Jet Propulsion Laboratory
California Institute of Technology

Small Satellite Technologies for Low-Cost Planetary Missions

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Kudos to the JWST Team!!

Today

- SmallSats provide novel and low-cost approaches to obtaining science and testing advanced technologies
- Smallsats are being adapted for use across a wide spectrum of science missions in Earth Science, Heliophysics, Astrophysics and Planetary Science to provide:
  - Better coverage and frequency of observations (temporal coverage),
  - Complimentary observations to larger-class missions, and
  - Cost effective constellations
- For example, NASA’s latest Earth Science Decadal Survey calls for much more frequent revisit times to improve our understanding of Earth system science
  - Unconventional solutions involving CubeSat and SmallSat constellations promise breakthroughs in achieving unprecedented coverage
  - Need for accurate timing and Precision Orbit Determination

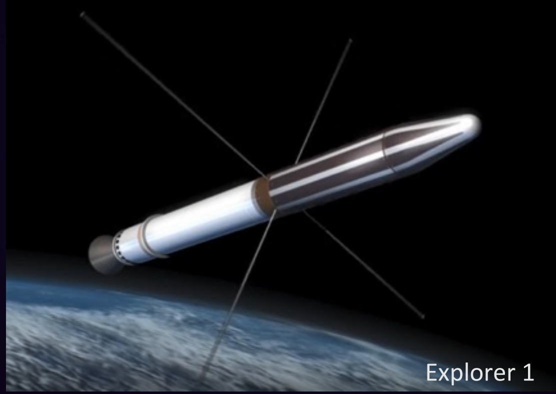
Background

- 10 years ago, current efforts were focused on LEO
- Planetary Missions typically cost >$250M
- Discovery Missions are getting close to $1B for the full lifecycle cost
- Larger planetary missions are even more expensive

So, how do you do planetary missions for a lot less money, yet still do meaningful science/exploration and more importantly, why?

Small Satellite Technologies

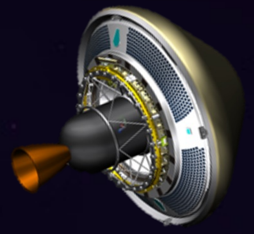
Introduction



- Why do this for Planetary exploration?
  - SmallSats can be used as probes and go into much riskier locations and do ground breaking science
  - Lower the cost / expand capabilities of planetary exploration through miniaturization
  - Make it possible for many more people and organizations to explore the planets
  - Lower mass and power components ultimately means being able to go farther out into the solar system (e.g interstellar probe with lots of caveats)

