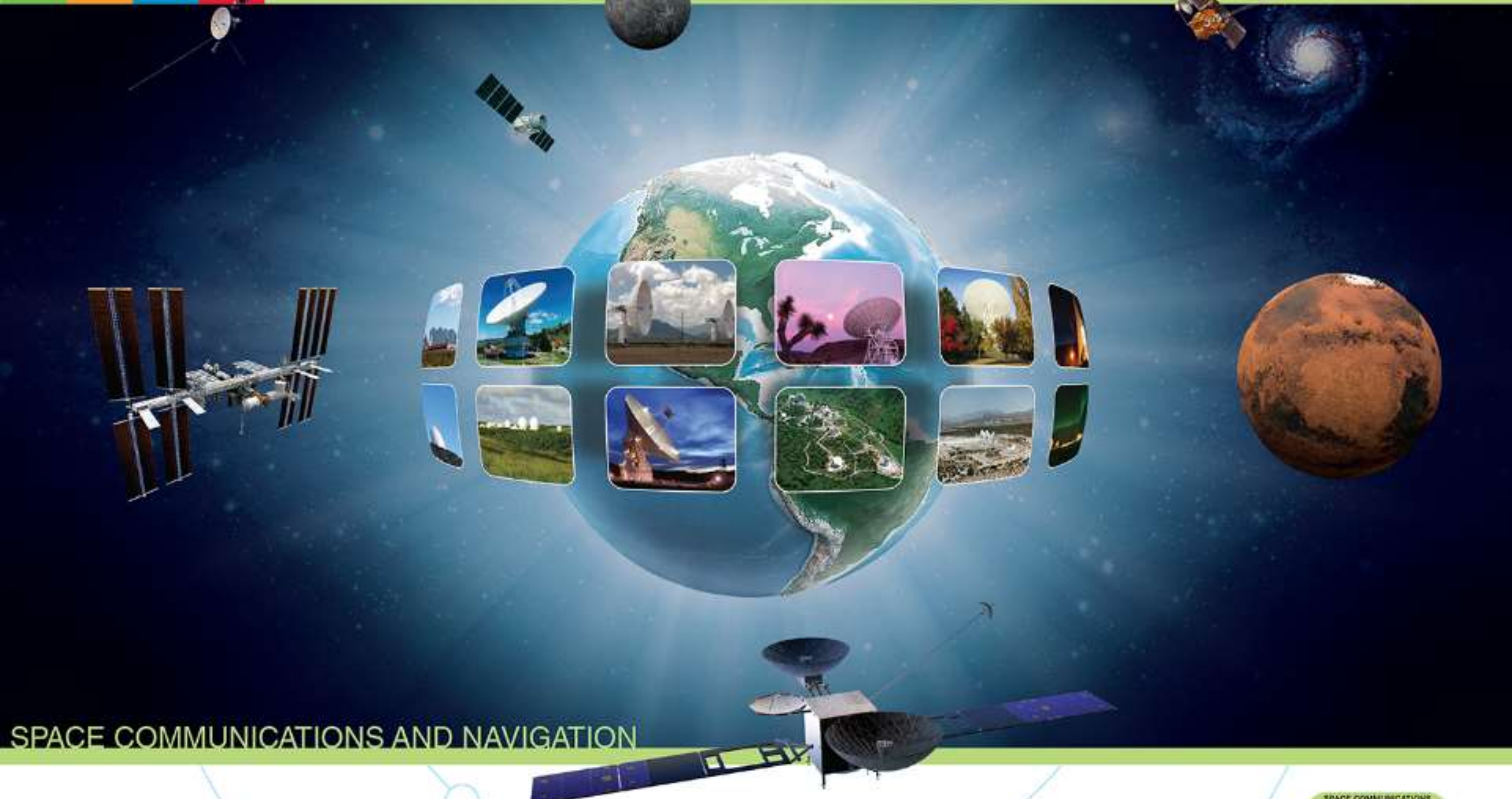
NASA's Deep Space Atomic Clock and Optical Communications Program for PNT Applications

National Aeronautics and Space Administration



Dr. Don Cornwell, Director
Advanced Communications and Navigation Division

www.nasa.gov

NASA's Space Comm and Nav (SCaN) Program Manages All 3 NASA Networks

Deep Space Network

Three global ground stations providing services to missions from Geostationary Earth Orbit (GEO) to beyond our solar system.

Focused on detecting and differentiating faint signals from stellar noise

Near Earth Network

Set of world-wide NASA and commercial ground stations providing services to missions in Low Earth Orbit (LEO) and High Earth Orbit (HEO) as far as the Moon.

