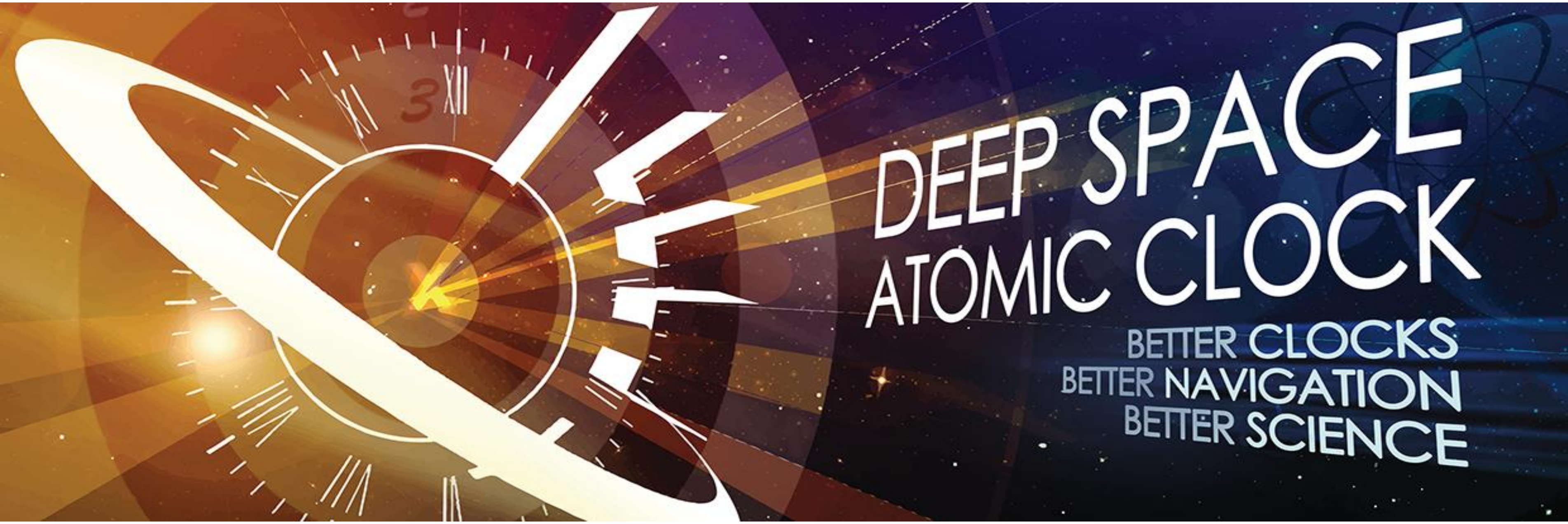


Mission Countdown for Deep Space Atomic Clock

Todd Ely

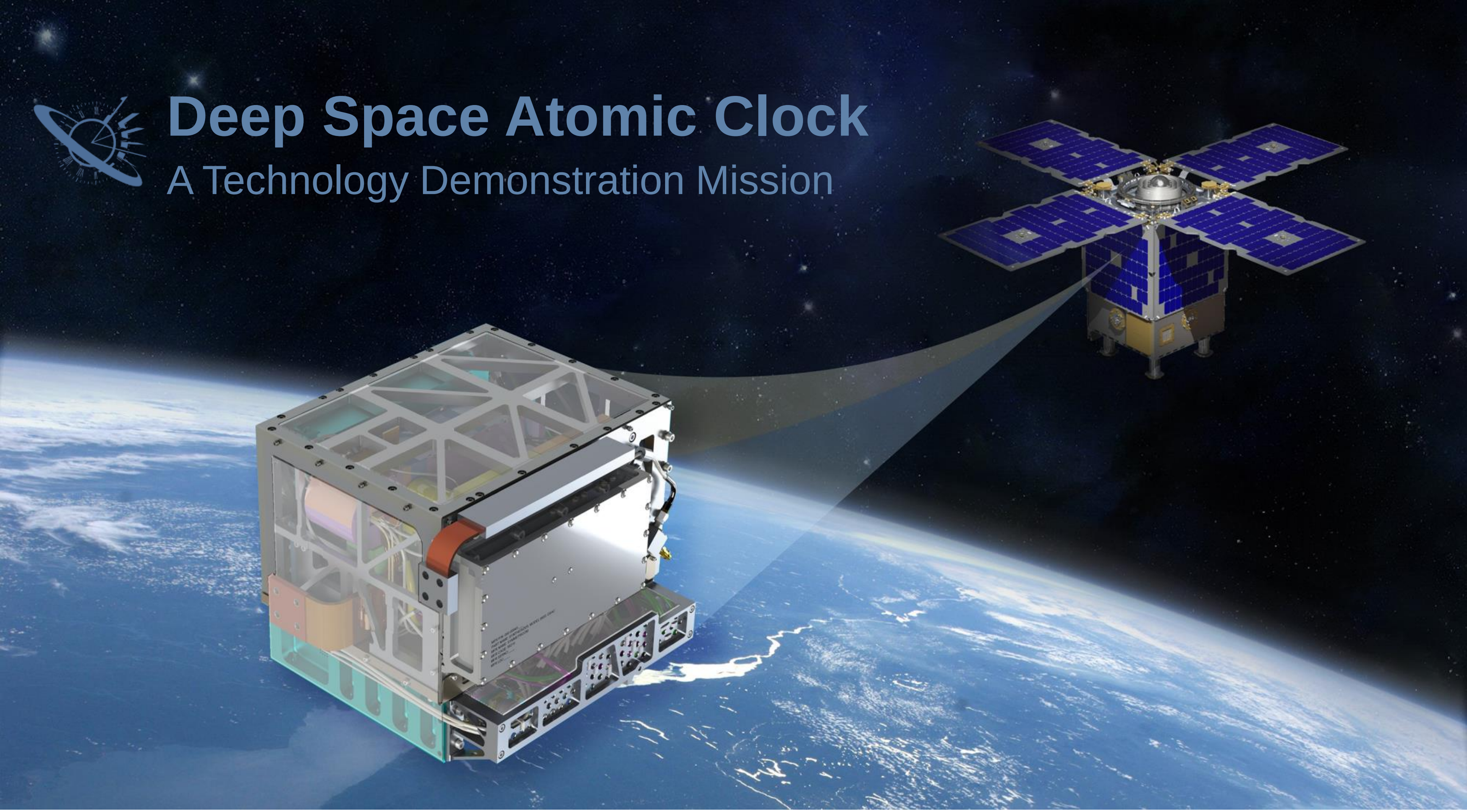
Principal Investigator/Project Manager

December 2018

Jet Propulsion Laboratory
California Institute of Technology

