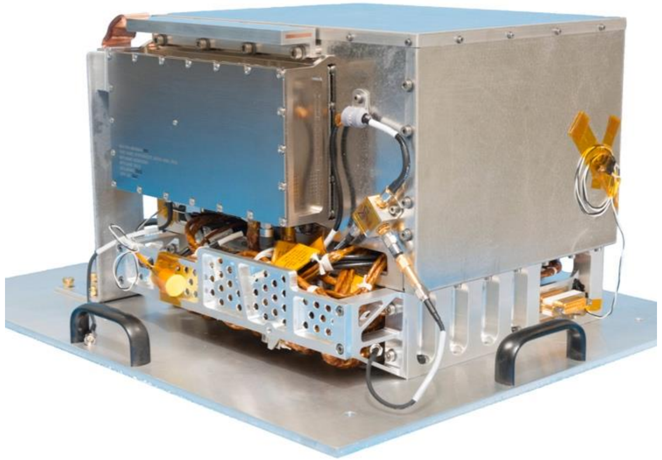
The DSAC Technology Demonstration Mission

IEEE TUFFC, Vol. 63, No. 7, July 2016.

Titanium Vacuum Tube



Mercury UV Lamp Testing



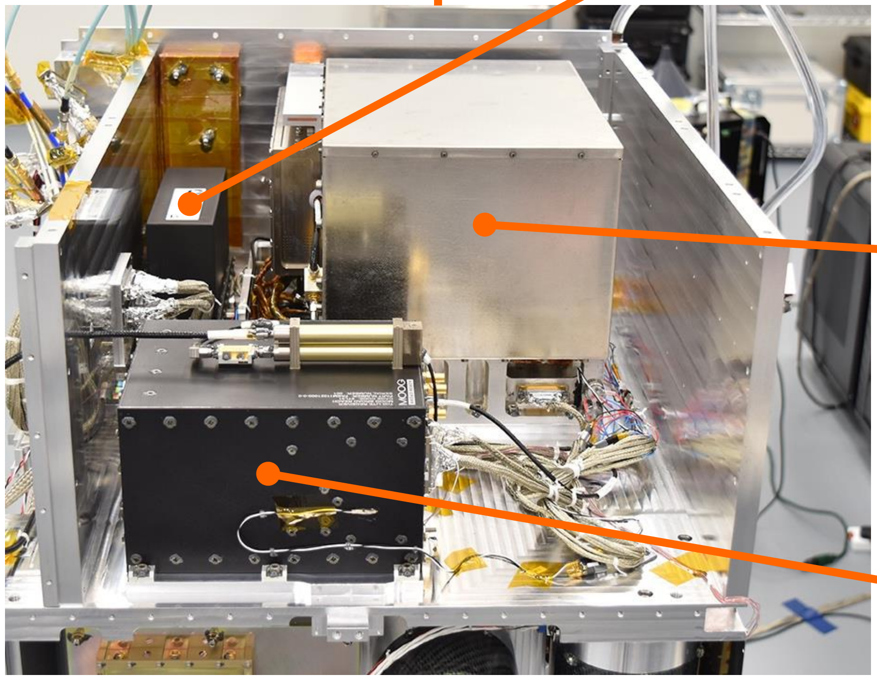
DSAC Demonstration Unit

DSAC experimental mercury-ion atomic clock goals:

- One year operation demonstration in space
- Mature technology and reduce Size, Weight, and Power (SWaP)
- Study trades and identify pathway for future operational ion clock design

DSAC Payload and location on the Orbital Test Bed (OTB) Spacecraft

General Atomics (GA)
Orbital Test Bed (OTB)