Space Network

Fleet of Tracking and Data Relay Satellites (TDRS) and their ground stations providing services to missions in Low Earth Orbit (LEO)

Optimized for continuous, high data rate communications

Critical for human spaceflight safety and critical event coverage

UNCLASSIFIED//FOUO

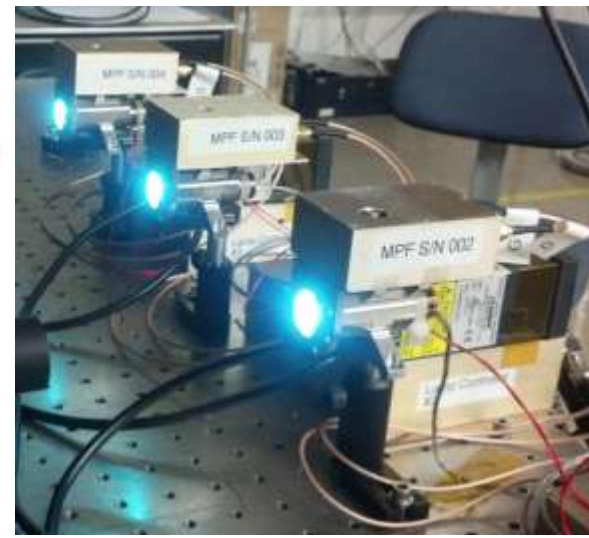
SCaN's Advanced Communication and Navigation High-Level Roadmap

DSAC Mercury Ion Clock Technology Demonstration Mission

DSAC Demonstration Unit

Titanium Vacuum Tube

Mercury UV Lamp Testing



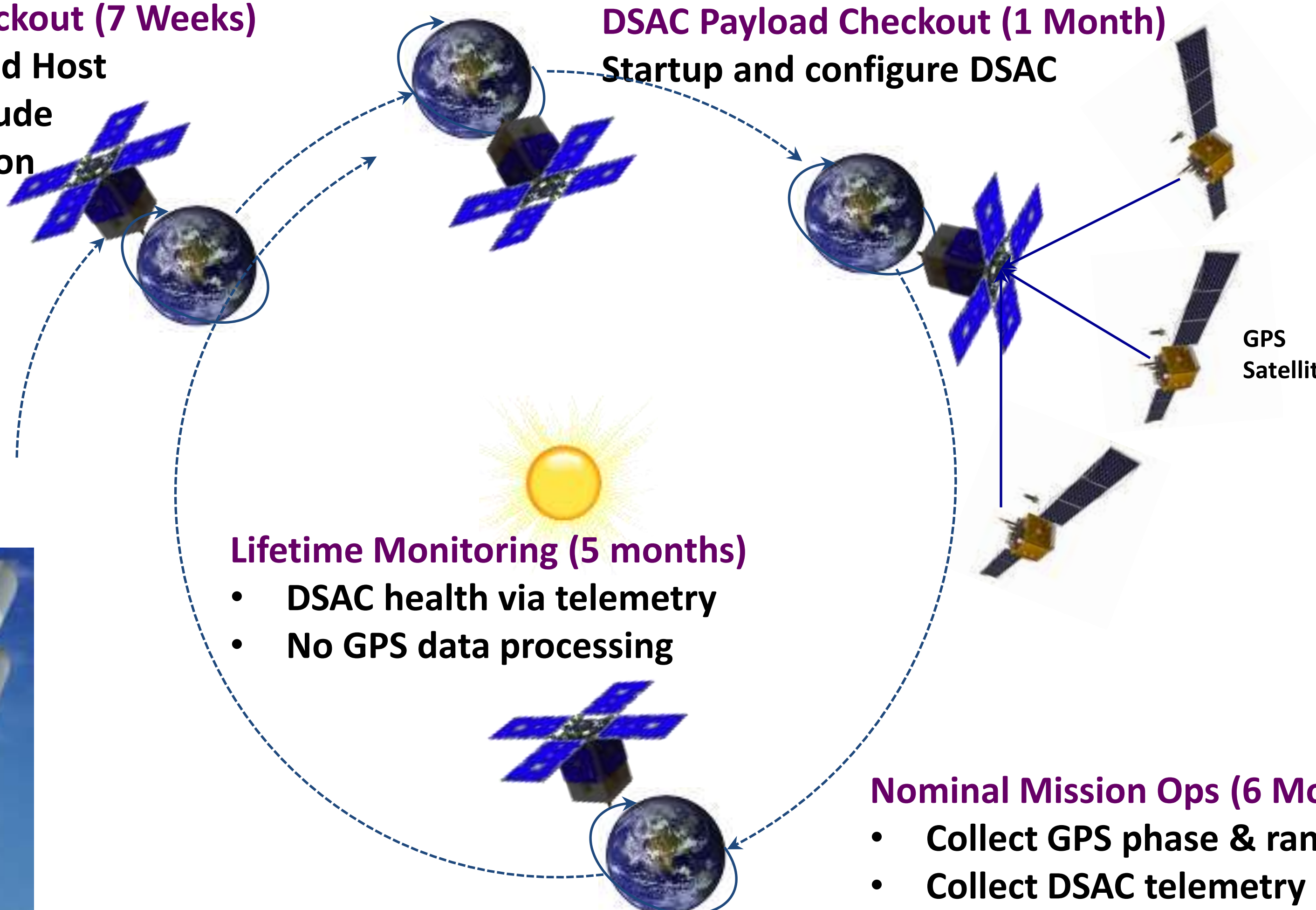
Develop advanced prototype ('Demo Unit') mercury-ion atomic clock for navigation/science in deep space and Earth