Deep Space Atomic Clock

A Technology Demonstration Mission



NASA TDM

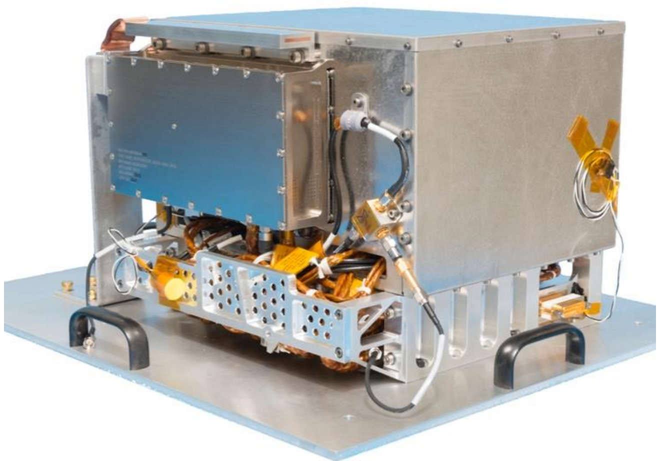
SPACE COMMUNICATIONS SCaN AND NAVIGATION

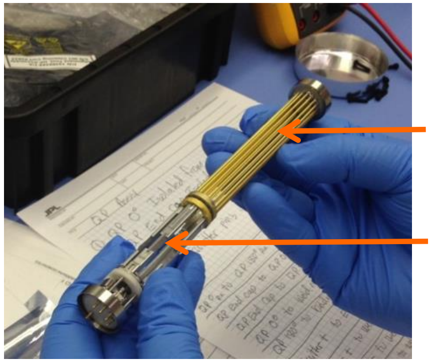
JPL Jet Propulsion Laboratory California Institute of Technology

