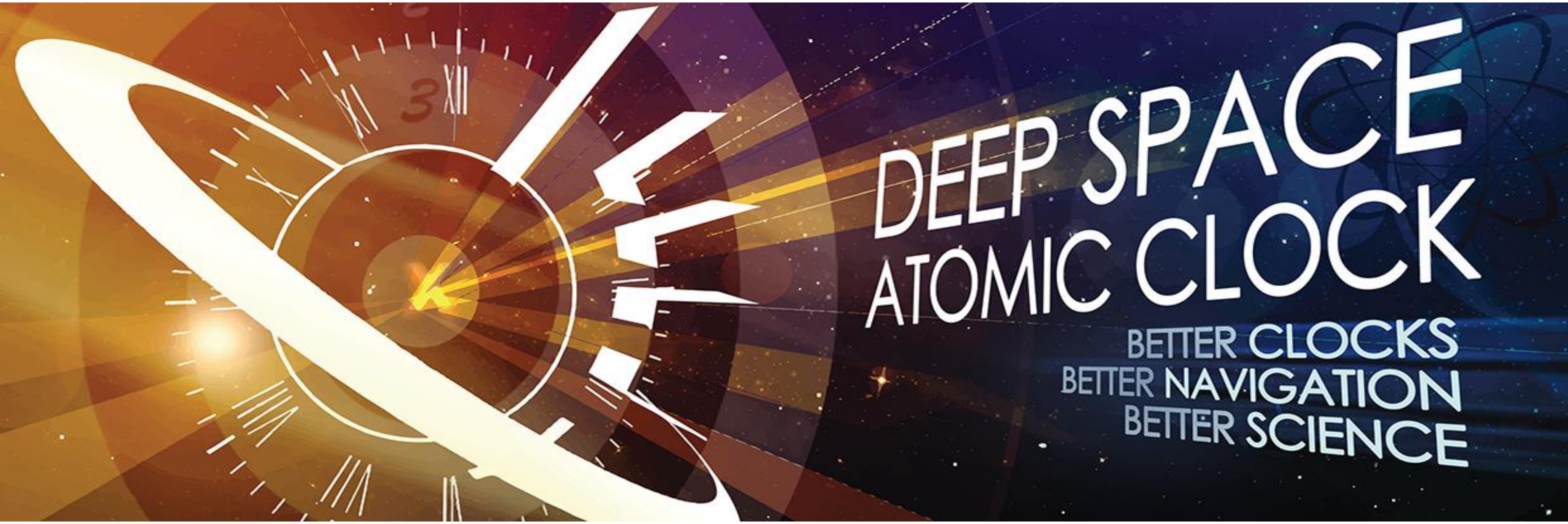

Deep Space Atomic Clock Overview

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February 2017

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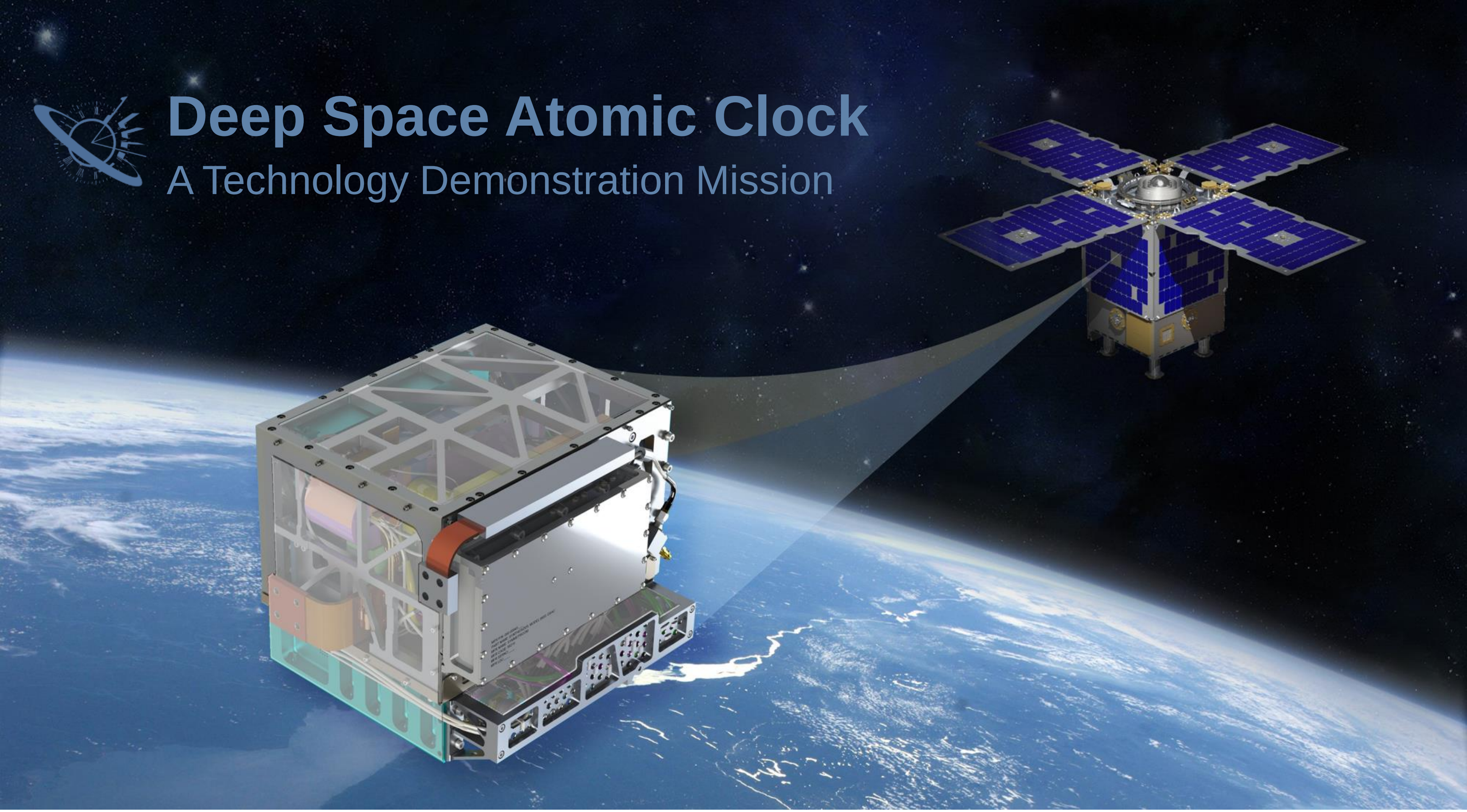
California Institute of Technology