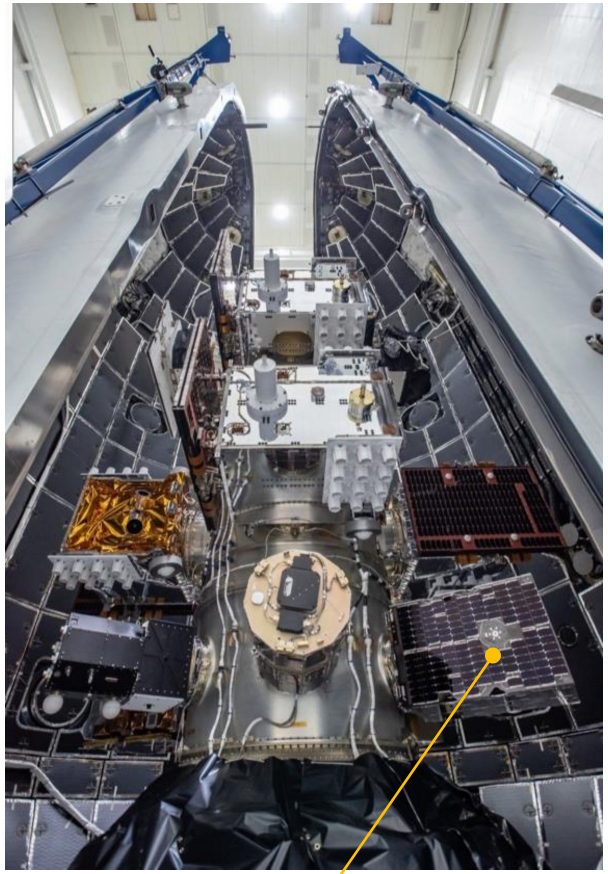


Ultra-Stable
Oscillator (USO)
Local Oscillator (FEI)

Demo Unit (DU)
Atomic Resonator (JPL)
Volume: 285 x 265 x 228 mm
Mass: 17 kg
Power: 45 W

GPS Receiver
Validation System (JPL-Moog)

Orbital Test Bed (OTB) Integration and Launch…



General Atomics OTB
(one of 26 spacecraft)

USAF STP-2
Space-X Falcon Heavy

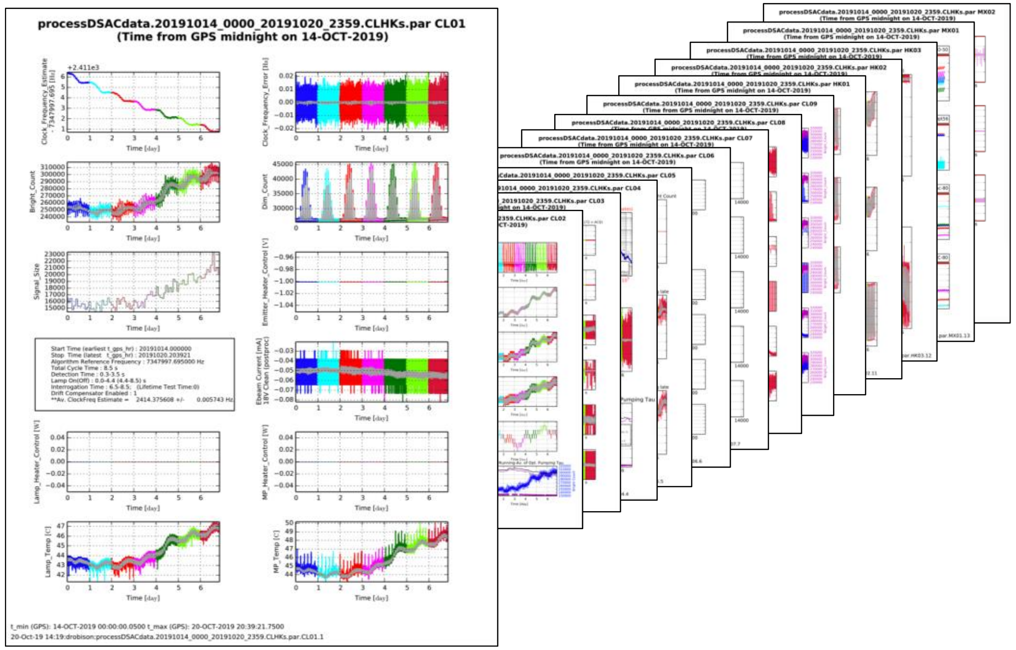
June 25, 2019

DSAC Mission Operations

Mission Goals:

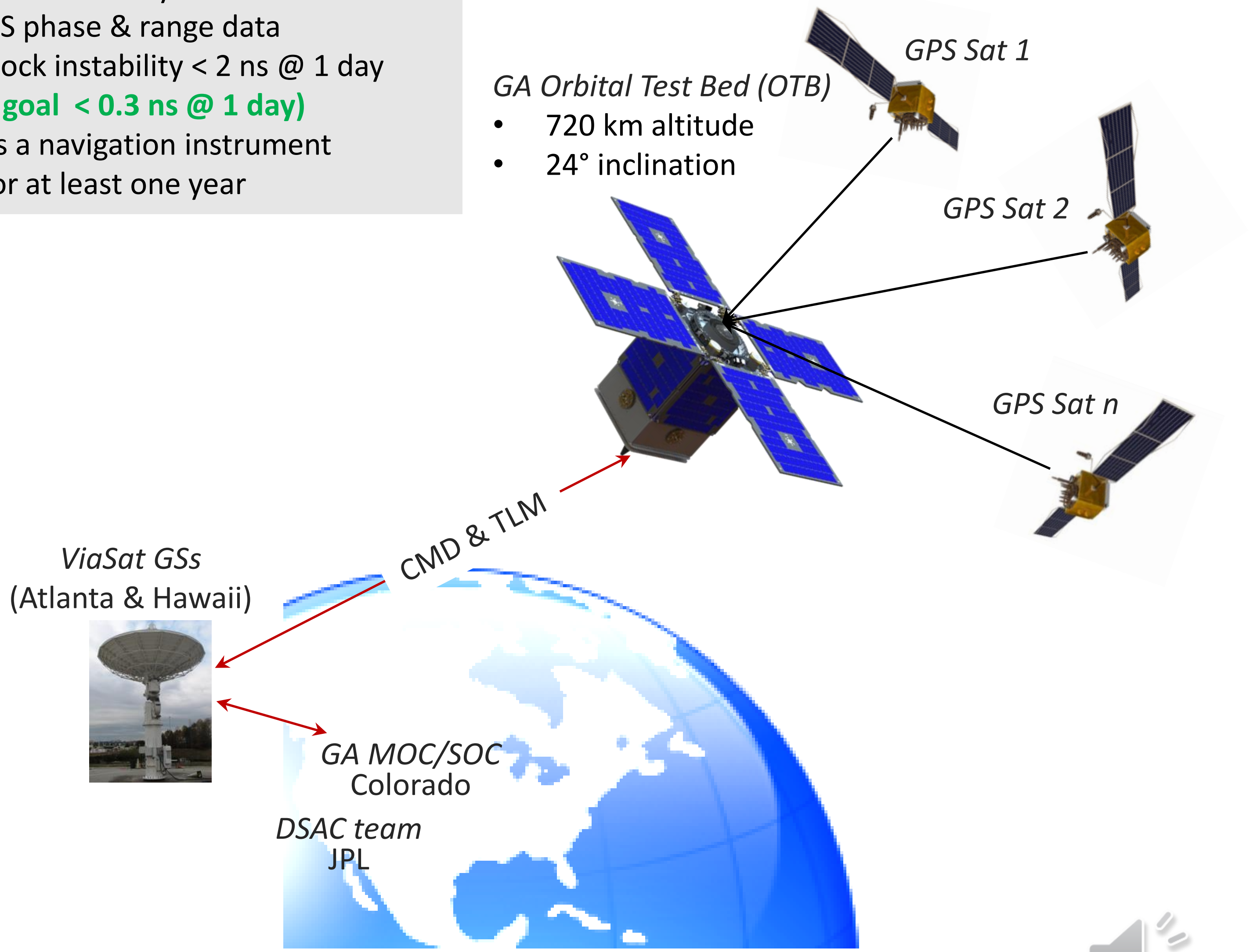
- Collect DSAC telemetry
- Collect GPS phase & range data
- Validate clock instability < 2 ns @ 1 day
  (achieved goal < 0.3 ns @ 1 day)
- Validate as a navigation instrument
- Operate for at least one year

Daily Telemetry:

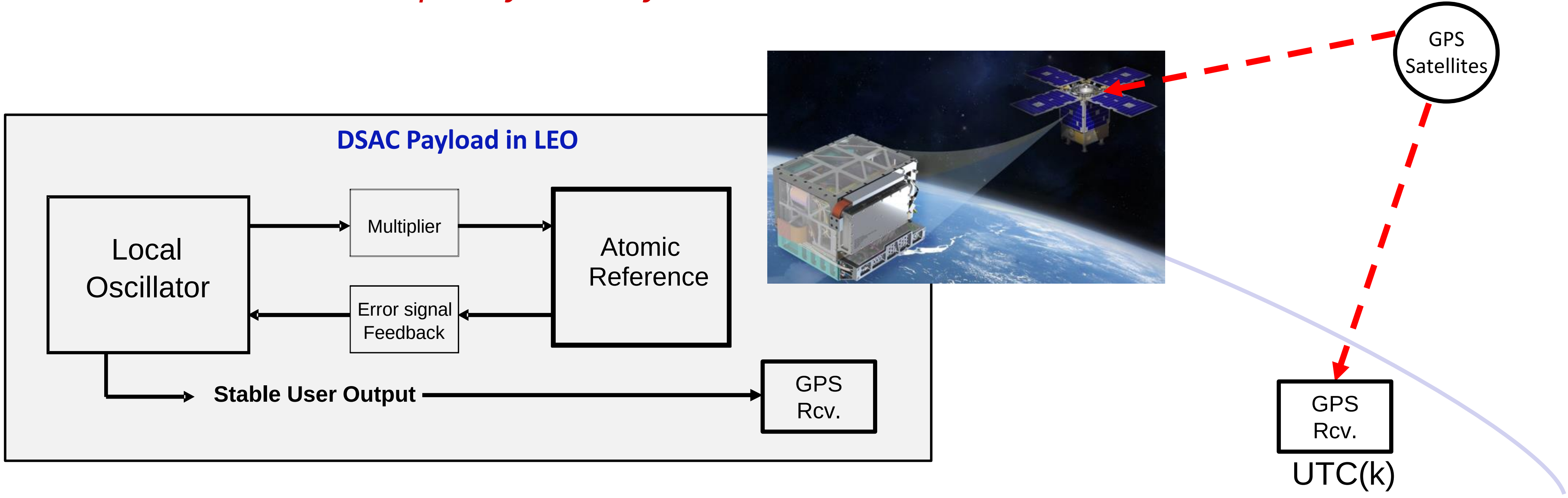


Health & Status

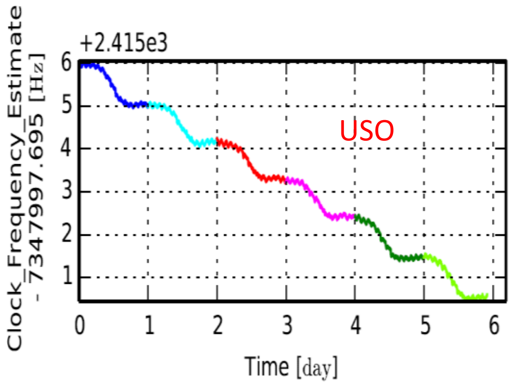
Environment



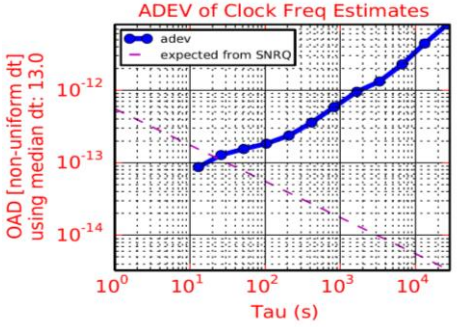
DSAC Frequency Stability Measurements vs UTC via GPS



Internal stability products via telemetry (USO vs Hg+):

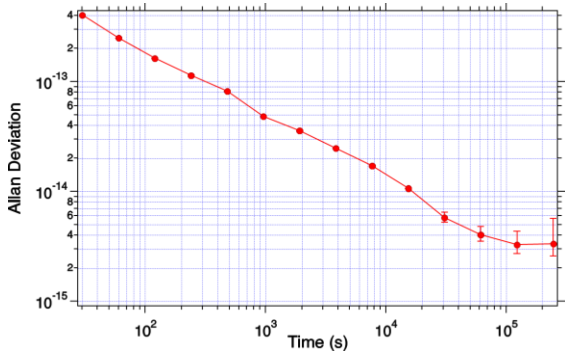


Adev(CFE)



Hg+ stability vs UTC (> ~20,000 s) via GPS time transfer:
Requires precision OD, relativity and J2 corrections