GENERAL ATOMICS

DSAC Technology Demonstration Mission

DSAC Demonstration Unit



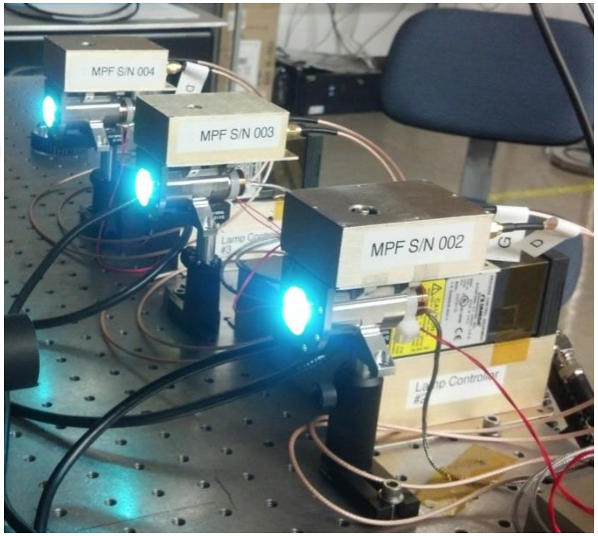


Multi-pole Trap

Quadrupole Trap

Titanium Vacuum Tube

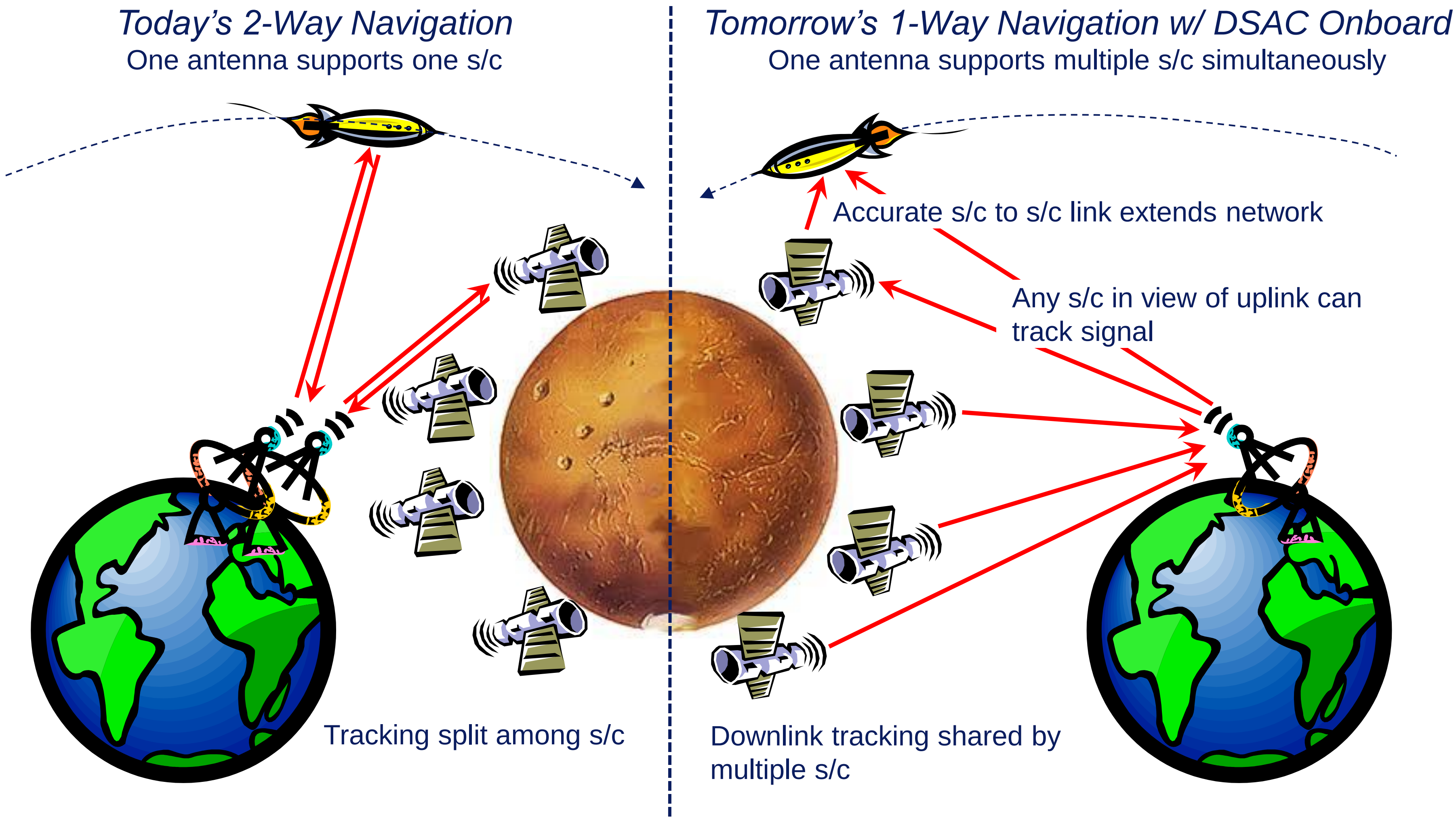
Mercury UV Lamp Testing



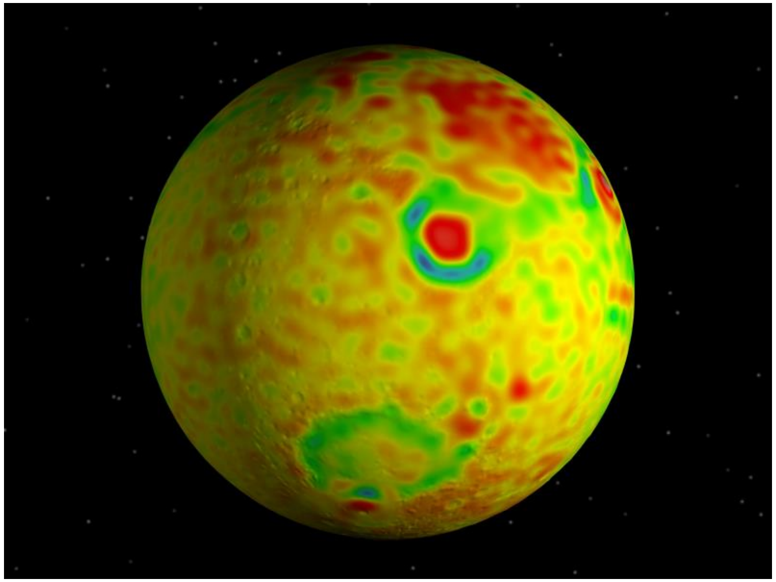
Develop advanced prototype (‘Demo Unit’) mercury-ion atomic clock for navigation/science in deep space and Earth