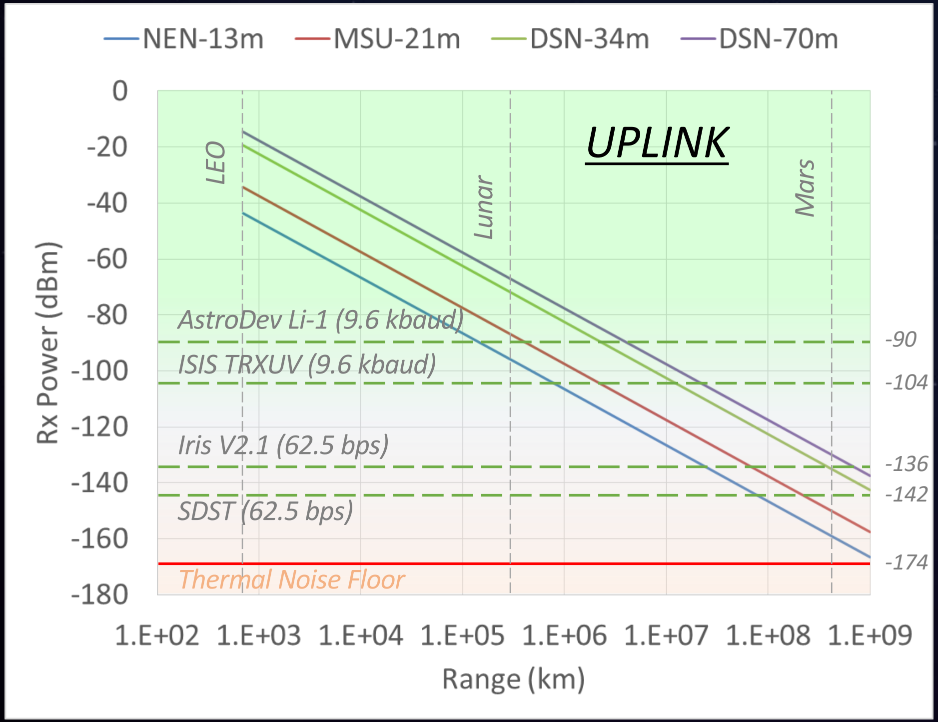
Small Satellite Technologies

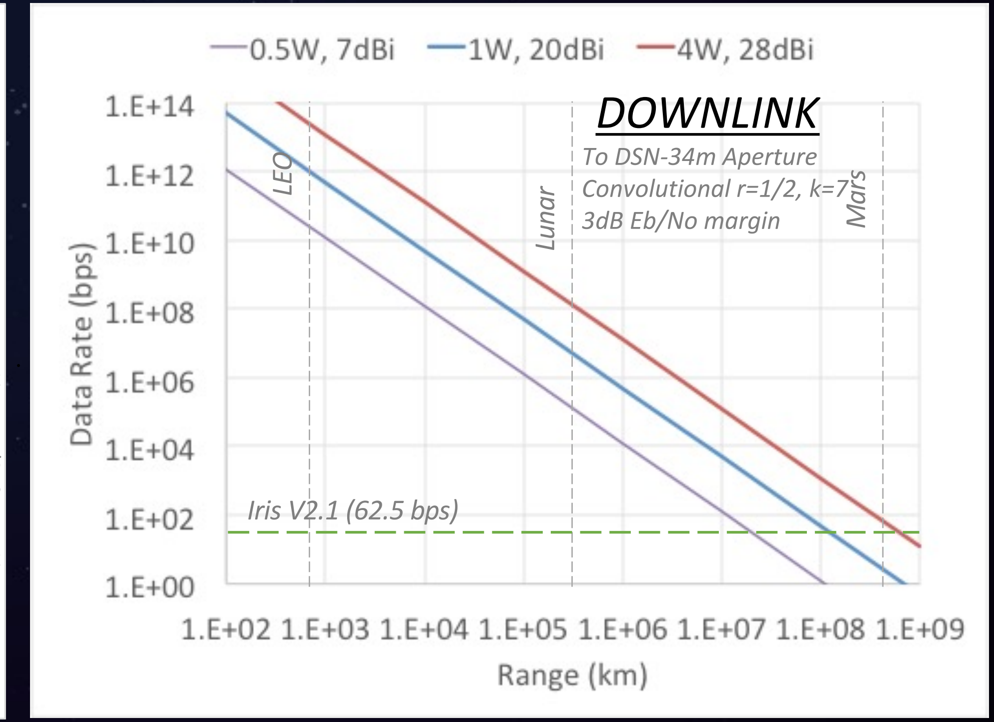
Challenges of Deep Space



- **What's different from LEO**
  - Communication over great distances
  - Navigation without GPS
  - Environments: Thermal and Radiation
  - Power for distances >1 AU
  - Thermal (especially at the Moon)
  - ACS (3-axis controlled)
  - Spacecraft Fault protection and Flight Software
  - Operations (much less frequent comm, S/C has to be more self sufficient)
  - Propulsion (need much higher delta-v and also for momentum management)

Overcoming Large Distances





*2kW assumed for EIRP calculation

Navigation in Deep Space

Support radiometric navigation (ranging, Doppler track, VLBI) for orbit determination