Deep Space Atomic Clock

A Technology Demonstration Mission



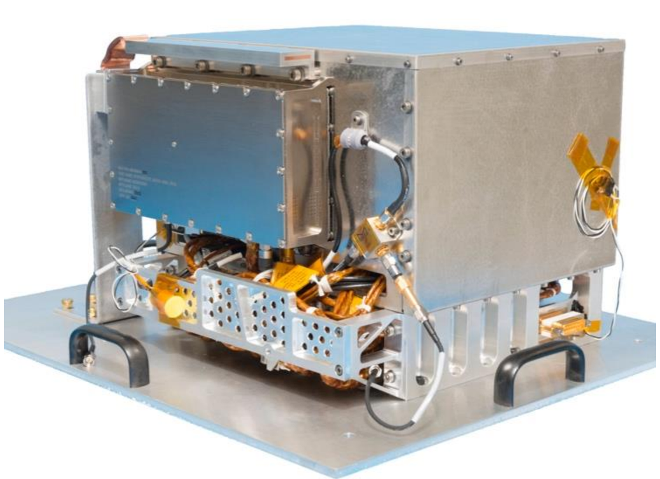
NASA TDM SCaN Space Communications and Navigation

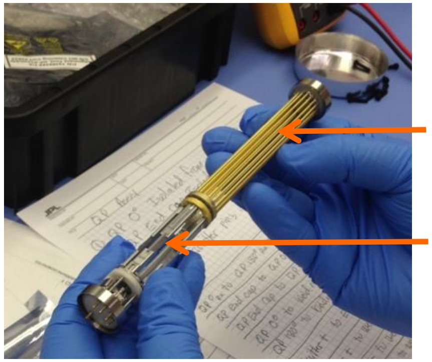
JPL Jet Propulsion Laboratory California Institute of Technology

SURREY Satellite Technology US

DSAC Technology Demonstration Mission

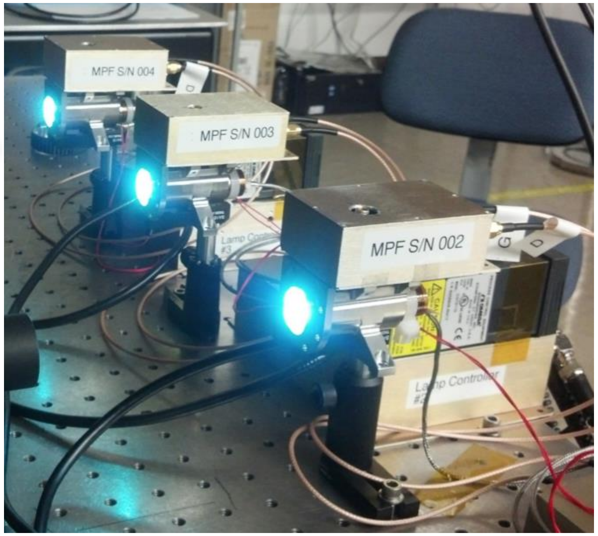
DSAC Demonstration Unit





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 Sept 2017+ – 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

Broad Benefits for Enhanced Exploration & National Security

Enable routine use of 1-Way tracking - more flexible/robust mission ops than with 2-Way tracking

- *Ex.: 3X more radio science data during Europa flybys without constraining other science*

Fundamental to enabling real-time, on-board deep space radio navigation

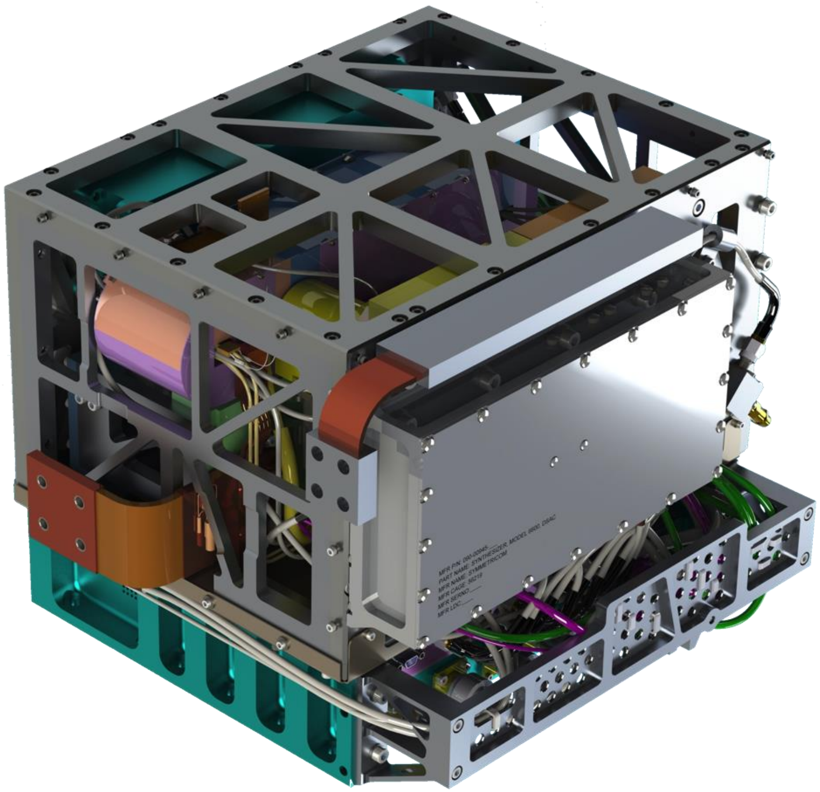
- *Ex.: Trajectory knowledge to 10's of meters at entry to Mars' atmosphere*