- **Perform up to year-long demonstration in space beginning Fall 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**

DSAC Mission Architecture and Timeline: Current LRD Sept 2017 (TBD)

Surrey OTB Checkout (7 Weeks)
- DSAC Payload Host
- 720 km altitude
- 24º inclination

DSAC Payload Checkout (1 Month)
Startup and configure DSAC



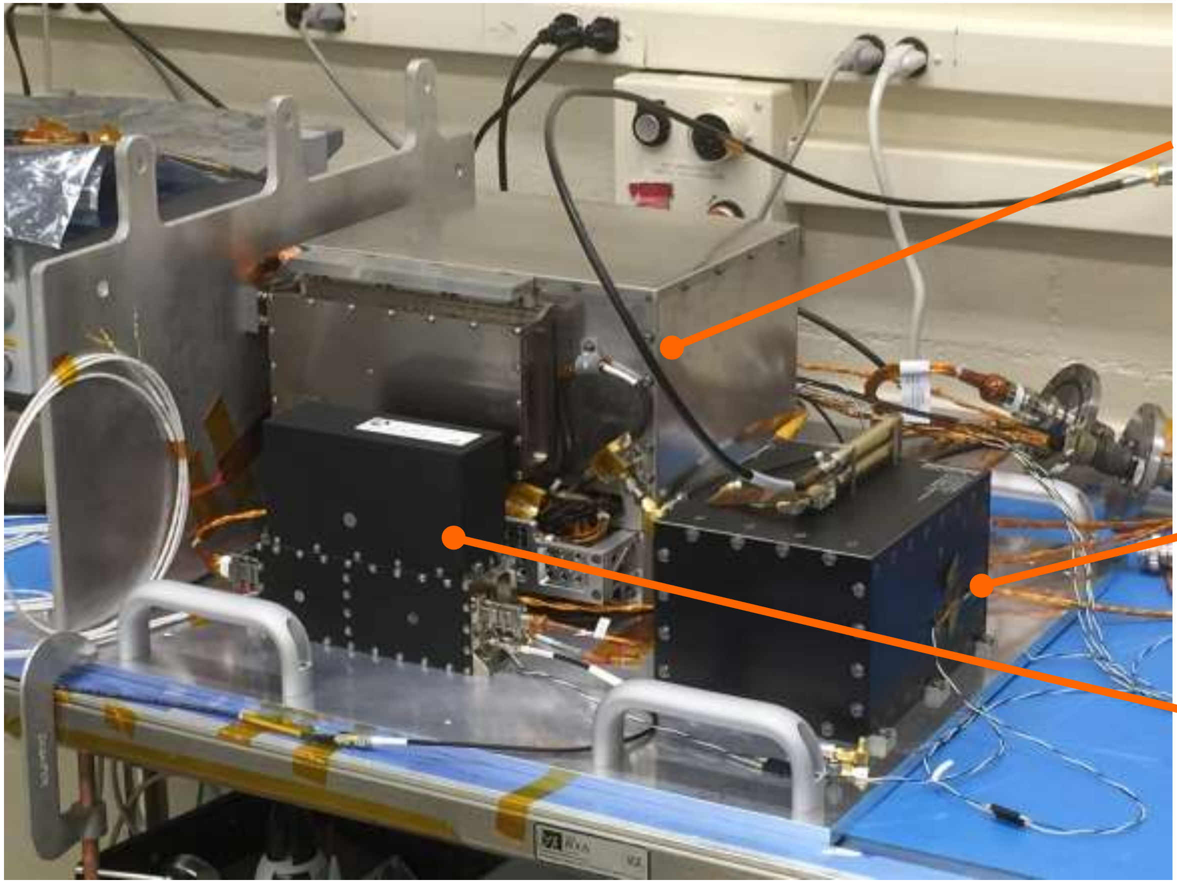
Launch
USAF STP-2
(Falcon
Heavy)

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 Fall 2017 for one-year demonstration

DSAC Payload Integration & Test with Flight Hardware



DSAC Demo Unit (DU)

Atomic Resonator (JPL)

V: 285 x 265 x 228 mm

M: 16 kg, Physics Pkg – 5.7 kg

P: 45 W, Physics Pkg – 24 W

GPS Receiver

Validation System (JPL-Moog)

Ultra-Stable Oscillator (USO)

Local Oscillator (FEI)

The DSAC Demonstration Unit was designed for prototyping flexibility and has significant room for mass, power, and volume optimization.