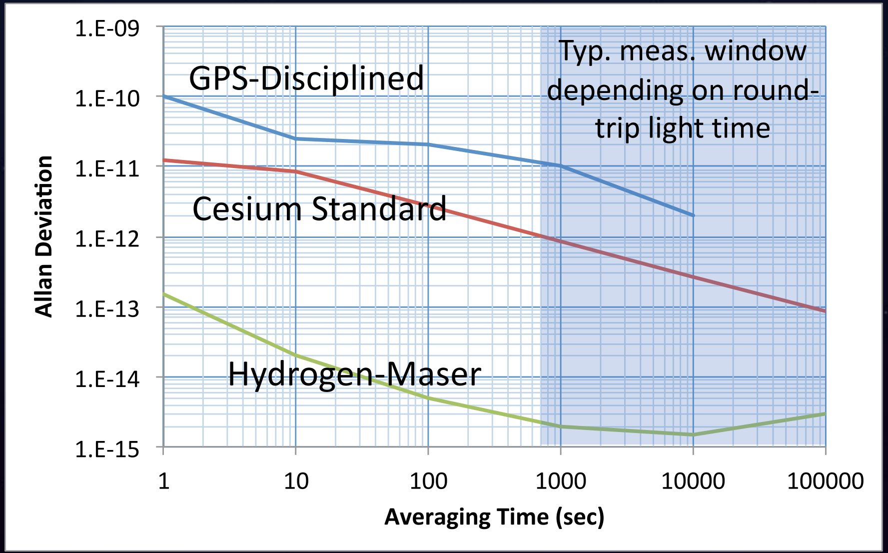
- A carefully characterized Coherent Radio Transponder is necessary for turn-around ranging on the S/C
- Transmitter with special DOR tones for VLBI support (note: need two Earth stations to support)
- Earth Station equipped with navigation processing tools

Stable reference clock for reduced navigational error

- Detect milli-Hertz variations within GHz signals.
- Long integration times with low frequency drift
  - Stability required over round-trip light time (ranging)
  - VLBI tracking times 8-12 hours.

Overcome S/C dynamic effects

- Configurable carrier tracking loops for varying dynamics
- Pre-emphasis Doppler compensation from Earth station