Enable use of existing DSN Ka-band downlink tracking capability – improve data accuracy by 10X

- *Ex.: Determine Mars' long period gravity and orientation to GRACE-quality using one spacecraft*

National security resource to GPS, protected command and control, and other applications

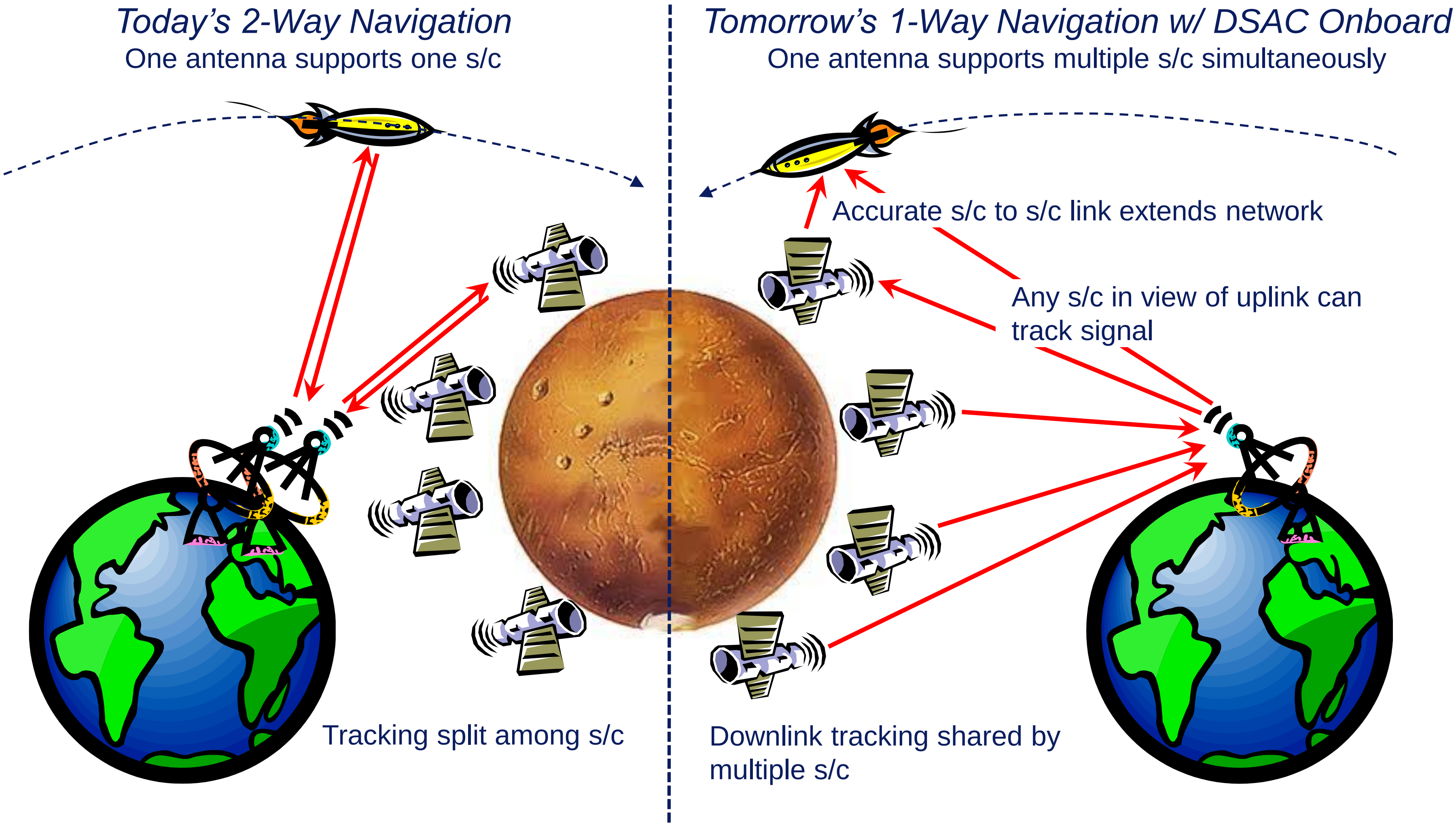
- *Ex.: Improves upon existing GPS clock performance by 50 times or more*



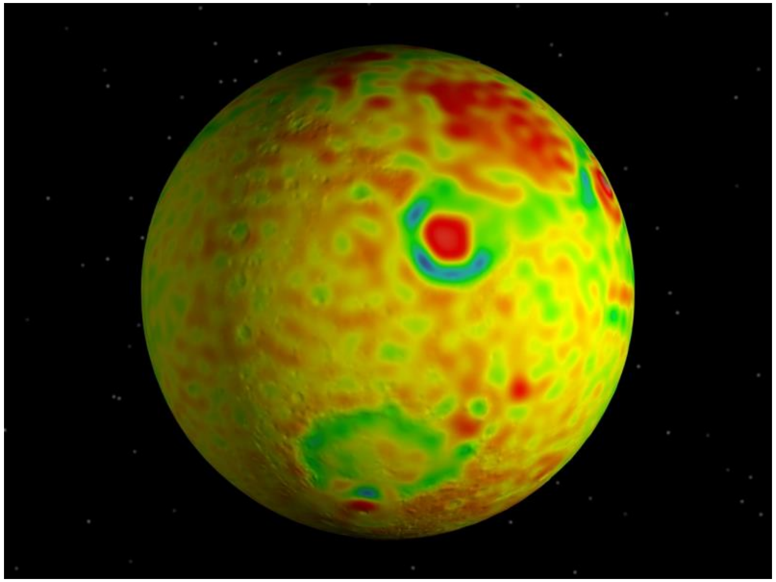
DSAC Benefits the DSN and Mission Operations