Aerospace Corp Study recommended that GPS Program Support the DSAC technology (October 2015)

- ***"Pragmatically, recognizing specific program funding limitations, and the fact that a space-qualified Hg+ clock is already under construction, we recommend uninterrupted and adequate GPS support for development of JPL's space-qualified Hg+ clock."***

Parameter	*GPS-IIF RAFS*	*Hg^+ Clock JPL*	*Laser-Rb Clock INRIM*
Size ($in.^3$)	350 [a]	1050 [e]	1030 [g]
Total Power (W)	50 [b] – warm-up 14 [b] – vacuum	45 [e]	40 [h]
Total Weight (lbs.)	14 [c]	35 [e]	20 [h]
Frequency Aging (day^{-1})	3×10^{-14} [d]	$< 10^{-15}$ [f]	3×10^{-15} [h]

Comparison of JPL vs Italian Clock Technology

Hg^+ Clock		Pulsed-Laser Rb Clock	
Advantage	*Obstacle*	*Advantage*	*Obstacle*
B-Field Insensitivity	Lamp Reliability	No Discharge Lamp	Laser Reliability
Temperature Insensitivity	Getter Lifetime	Evidence of Long Life	Temperature Sensitivity
Long History	Capture Range	Long History	
No New Physics		No New Physics	

Mercury Ion Clock for a NASA Technology Demonstration Mission

Robert L. Tjoelker, *Senior Member, IEEE*, John D. Prestage, *Member, IEEE*, Eric A. Burt, *Member, IEEE*, Pin Chen, Yong J. Chong, Sang K. Chung, William Diener, Todd Ely, Daphna G. Enzer, Hadi Mojaradi, Clay Okino, Mike Pauken, David Robison, Bradford L. Swenson, Blake Tucker, and Rabi Wang

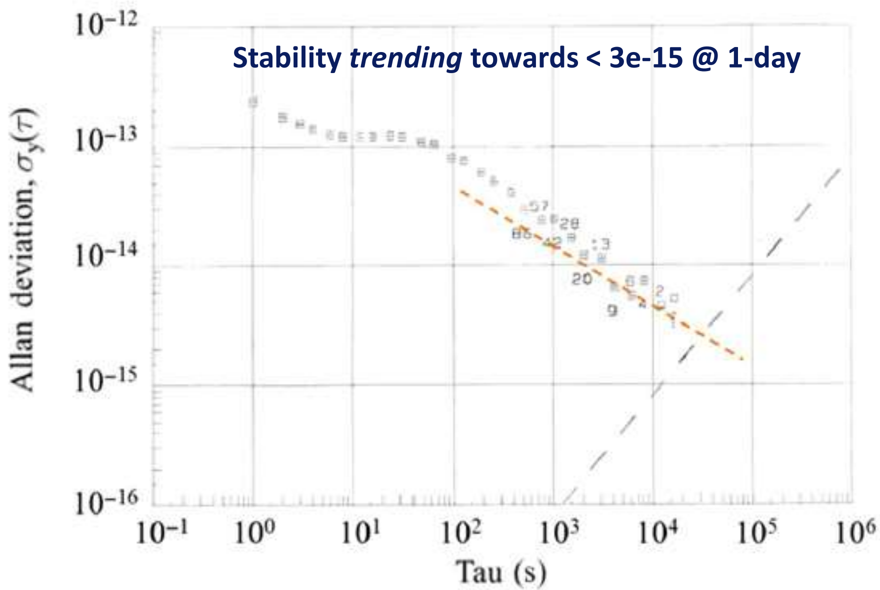


Fig. 15. Initial stability with the DSAC ion clock DU disciplining the LO drift originating from the USO. The degradation at 1 s is due to the 20.456-MHz DDS implementation and the red dashed line shows the SNR*Q limited stability at the time of the measurement.