- Perform year-long demonstration in space beginning Spring 2019 – advancing to TRL 7
- Focus on maturing the new technology – ion trap and optical systems – other system components (i.e. payload controllers, USO, GPS) size, weight, power (SWaP) dependent on resources/schedule
- Identify pathways to ‘spin’ the design of a future operational unit (TRL 7 → 9) to be smaller, more power efficient – facilitated by a detailed report written for the next DSAC manager/engineers

DSAC Enables a Scalable DSN Tracking Architecture



DSAC Enhances NASA Radio Science and Enables Robust Onboard Navigation

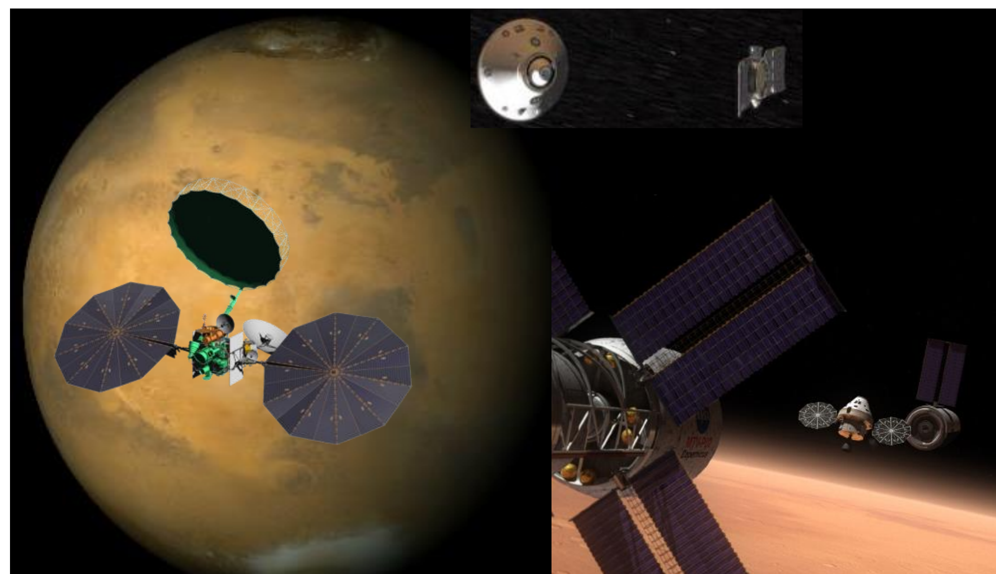


DSAC enables use of existing DSN Ka-band downlink tracking capability

- Ka-band data 10 x more accurate than X-band data
- Determine Mars long-wavelength, time variable gravity effects to GRACE-quality with single s/c
- Improve ring/atmosphere measurements by 100 x

Real time, onboard deep space radio navigation system with DSAC yields

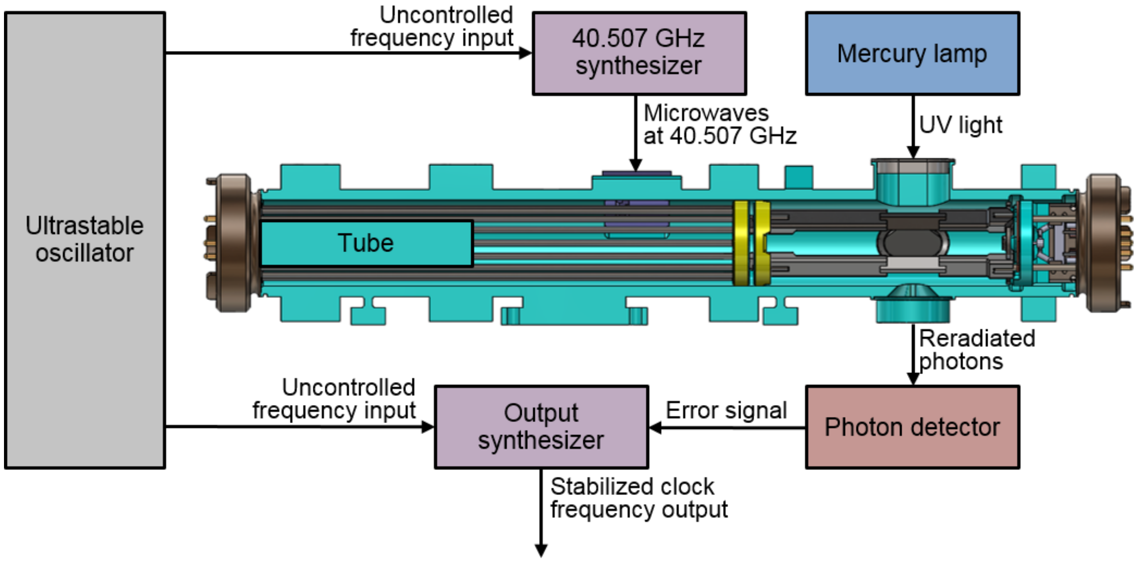
- 100 meter class trajectory knowledge at Mars atmosphere entry
- Enhanced navigation operations such as SEP spiraling into a low-altitude orbit
- Fault tolerant, robust navigation solutions required for safe human exploration