- One-way tracking improves existing tracking and onboard timing capabilities
  - Increase tracking data quantity via efficient use of uplink or downlink signals
    - Utilize multiple spacecraft per aperture downlink tracking – 2-3x more tracking for Mars assets
    - Enable use of uplink tracking with low gain antennas on s/c
      - » 3x more radio science and navigation data during Europa flybys
      - » Continuous tracking of *all* Mars s/c carrying DSAC
  - Eliminate need for three-way tracking at distant locations – removes multiple Earth antenna geometry and availability constraints
  - Increase bandwidth for downlink communications – use uplink for ranging

DSAC Enables a Scalable DSN Tracking Architecture

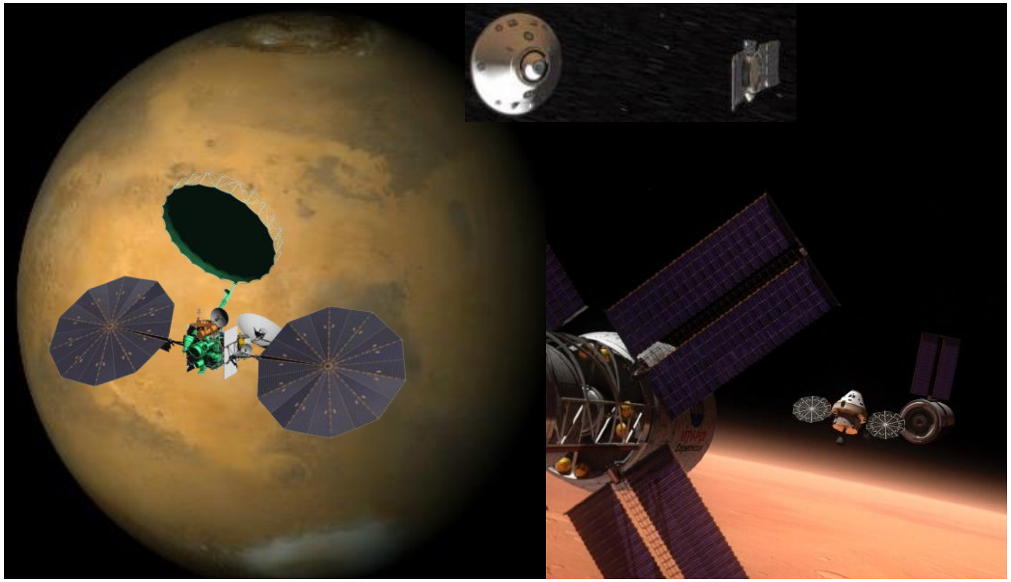


DSAC Enhances Science and Enables Robust Onboard Navigation



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

- Ka-band data an order of magnitude 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



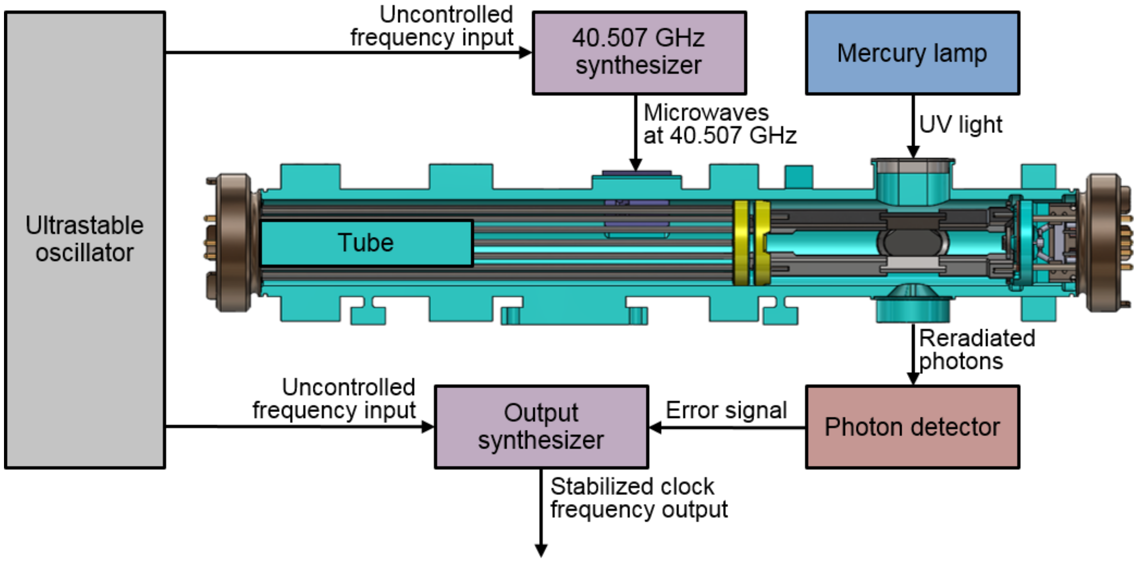
Real time, onboard deep space radio navigation system with DSAC yields