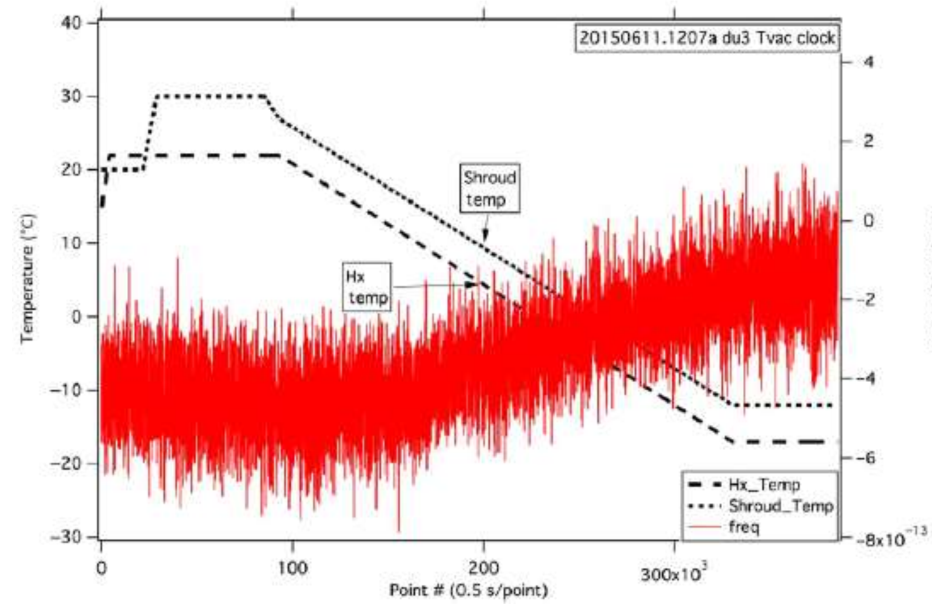
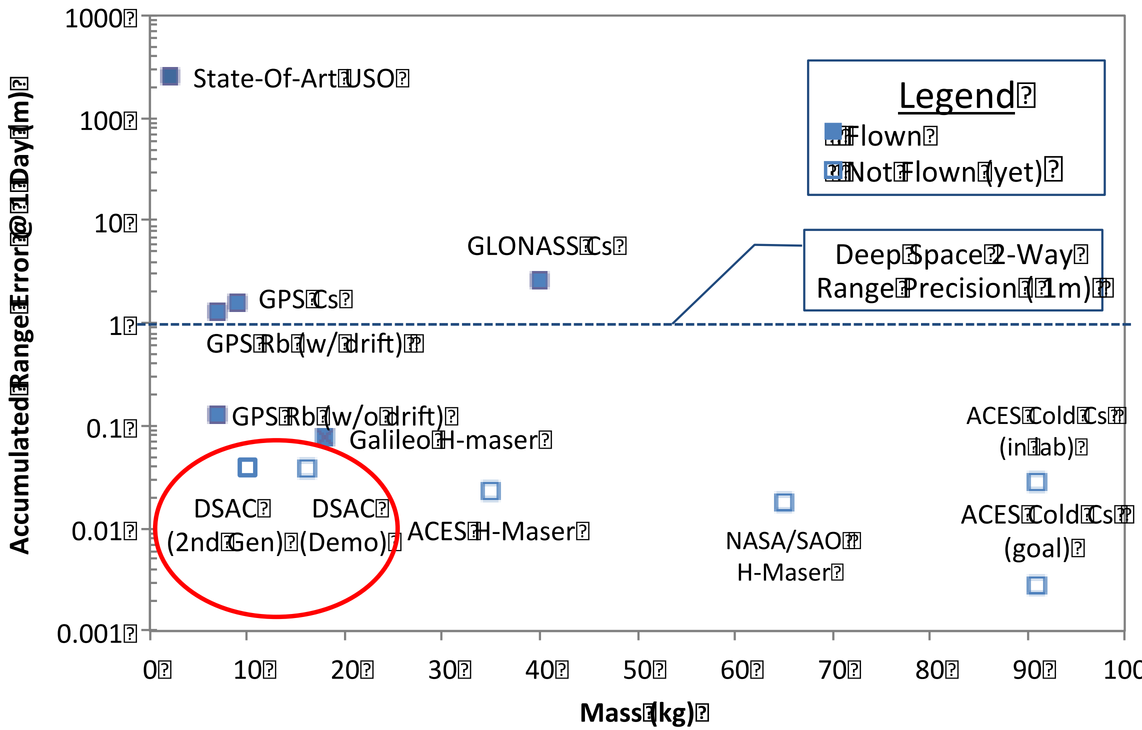


Fig. 17. Thermal-vacuum environmental testing showing the observed clock output frequency over a 42 °C temperature range. The test shows the robust operability over the entire range. There is no thermal control of the instrument except point heaters on the lamp bulb and the ion trap vacuum tube.

DSAC performance is better than expected, with minimal thermal or magnetic sensitivity

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

What's Next? Maturing the technology to an Operational DSAC

Modest continued investment in technology maturation should precede a fully committed project for developing an operational DSAC.

- **Focus area - *extend lifetime***
  - **Quantify and extend operational (and shelf) life of the vacuum tube assembly.**
    - Tube vacuum/gas life: study getter pump, Hg, buffer gas and vacuum tube material interactions and impact on clock stability and tube life
    - Electron emitter life
    - Distinguish operating life differences in QP and MP operation – model and fully understand MP shuttling dynamics
  - **Operational life of the lamp and resonator assembly**
    - Quantification of current aging process
    - Quantification of Hg buffer gas components in an improved fabrication process
    - Lamp alterations to increase life- e.g. Sapphire coatings or bulbs
    - Further quantify interactions and life of the O_2 lamp resonator cell and optics coatings

Maturing the DSAC Technology towards an Operational Version

- **Focus area – *identify SWaP reductions and improvements to manufacturability***
  - **System design architecture and simplification**
    - Simpler tube-feedthrough, trap, and assembly design/procedures.
    - Simpler magnetic system coil and shield approach
    - Packaging, power, and signal grounding architecture
    - Overall uniform thermal system design compatible with other assembly constraints
  - Integrated USO-40.5 GHz local oscillator and control methodologies

- **The above items would need to be integrated into the current flight project schedule/baseline costs.**
  - A very rough order of magnitude for these activities is ~$2M
  - This effort would include developing a industrialization plan for an operational DSAC

An Opportunity for the PNT Community: Developing the Next DSAC with NASA

- **Development of an operational mercury atomic frequency standard (MAFS) based on DSAC technology is realizable in the near-term time horizon**