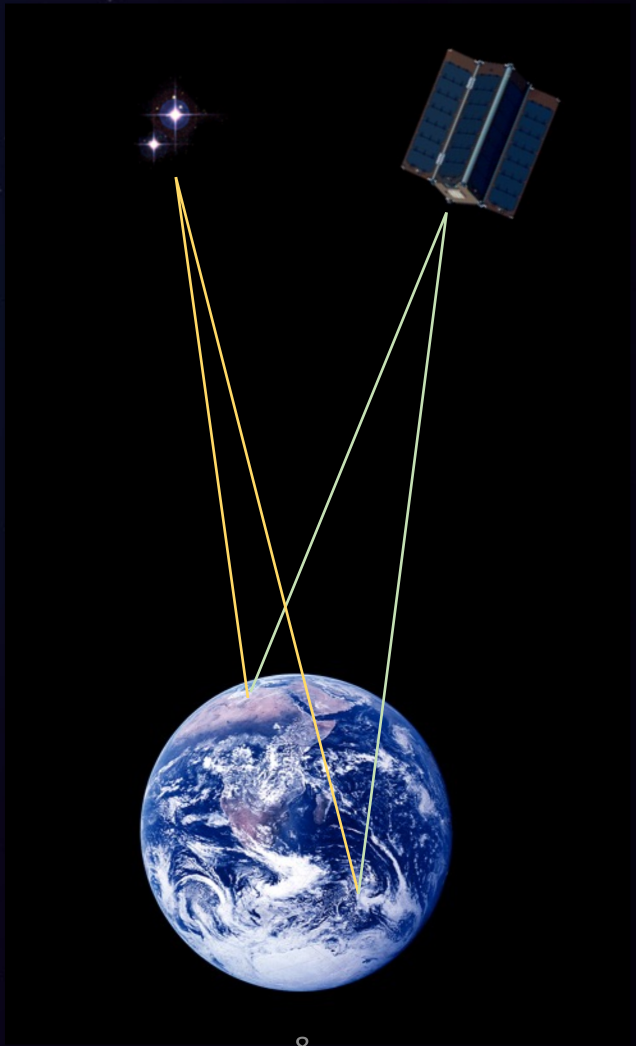
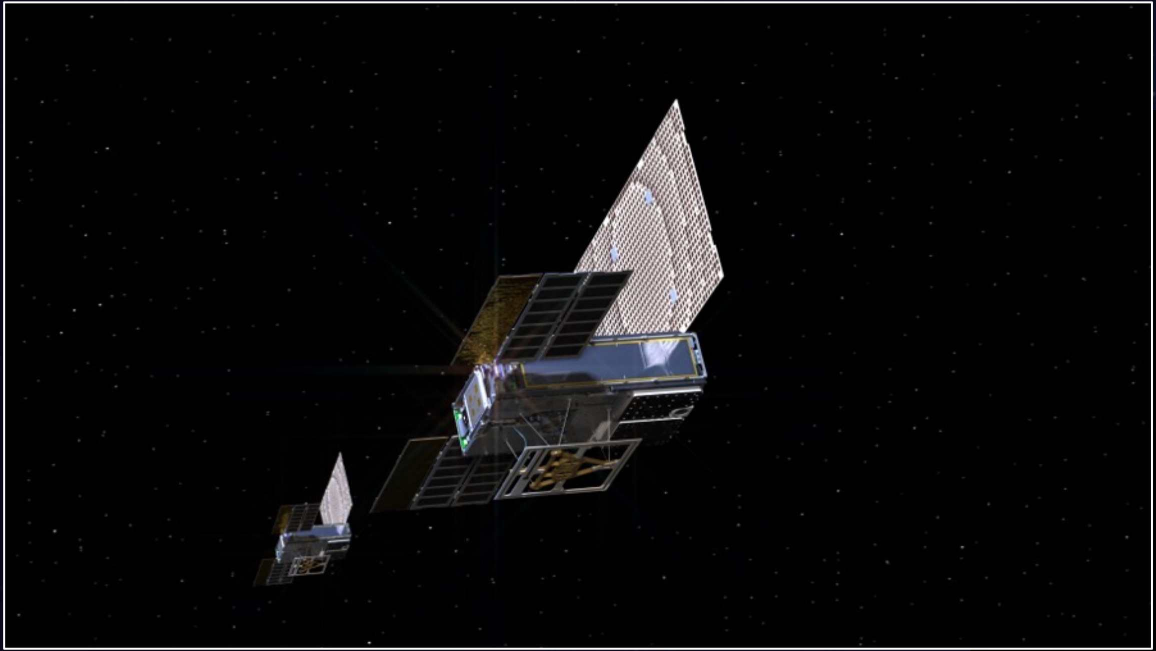
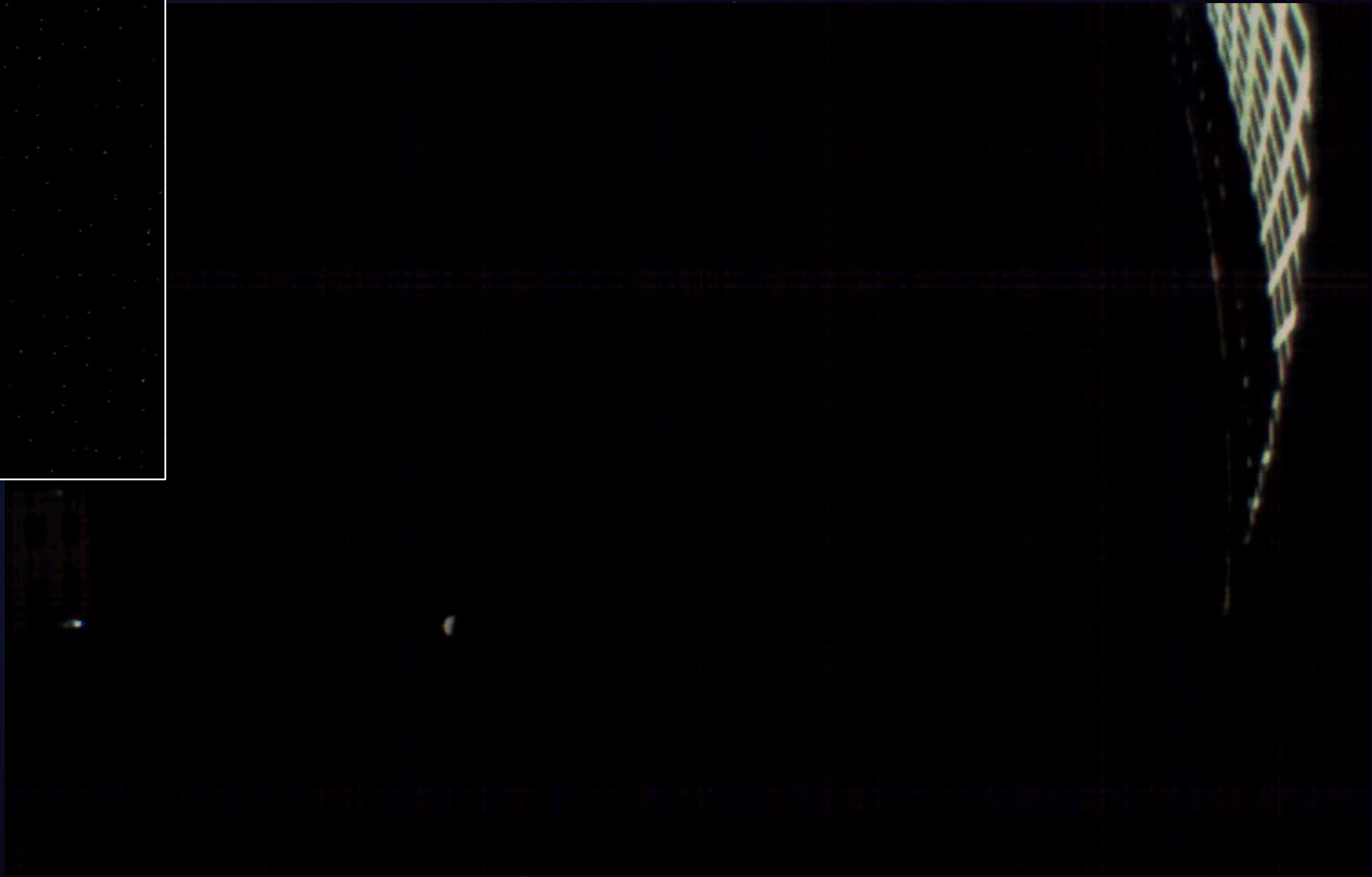