- Trajectory knowledge to 10s of meters 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 needed 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 the Local Oscillator (DSAC selected USO 2e-13 at 1 second)
- Longer term stability (> 10 sec) determined by the "atomic resonator" (Ion Trap & Light System)

Key Features for Reliable, Long-Life Use in Space

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

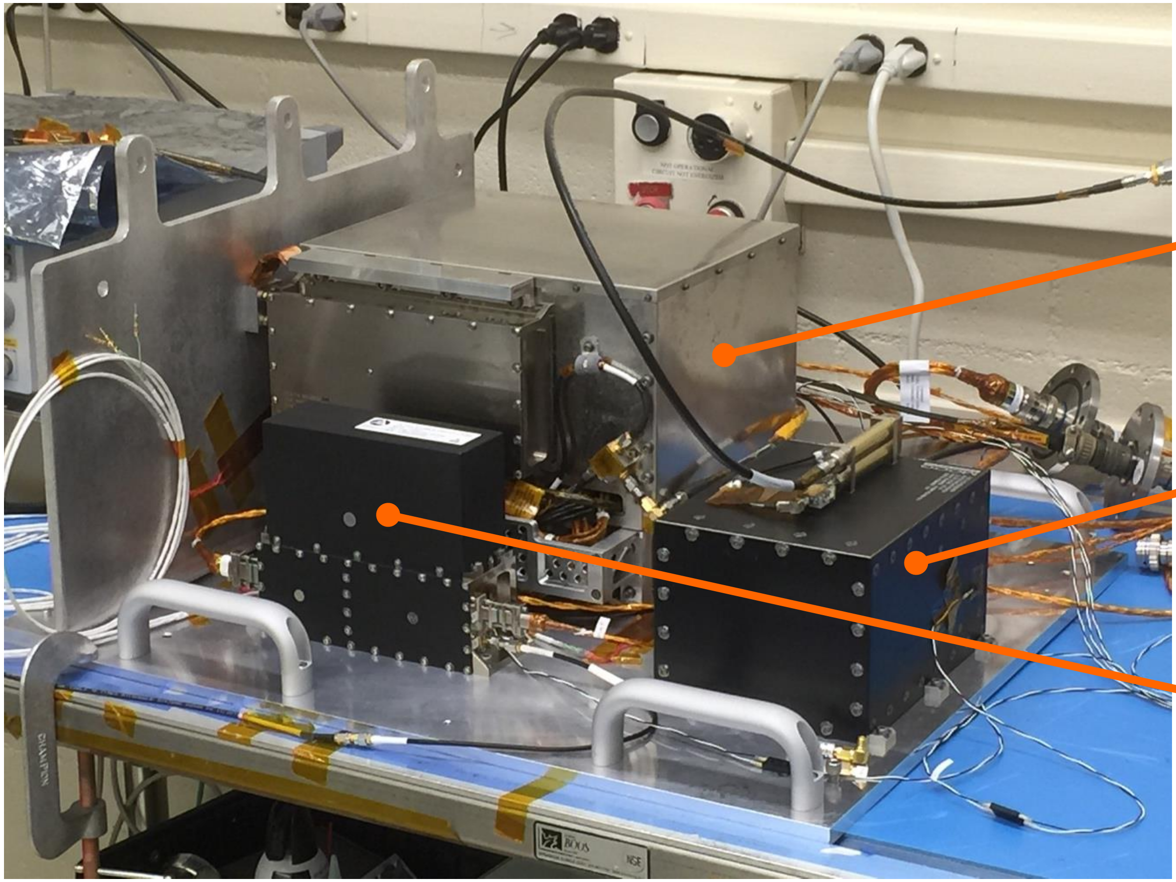
Ion Clock Technology Highlights

- State selection of 10^6-10^7 $^{199}Hg^+$ electric-field contained (no wall collisions) ions via optical pumping from $^{202}Hg^+$
- High Q microwave line allows precision measurement of clock transition at 40,507,347,996.8 Hz using DSAC/USO system

$$SNR \times Q < \frac{5 \times 10^{-13}}{\sqrt{\tau}} \quad \& \quad A.D. < 3 \times 10^{-15}$$

- Ion shuttling from quadrupole (QP) to multipole (MP) trap to best isolate from disturbances - QP only implementation offers major simplification
- Ions are in an uncooled Neon buffer-gas