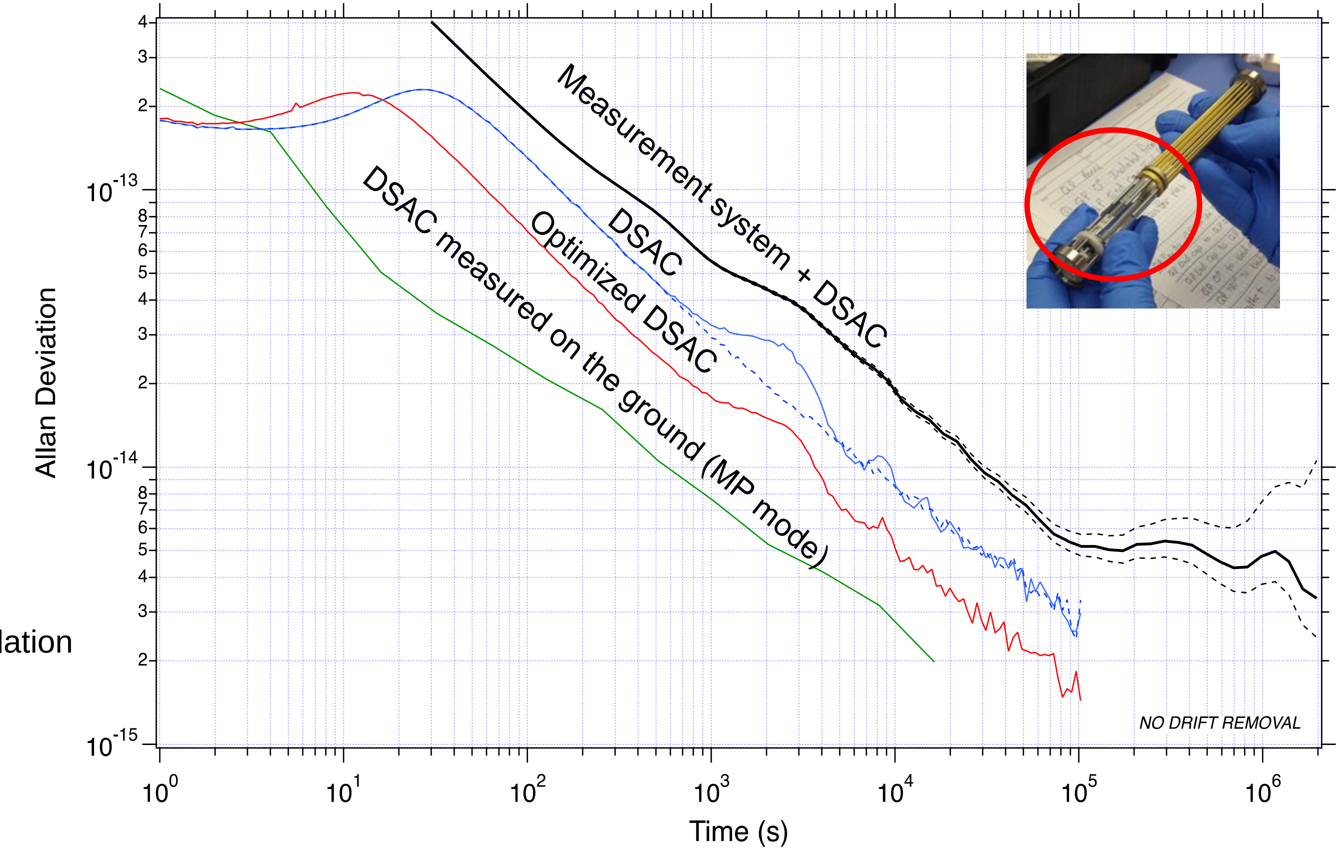
Adev(y(t))



DSAC TDM Result Summary to Date

(52 day continuous stability measurement in the quadrupole ion trap)

- Demonstrated operational robustness
  - ~500 days of operation to date (~80% if s/c availability)
  - All interruptions due to s/c safe modes.
  - No known clock h/w faults
- Exceeded stability demonstration goals:
  - 1-day stability = 3e-15 (required 2e-14)
  - Long term variations 3.0e-16/day (no drift removed)
    - Autonomy applications
- Evaluated performance in varying LEO environment:
  - Magnetic, temperature, and radiation.
  - Temperature sensitivity: achieved 1e-15/ºC, without thermal regulation



"Demonstration of a trapped ion clock in space"

Accepted for publication in Nature (2021).

What's Next and Future Opportunities

What's Next for DSAC:

- DSAC mission has been extended for operation through August 2021
  - Maximize stability
  - Further study systematic sensitivities
  - Execute long uninterrupted runs and collect lifetime data

- DSAC Follow-on technology programs have begun:
  - Extend life past DSAC TDM.
  - Improve form factor and manufacturability.
    - Lower SWaP, footprint compatible with both GNSS clock & commercial rack-mount