Image credit: NASA/DSN

MarCO – the first Interplanetary Cubesats



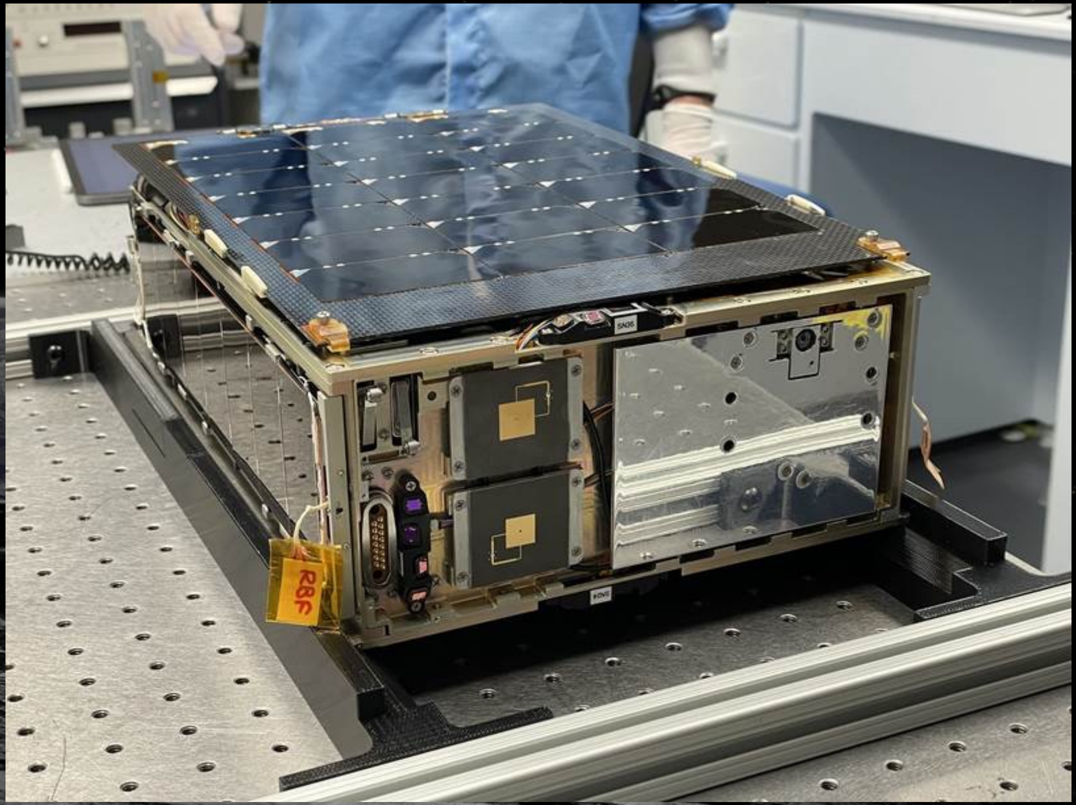


- PI: Andy Klesh, JPL
- Launched in May 2018
- Independent trajectory to Mars
- Relayed 97% of Insight landing telemetry back to Earth