Payload Integration & Test on Flight Hardware



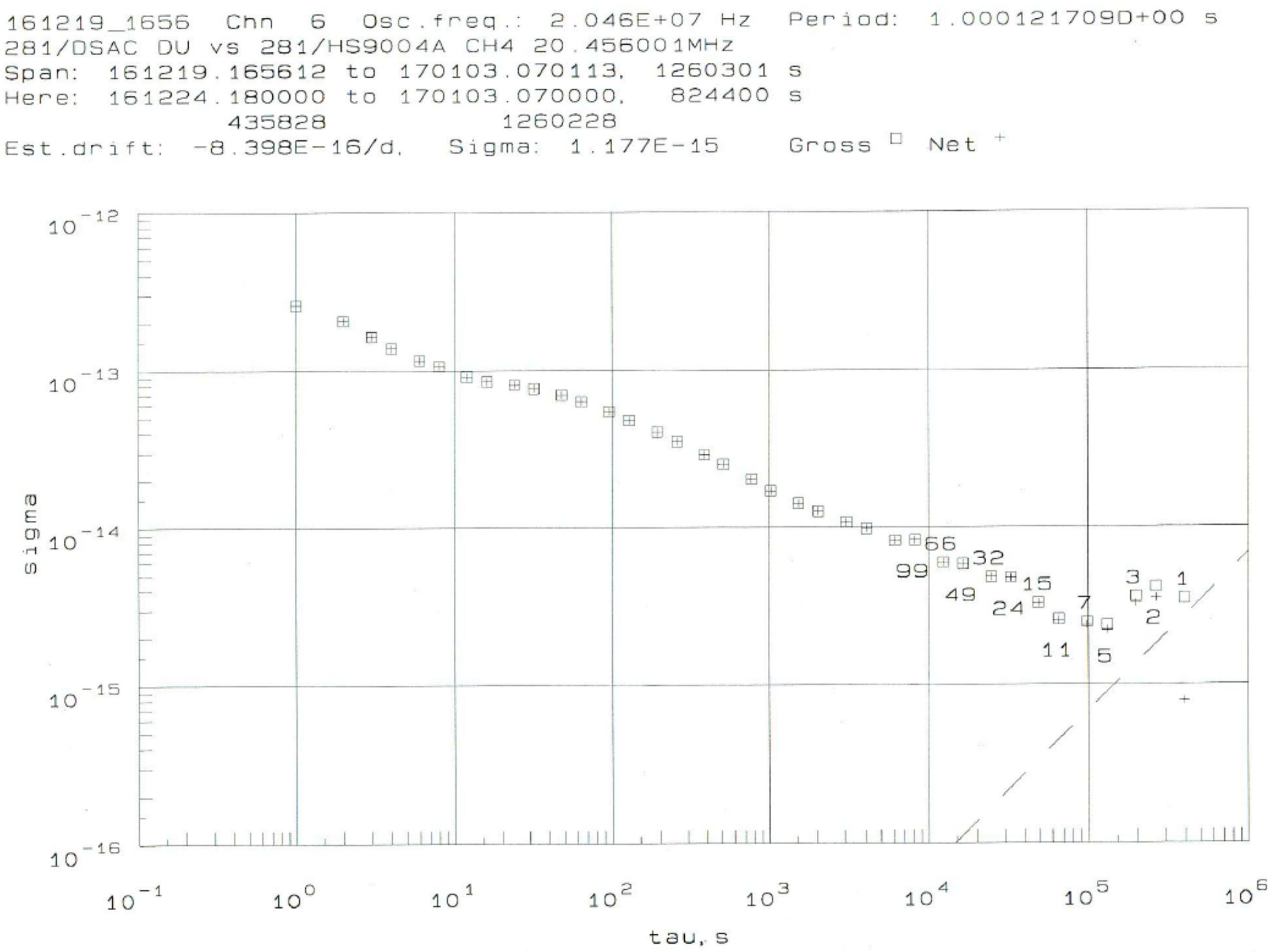
DSAC Demo Unit (DU)
Atomic Resonator (JPL)
V: 285 x 265 x 228 mm
M: 16 kg, Physics Pkg – 6.6 kg
P: 45 W, Physics Pkg – 17 W

GPS Receiver
Validation System (JPL-Moog)

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

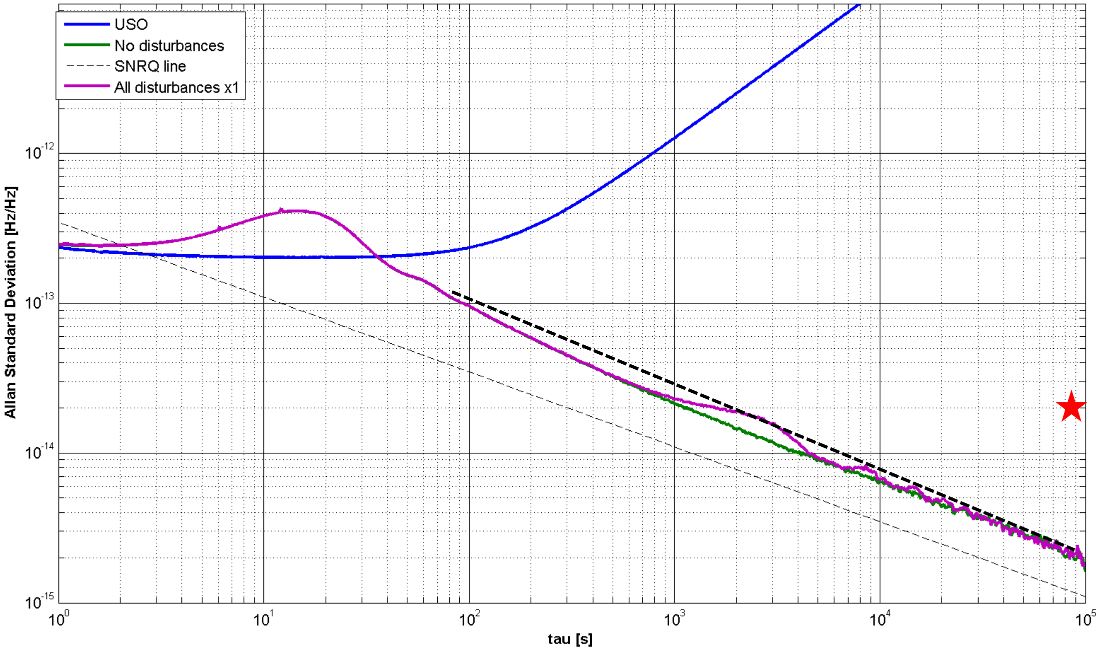
Demo Unit designed for prototyping flexibility – room to optimize mass, power, and volume.