GPS and Other DOD Applications

- DSAC short and long term performance useful for future GPS uses (FAA & autonomy) – DSAC short term performance is 10X better than RAFS, and long term performance 50X better
- DSAC performance sufficient for future GPS III URE goals (improved clocks needed to shorten a ‘tent pole’ contributing to URE – ephemeris error is the other ’tentpole’)
- DSAC performance (considering no intrinsic drift) well suited for autonomous operations needed for secure command and control satellite systems (follow-on AEHF) and other government agencies

Technology & Operation



Ion Clock Operation

- Short term (1 – 10 sec) stability depends on Local Oscillator (DSAC selected USO 2e-13 at 1 second)
- Longer term stability (> 10 sec) determined by "atomic resonator" (Ion Trap & Light System)

Key Features for Reliable, Long-Life Use in Space

- No lasers, cryogenics, microwave cavity
- Low sensitivity to temperatures, magnetics, voltages
- Radiation tolerant at levels similar to GPS Rb Clocks

Ion Clock Technology Highlights

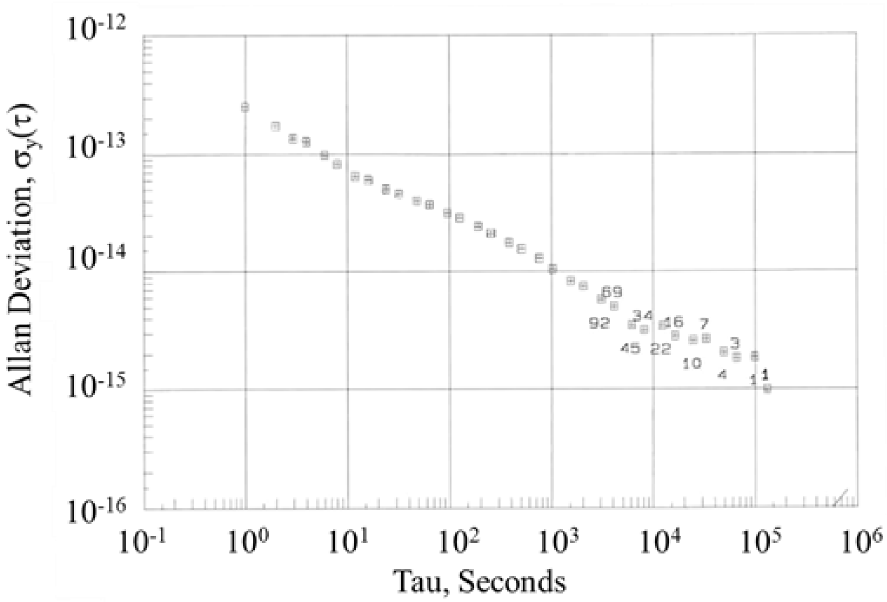
- State selection of 10^6-10^7 $^{199}Hg^+$ electric-field contained ions (no wall collisions) via optical pumping from $^{202}Hg^+$
- High Q microwave line allows precise measurement of clock transition at 40.5 GHz using DSAC/USO system
- Ion shuttling from quadrupole (QP) to multipole (MP) trap for best disturbance isolation

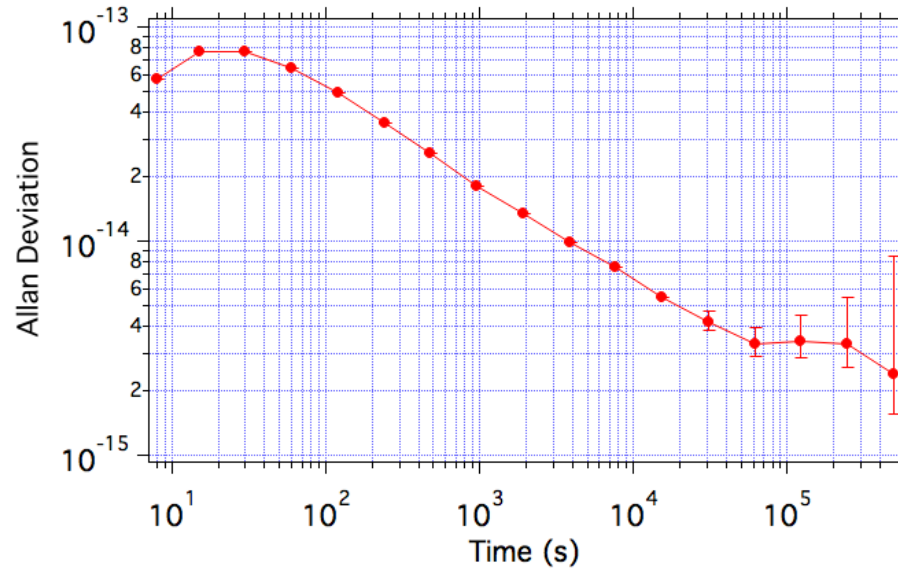
$$\text{MP Test Bed: } SNR \times Q < \frac{3 \times 10^{-13}}{\sqrt{\tau}} \;\; \& \;\; A.D. \sim 1 \times 10^{-15}$$