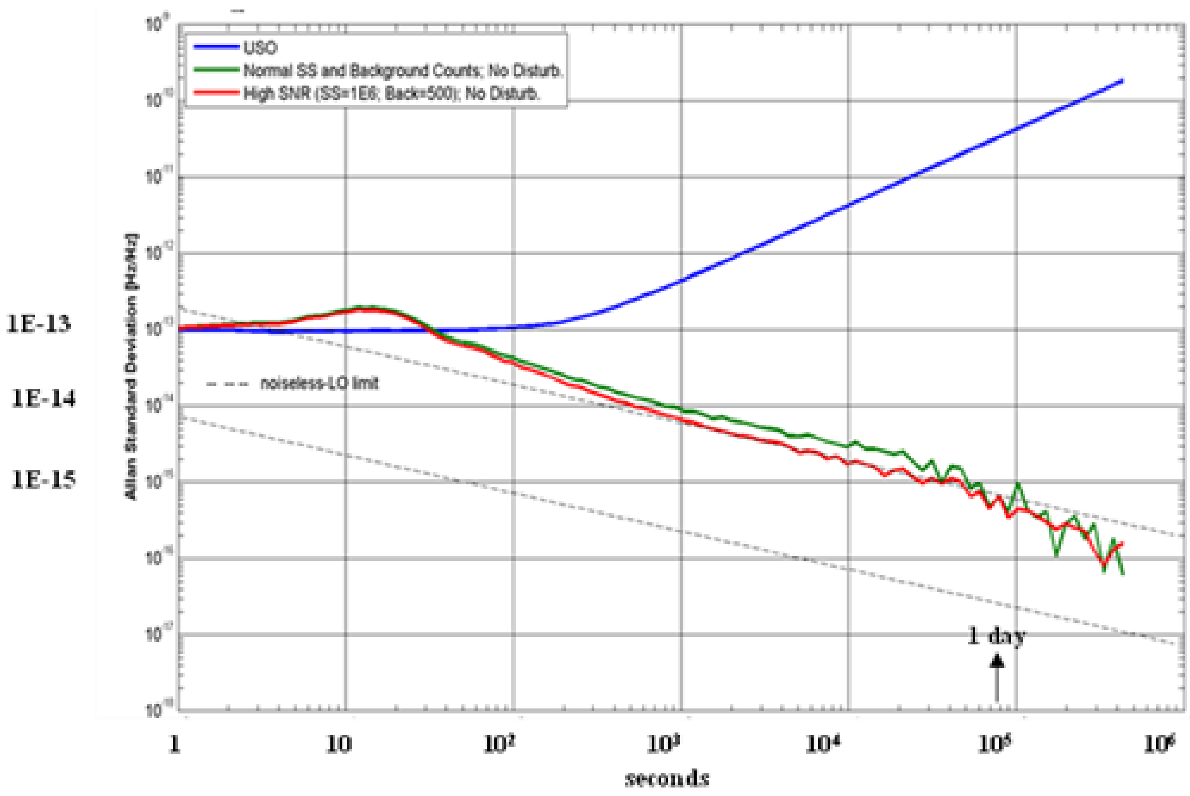
- Several space missions opportunities being explored.

Beyond the DSAC Mission

Follow-on Features

- **Frequency Stability Class:**
  - Local Oscillator = 1E-13 class USO
  - 1E-13 at 1 second, 2E-13/sqrt(tau), 1E-15 at 1 day.
  - long term drift <1E-15/day
- **Size, Weight, Power:**
  - Footprint Drivers: For Space: GPS clock footprint
    For Ground: Cs 3U chassis height (5.25").

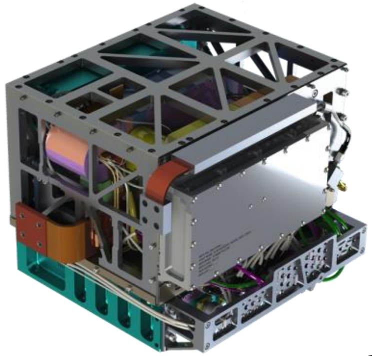
	DSAC Follow On		DSAC
	Scenario 1	Scenario 2	as flown
Stability	1e-13 at 1-s 1e-14 at 1000 s 1e-15 at 1-d		1.5E-13 at 1-s < 3E-14 at 1000 s ~ 3E-15 at 1-d
Power	42 W	33 W	47-56 W
Mass	13 kg	10 kg	19 kg
Volume	13 L	10 L	19 L
Lifetime	5-10 yrs		> 3 yrs



Modeled Ion Clock Frequency Stability and a Quartz USO LO

Beyond the DSAC Mission

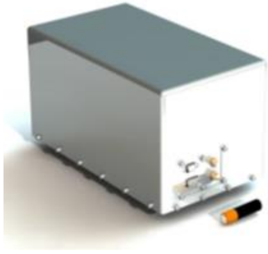
Potential Space & Ground Clock Opportunities



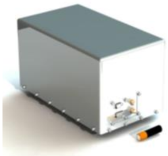
DSAC Technology

Space clocks

NASA
- Deep Space
- Lunar
- LEO, MEO, GEO



GNSS
- LEO, MEO



Other

Ground clocks

3U rack mount
Hg+ Std

- NASA/JPL's ground clock needs and interests:
  - DSN FTS H-maser and Cs std (replacements ~2030?)
    - Timekeeping, UTC maintenance, VLBI
  - Healthy ground market could enable smaller space clock market.