  - Alternate technologies (optical Rb and cold atom Cs) are at much lower readiness levels with TRL 7 not achievable for quite sometime (5 years or more)
    - ***=> Recent Aerospace report recommended DSAC as the only viable US technology for near term deployment on GPS***

  - Current DSAC is a point of departure for MAFS with 2017 flight experiment results that will feed into MAFS design and development

  - Modest continued investment in technology maturation could precede fully committed project developing an operational MAFS

- **An operational demonstration of MAFS on NTS-III or the 4th slot (with monitoring capability) of a future GPS satellite provides a pathway for new technology adoption in DOD PNT, secure comms, and OGAs**

OPTICAL CROSSLINKS FOR CONSTELLATIONS

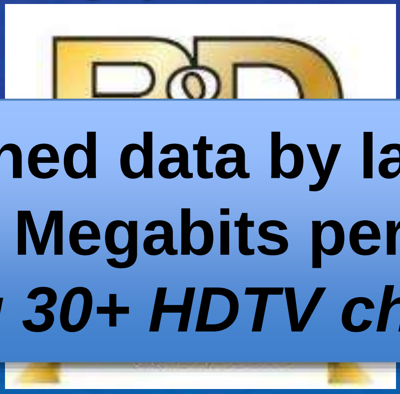
2013: NASA's First, Historic Lasercom Mission

The Lunar Laser Communication Demonstration (LLCD)

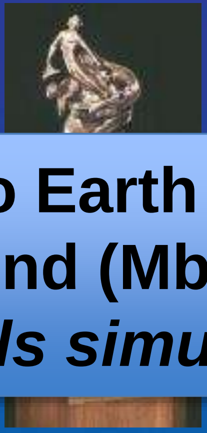
MIT Lincoln Laboratory, NASA GSFC, NASA Ames, NASA JPL, and ESA