Demo Unit Measured Stability (Maser Input)



- 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

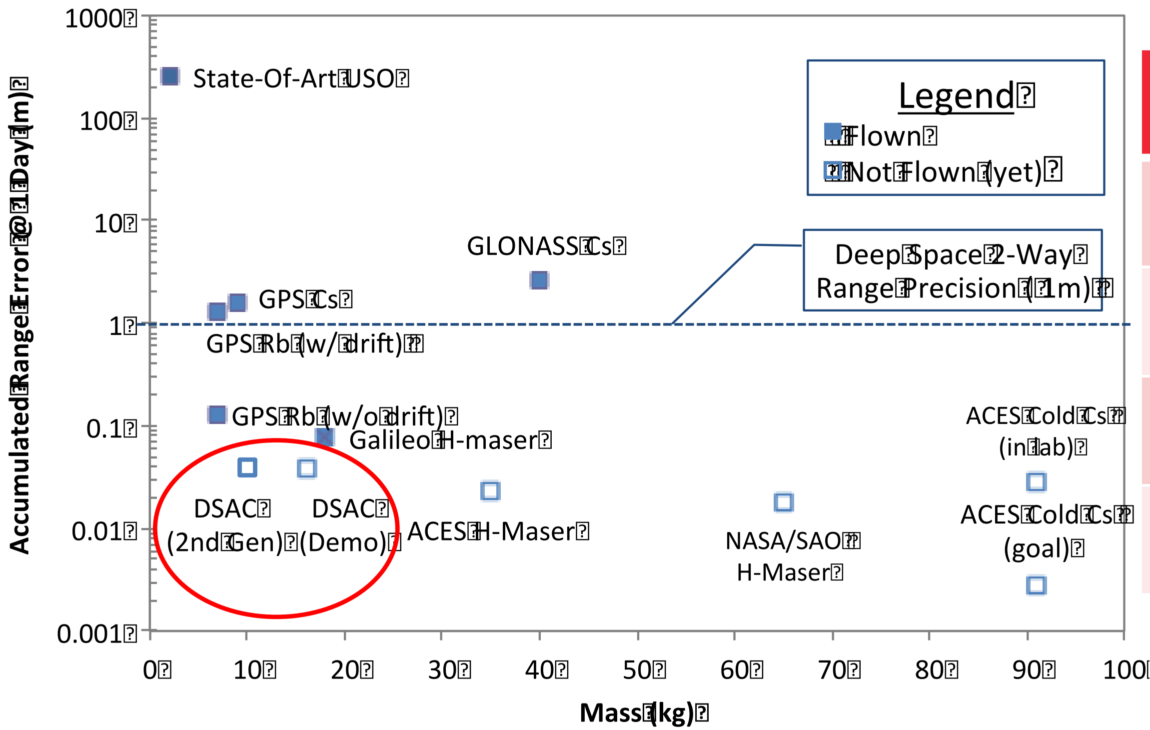
Model-based simulated on-orbit performance of DSAC in QP mode



- DSAC is predicted to have an AD ~ 3e-15 with expected orbital thermal and magnetic variations
- GPS systematic errors (predicted to be ~2.2e-15) raises this to ~ 3.7e-15 (via rss'ing)
- Using 14 days of data (nominal operational cadence), yields an equivalent 1-sigma upper confidence limit of ~ 4.1e-15