- QP -Only implementation offers major simplification

$$\text{QP−Only DU: } SNR \times Q < \frac{5 \times 10^{-13}}{\sqrt{\tau}} \;\; \& \;\; A.D. < 3 \times 10^{-15}$$

DSAC Demo Unit Ground-Based Measured Stability

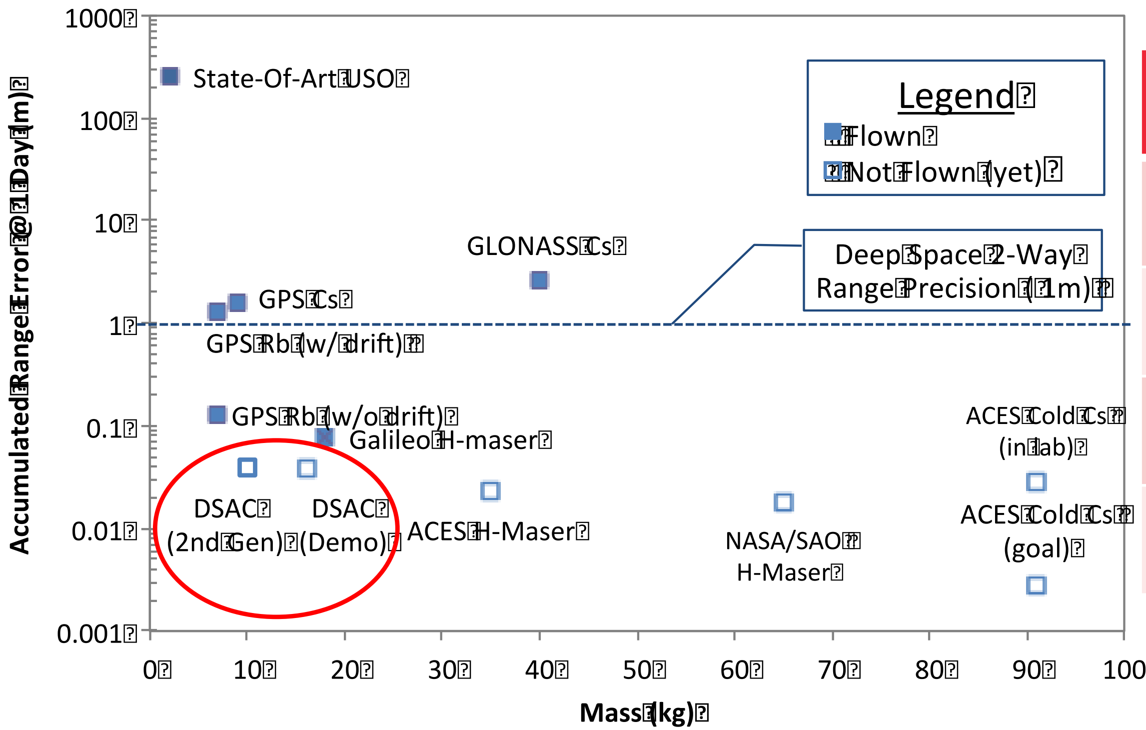




- DU in MP with Maser input at constant temperature
- Stability ~1e-15 @ 1-day in MP mode (*no drift removed*)
  → 87 ps/day or 26 mm/day

- DU in QP with Maser input at constant temperature
- DU/USO configuration tested with similar results
- Stability < 3e-15 @ 1-day in QP mode (*no drift removed*)
  → 0.26 ns/day or 8 cm/day

DSAC Compared to Other Space Clocks



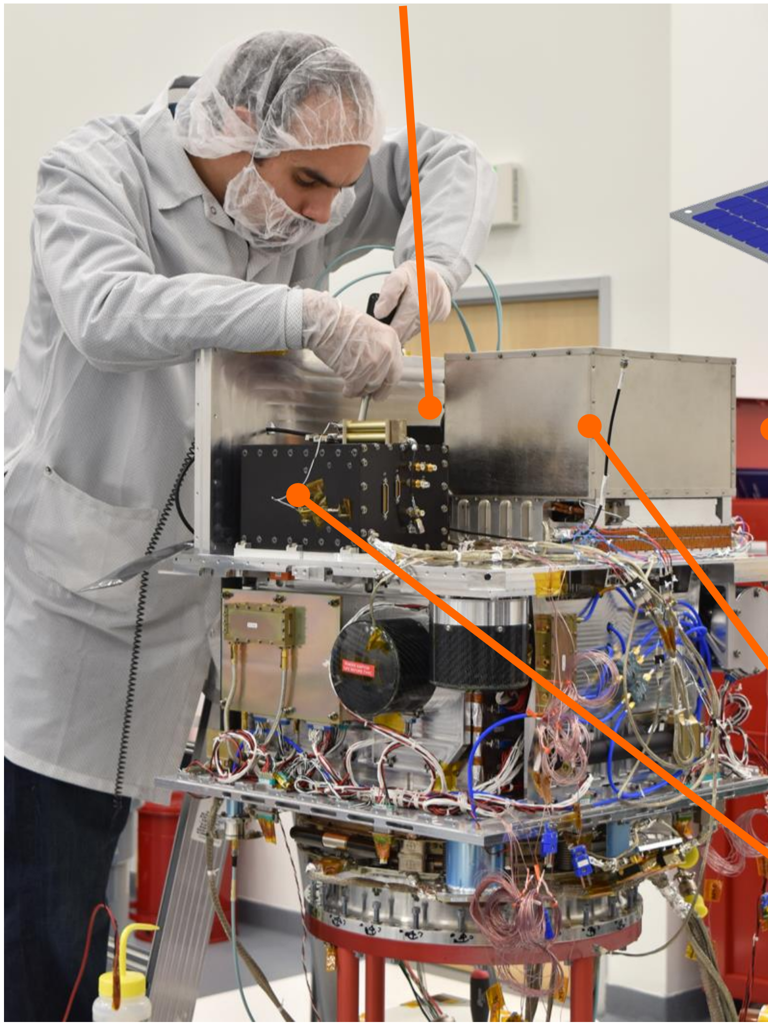
Atomic Frequency Standard	Mass	Average Power
DSAC Demo Unit (1st Generation)	16 kg	< 50 W
DSAC Future Unit (2nd Generation)	< 10 kg	< 30 W
GPS IIF Rb (5th Generation)	7 kg	< 40 W
Galileo H-Maser (2nd Generation)	18 kg	< 60 W