2014 Popular Mechanics Breakthrough Award for Leadership and Innovation for LADEE

2014 R&D 100 Winning Technology in Communications category



Nominated for the National Aeronautic Association's Robert J. Collier Trophy

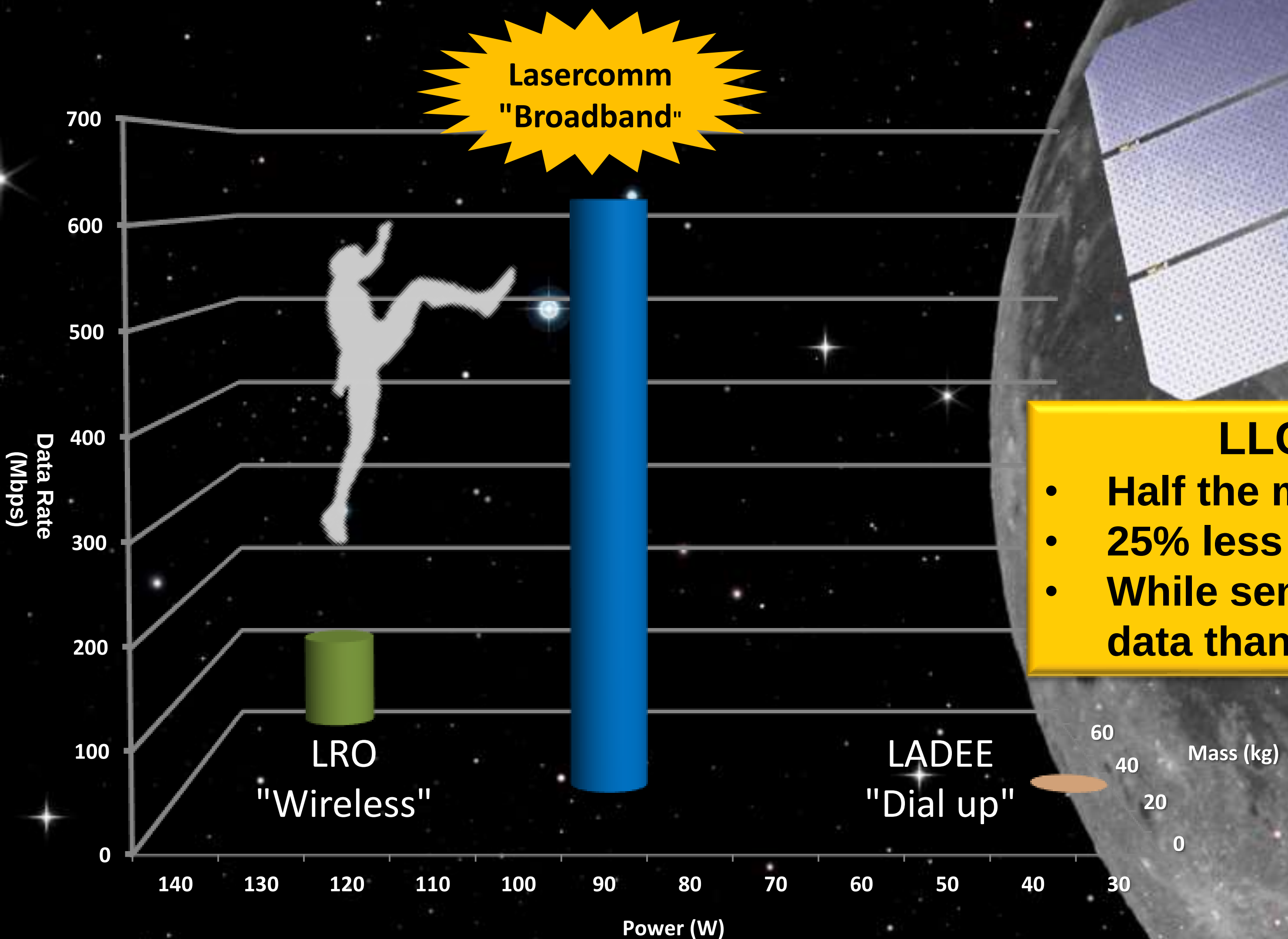


Winner of the National Space Club's Nelson P. Jackson Award for 2015

LLCD returned data by laser to Earth at a record 622 Megabits per second (Mbps)
= streaming 30+ HDTV channels simultaneously!

Laser Communications: Higher Performance AND Increased Efficiency

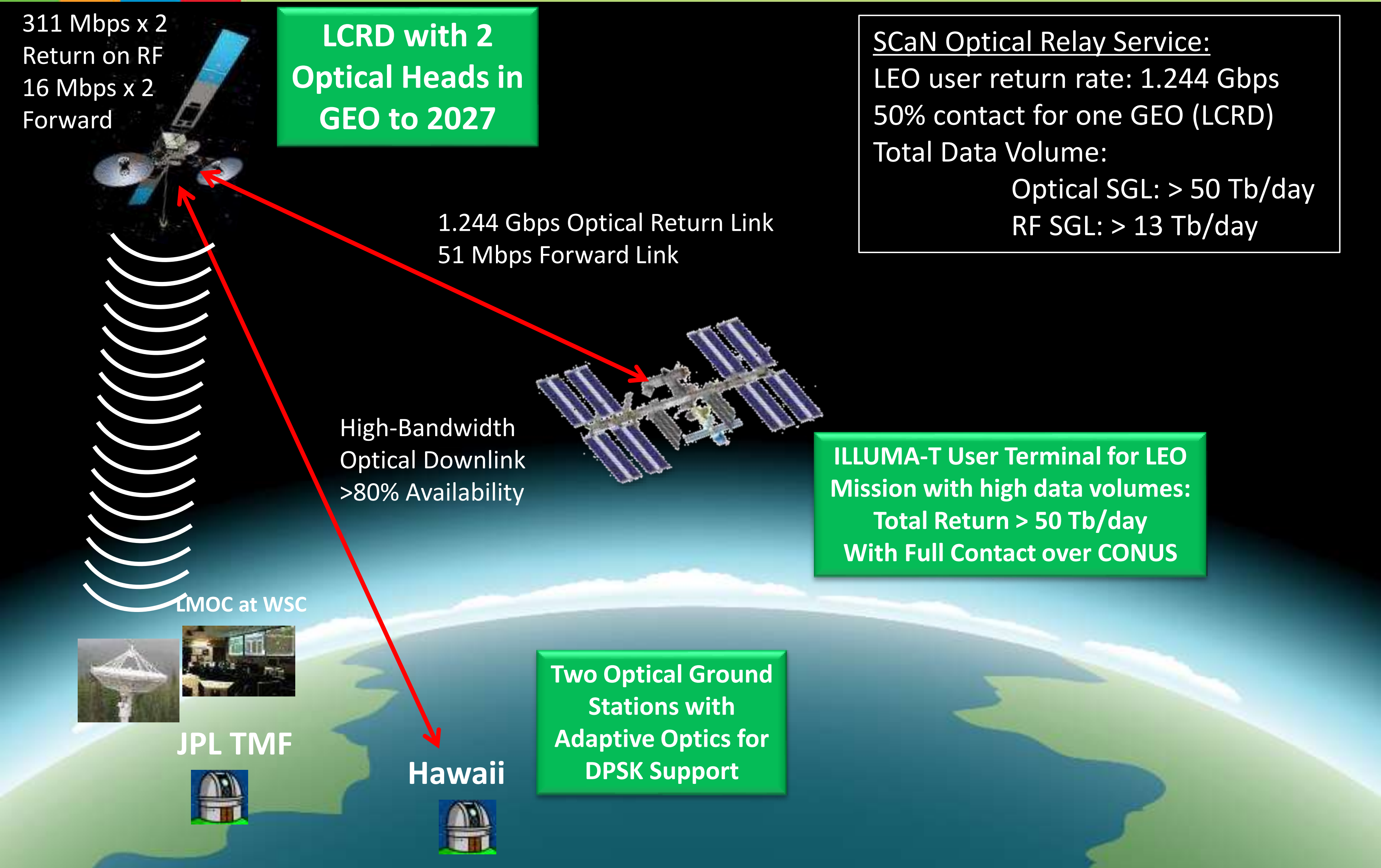
A Giant Leap in Data Rate Performance for Less Mass and Power



LLCD used:

- Half the mass
- 25% less power
- While sending 6x more data than Ka-band on LRO.