- Reduce Hg clock manufacturing and life cycle costs.
  - Cesium stds ~100k$ Qty. = hundreds/ year
  - H-maser stds. ~300k$ Qty. = several/ year
  - Space Clocks ~$$ Qty. = several/ decade

Deep Space Network Frequency Standards

H-Masers

Cesium

Acknowledgements

Jet Propulsion Laboratory
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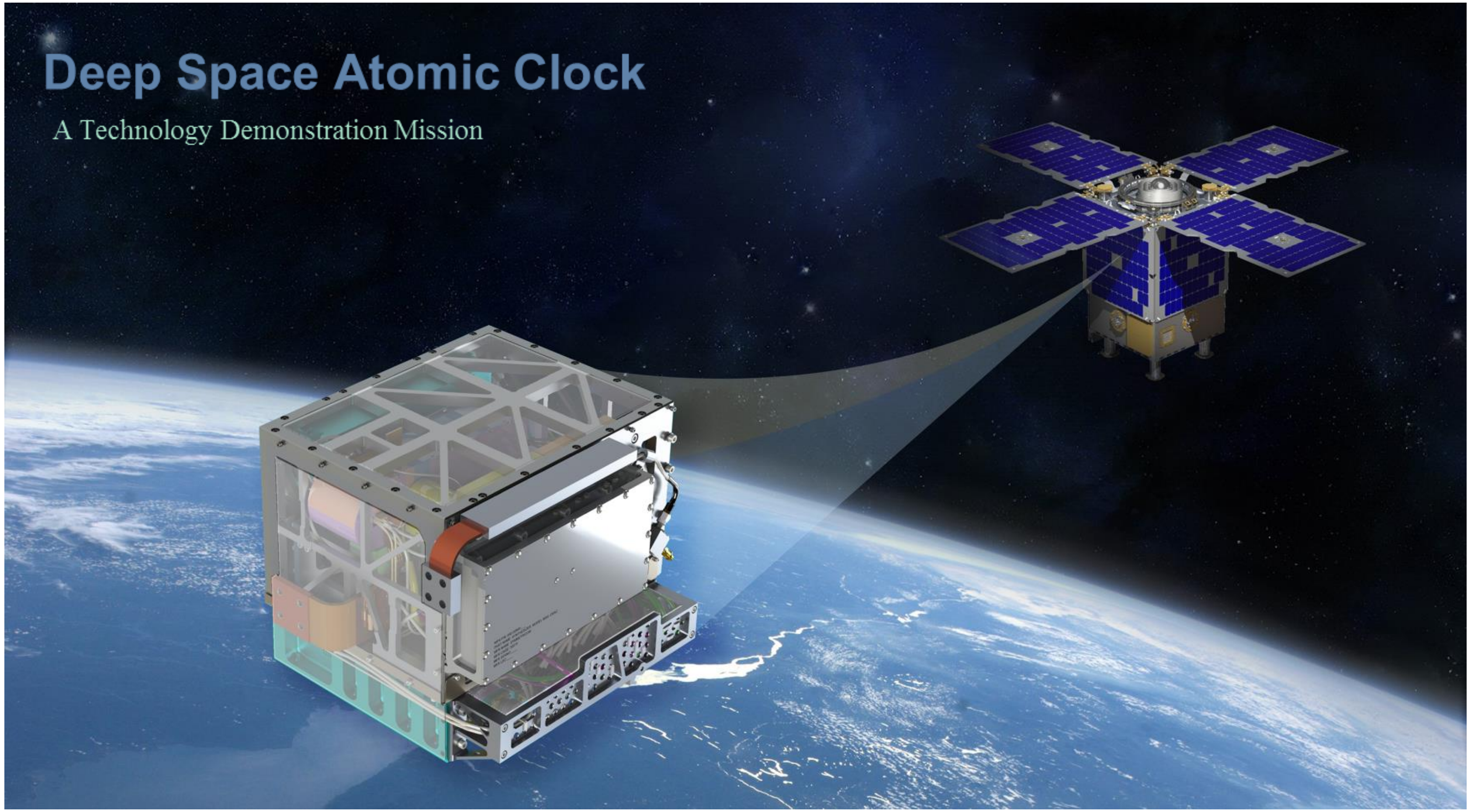
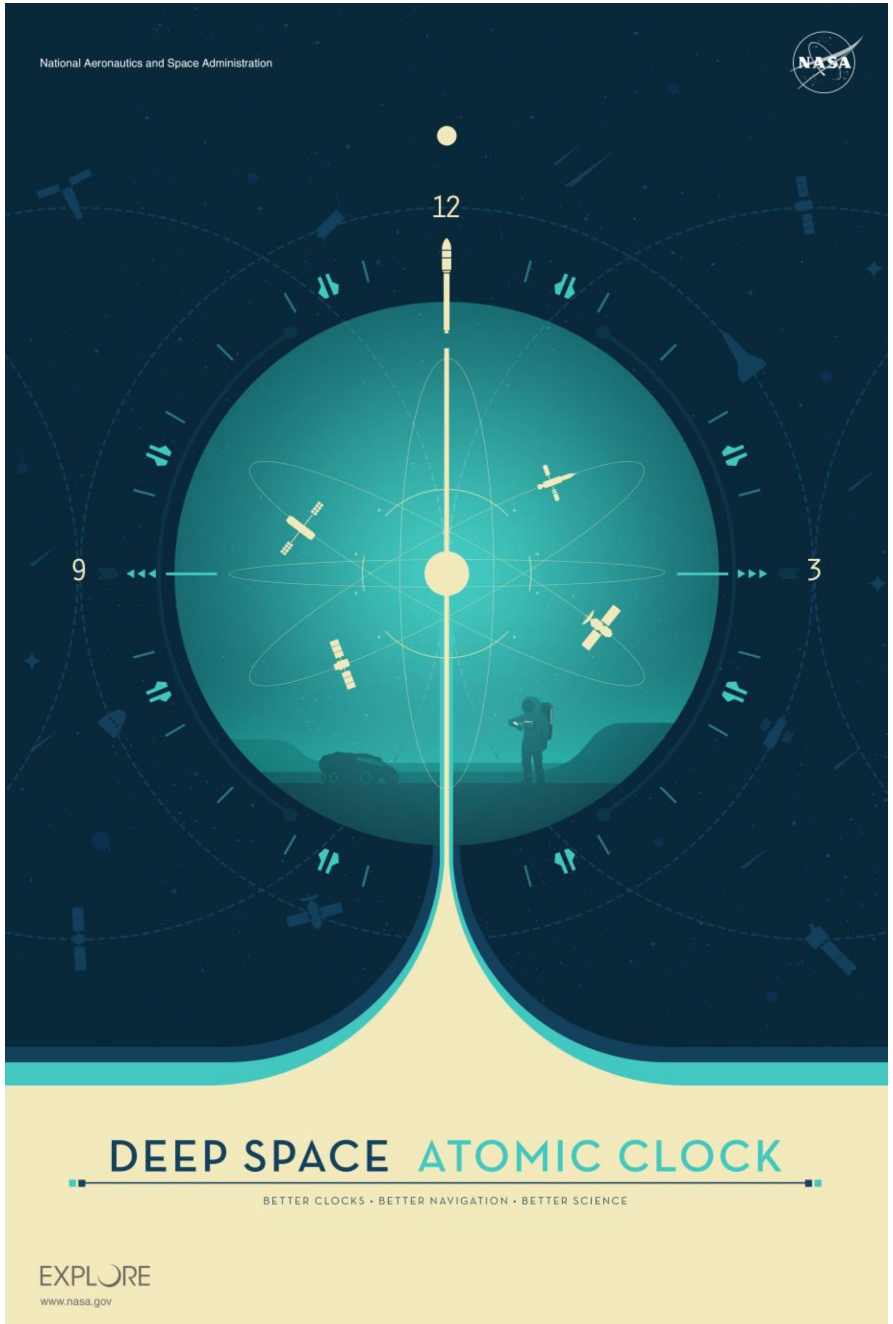