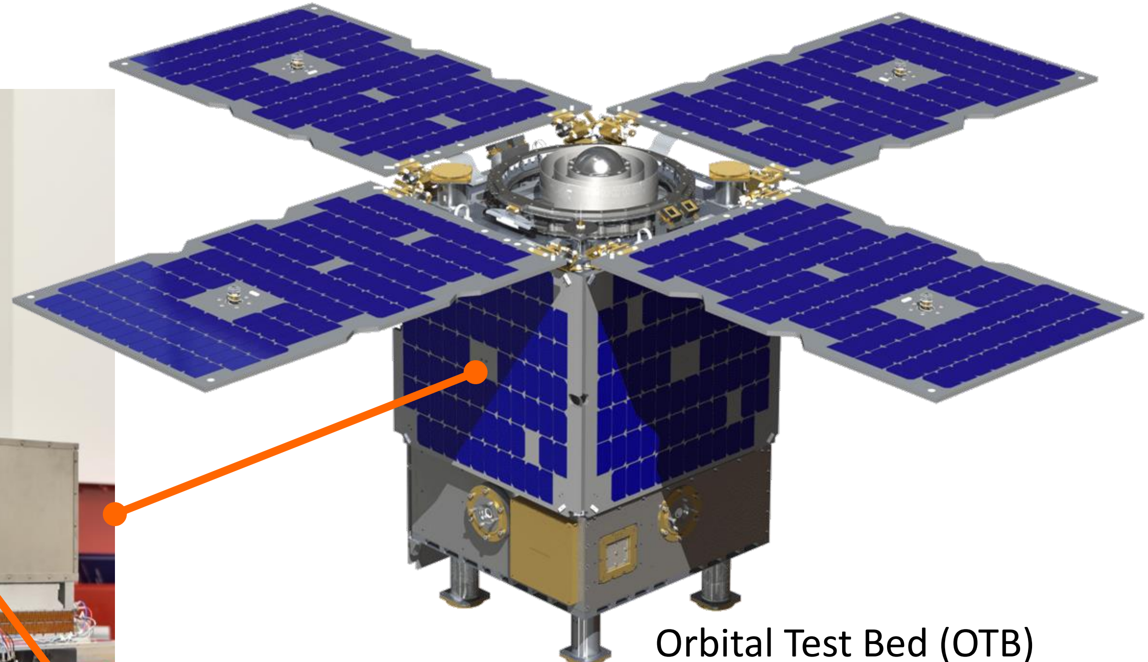
- Anticipated Allan Deviation (including drift) < 3e-15 at one-day will outperform all existing space atomic frequency standards
- Mass and power of DSAC Demo Unit competitive with existing atomic frequency standards – future version could be < 10 kg and < 30 W with modest investment

DSAC is an ideal technology for infusion into deep space exploration and national security systems

DSAC Payload Integrated on the Orbital Test Bed Spacecraft

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





Orbital Test Bed (OTB)
Host Spacecraft (GA-EMS)

DSAC Demo Unit (DU)
Atomic Resonator (JPL)

GPS Receiver
Validation System (JPL-Moog)

Demo Unit designed for maximal instrument telemetry and prototyping flexibility and demonstration