Baseline LCRD Architecture: LCRD GEO Node (2019) and ILLUMA-T User Terminal (2020)

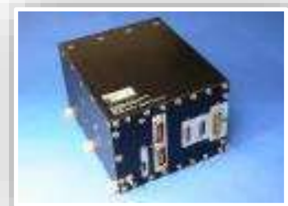


ILLUMA-T: A Commercial, Low-Cost, Low-SWaP Relay User Terminal

- **SCaN is currently funding commercial development of a user terminal for LCRD (and future) relays**
  - ➢ Scheduled to fly on ISS JEM platform in early 2021
- **ILLUMA-T Specifications**
  - ➢ On-board CODEC: 1.244 Gbps Tx/51 Mbps Rx
  - ➢ < 30 kg in a modular architecture
  - ➢ < 120 W
  - ➢ Target $5M per terminal (Qty. >5)
    - ⇒ SCaN would GFE to missions if accepted as a DTO with operational support through 2027 based on LCRD
- **Status and Forward Milestones**
  - ➢ Designed by MIT Lincoln Lab
  - ➢ Flight-like EDU Optical Module to be integrated and tested in April 2017
  - ➢ RFP for Commercial modem in Jan 2017 (GSFC)
  - ➢ RFP for Commercial integrator in 2017 (GSFC)

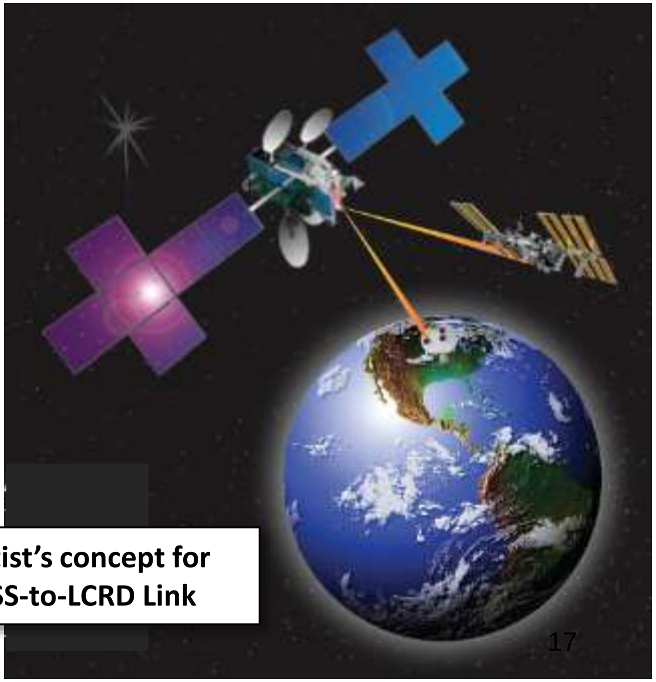
Modem and HPOA

+



Controller Electronics

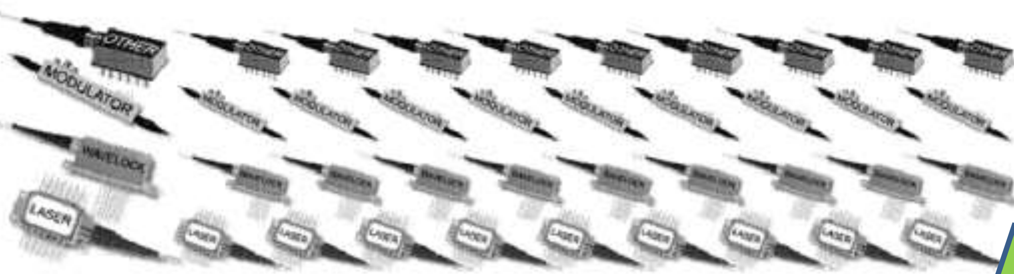
Next-Gen Terminal (NGT)



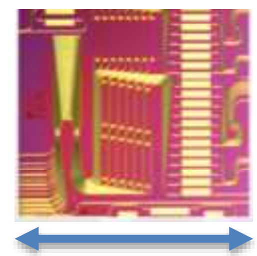
Artist's concept for ISS-to-LCRD Link

The Key to Reducing SWaP and Cost: Photonic Integrated Circuits

US Industry has commercialized "Integrated photonics" to allow many electro-optical components, even glass fibers, to be "squeezed down"…..



…into the optical equivalent of a micro-electronics "integrated circuit"



1 cm

For NASA, this means that optical systems for communications and sensors can be reduced in <u>size</u>, <u>mass</u>, and <u>cost</u> by >> 100x by leveraging this commercially-available technology (some customization may be required)

Questions?

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