JPL DSAC Mission Team

- Eric Burt Clock Ops lead
- Todd Ely PM, Mission PI
- Daphna Enzer Clock data/analyst
- Angie Dorsey GPS
- Da Kuang GPS , orbit analyst
- Dave Murphy GPS , orbit analyst
- John Prestage Clock Co-I
- David Robison S/W, Ops lead
- Jill Seubert Deputy PM
- Bob Tjoelker Clock Co-I
- Rabi Wang DSAC I&T
- … many others
- … many industry partners

NASA TDM SCaN JPL Jet Propulsion Laboratory California Institute of Technology GENERAL ATOMICS



DSAC References

Deep Space Atomic Clock (DSAC):

"Mercury Ion Clock for a NASA Technology Demonstration Mission"

IEEE Transactions (TUFFC), Vol. 63, No. 7, July 2016.

Clock System Interactions in Variable Environments:

"Drifts and Environmental Disturbances in Atomic Clock Subsystems: Quantifying Local Oscillator, Control Loop, & Ion Resonance Interactions"

IEEE Transactions (TUFFC), Vol. 64, No. 3, March 2017.

DSAC Mission Update and Navigation Applications:

"Using the Deep Space Atomic Clock for Navigation and Science"

IEEE Transactions (TUFFC), May 2018. Vol. 65 , No. 6, June 2018.

DSAC Mission Results:

"Demonstration of a Trapped Ion Atomic Clock in Space"

Accepted for publication in Nature, 2021.

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