Mission Architecture and Timeline

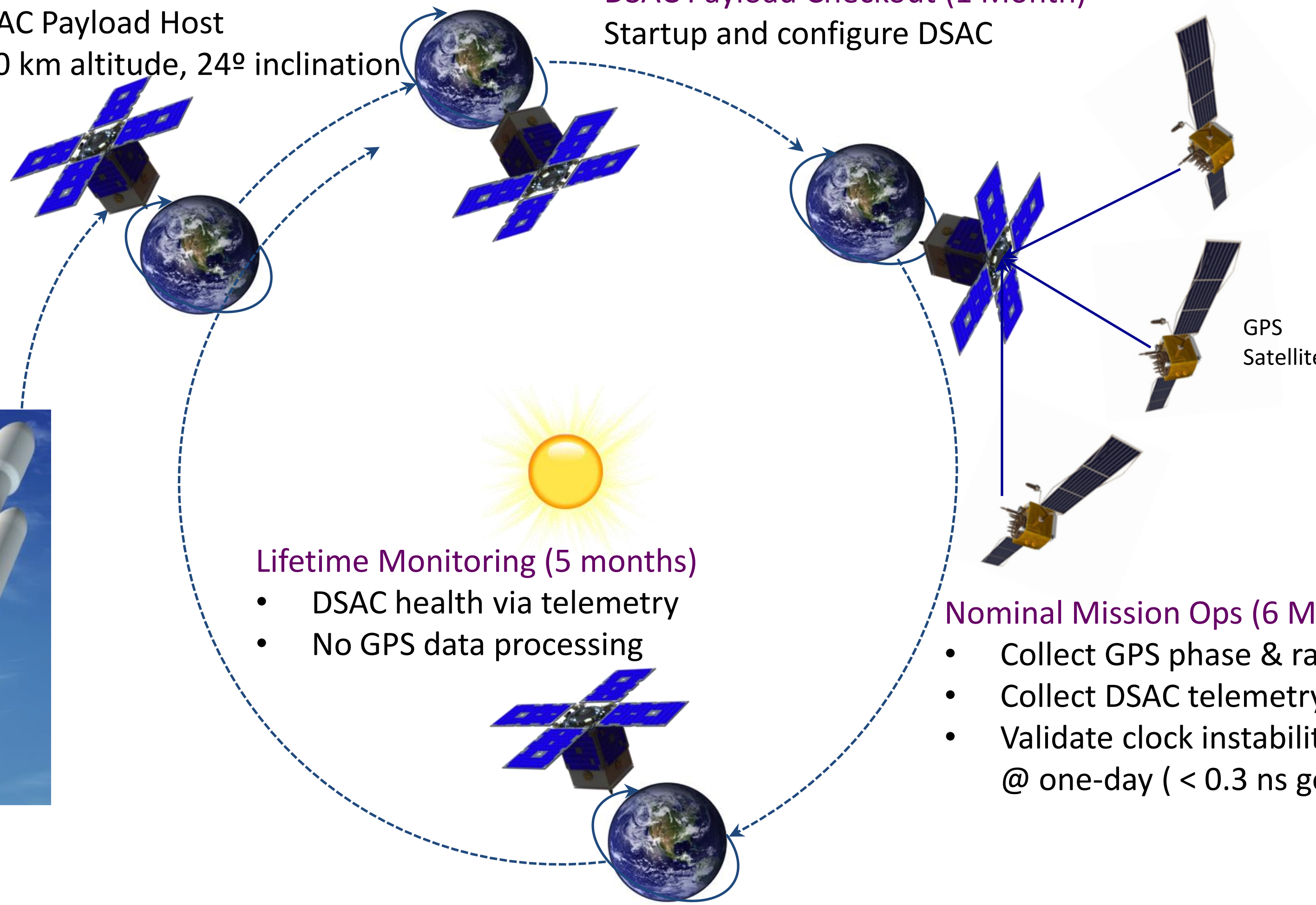
Launch
USAF STP-2
(Falcon Heavy)

GA-EMS OTB Checkout (7 Weeks)

- DSAC Payload Host
- 720 km altitude, 24º inclination

DSAC Payload Checkout (1 Month)

Startup and configure DSAC



Lifetime Monitoring (5 months)

- DSAC health via telemetry
- No GPS data processing

Nominal Mission Ops (6 Months)

- Collect GPS phase & range data
- Collect DSAC telemetry
- Validate clock instability < 2 ns @ one-day (< 0.3 ns goal)

Launch Spring 2019 for one-year demonstration

Schedule

• MDR & SRR	February 2012 ✔
• Preliminary Design Review	May 2013 ✔
• Key Decision Point–C	November 2013 ✔
• Clock Critical Design Review	May 2014 ✔
• Mission CDR & System Integration Review	Nov 2014 ✔
• Pre-Ship Review	Jan 2017 ✔
• System-End-to-End Test	Oct 2017 ✔
• Mission Readiness Review	June 2018 ✔
• Launch	Spring 2019
• Mission Operations	Launch + 1 Year

Towards a GPS ready version of DSAC

- Development of an operational mercury atomic frequency standard (MAFS) based on DSAC technology realizable in the near-term
  - Alternate technologies (optical Rb and cold atom Cs) at much lower readiness levels with TRL 7 not achievable for 10 years or more
    - Recent Aerospace report recommended DSAC as the only viable US technology for near term deployment on GPS
  - DSAC Demo Unit a point of departure with demo results feeding into MAFS design and development
- In discussions with the GPS program office on *potential* for a GPS-demo version of DSAC to fly in a GPS III spare clock slot
  - A smart approach is to pair with the right commercial partner and develop a clock that is easily adapted for multipurpose use – GPS, AEHF, NASA

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