On-orbit performance expected to be verified at < 5.e-15 at one-day

DSAC Compared to Other Space Clocks

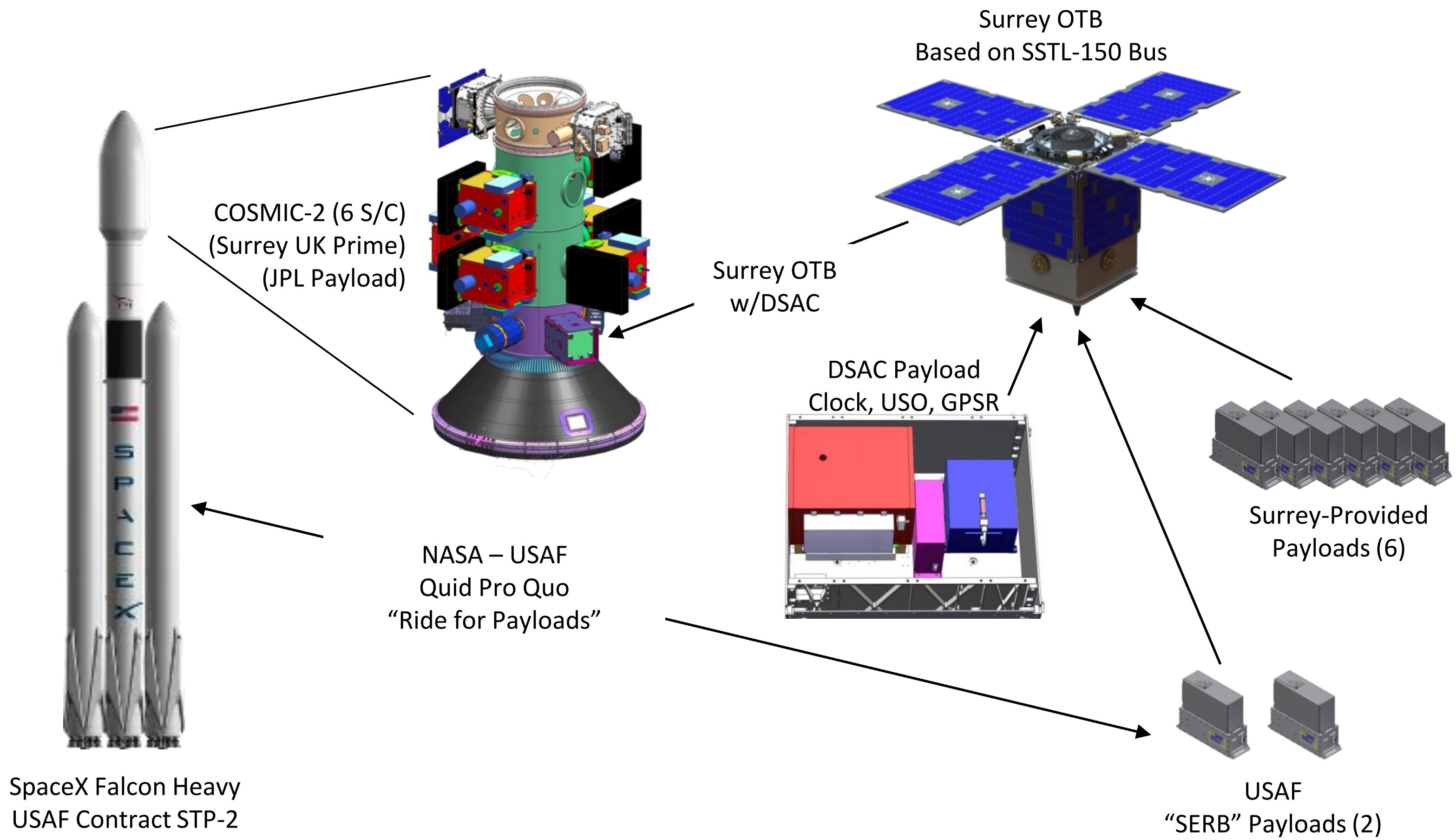


Atomic Frequency Standard	Mass	Average Power
DSAC Demo Unit (1st Generation)	16 kg	< 50 W
DSAC Future Unit (2nd Generation)	< 10 kg	< 30 W
GPS IIF Rb (5th Generation)	7 kg	< 40 W
Galileo H-Maser (2nd Generation)	18 kg	< 60 W

- Anticipated Allan Deviation (including drift) of < 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

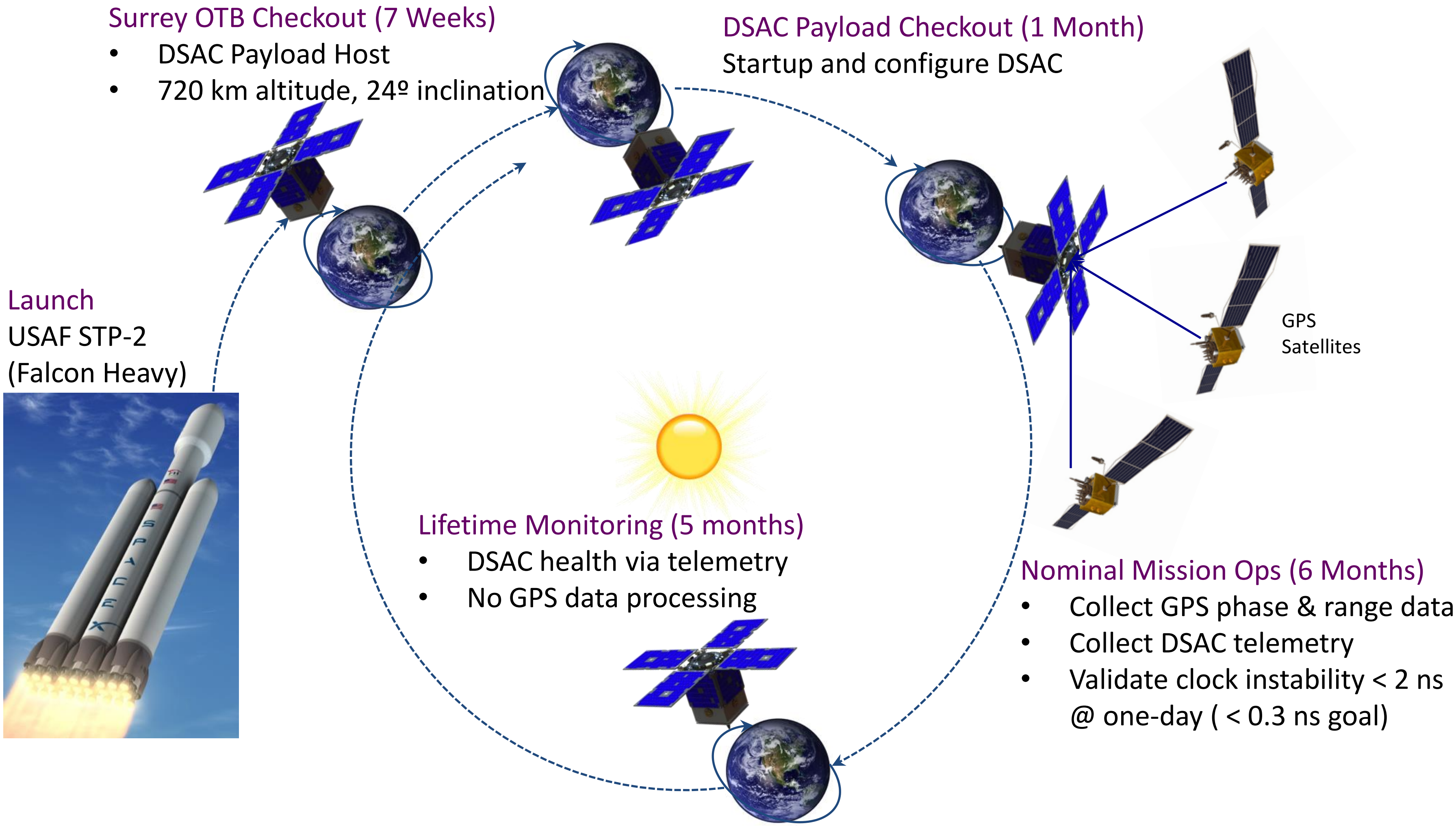
DSAC is an ideal technology for infusion into deep space exploration and national security systems

Ride Story



Flight Services Agreement in Place (S/C Host), STP-2 MOU Signed (LV), Ground Stations AF/JSC …

Mission Architecture and Timeline



DSAC currently being integrated with OTB. Launch Sept 2017+ for one-year demonstration

Jet Propulsion Laboratory
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jpl.nasa.gov