Lunar Flashlight

Project Manager: John Baker, Philippe Adell (JPL)
Principal Investigator: Dr. Barbara Cohen (GSFC)

Propulsion: MSFC-Georgia Tech-JPL
I&T, Ops: Georgia Tech



- ✓Innovative tech demo mission to look for lunar south pole volatiles
- ✓the first planetary CubeSat mission to use green propulsion, and
- ✓the first mission to use high power lasers to look for water ice

Some Other Deep Space SmallSat Missions

- Procyon (JAXA) – Mission complete
- CAPSTONE - Mission started
- LICIA Cube – Deploys Sep 16 from DART
- NEAScout
- BioSentinel
- Lunar IceCube
- LunaHMap
- CuSP
- LunIR
- ArgoMoon (ASI)
- Omotenashi (JAXA)
- Equuleus (JAXA)

Artemis-1 (NEAScout through Equuleus)

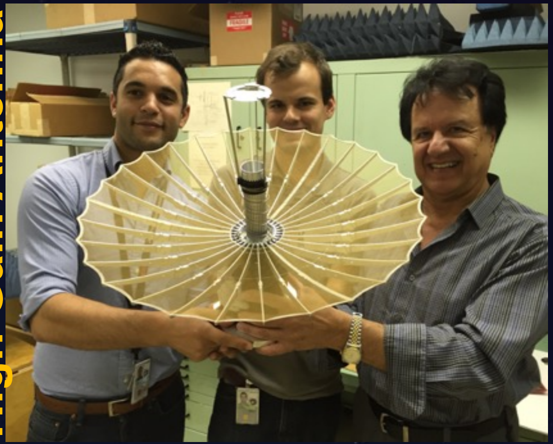
- SunRise

New Miniaturized Spacecraft Capabilities

Deep Space Transponder

The Iris software defined radio provides low cost two-way X/S/Ka-band deep space comm and precision navigational aids. Iris has been licensed to SDL.

High Gain Antenna



Deployable X/Ka-band antenna supports higher data rates for deep space SmallSats. Requires 1.5 U of volume and deploys to create a 0.5m parabolic dish. This has been licensed to Tendeg

Flight Software

Modular component based software allows for high re-use and easy tailoring. Code is open source

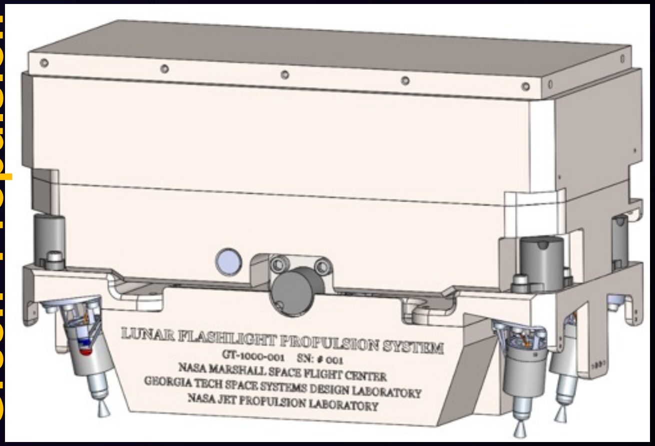
Flight Computer

Dual-core rad hard LEON 3 FT based computer uses minimal power, was designed to enable increased autonomy and data processing. Sphinx has been licensed to Cobham Aeroflex.

Attitude Determination and Control

A miniaturized modular ADCS for deep space from BCT. Includes star tracker, Inertial Measurement Unit (IMU), sun sensors and reaction wheels to provide attitude control capability and deep space maneuvers.

‘Green‘ Propulsion



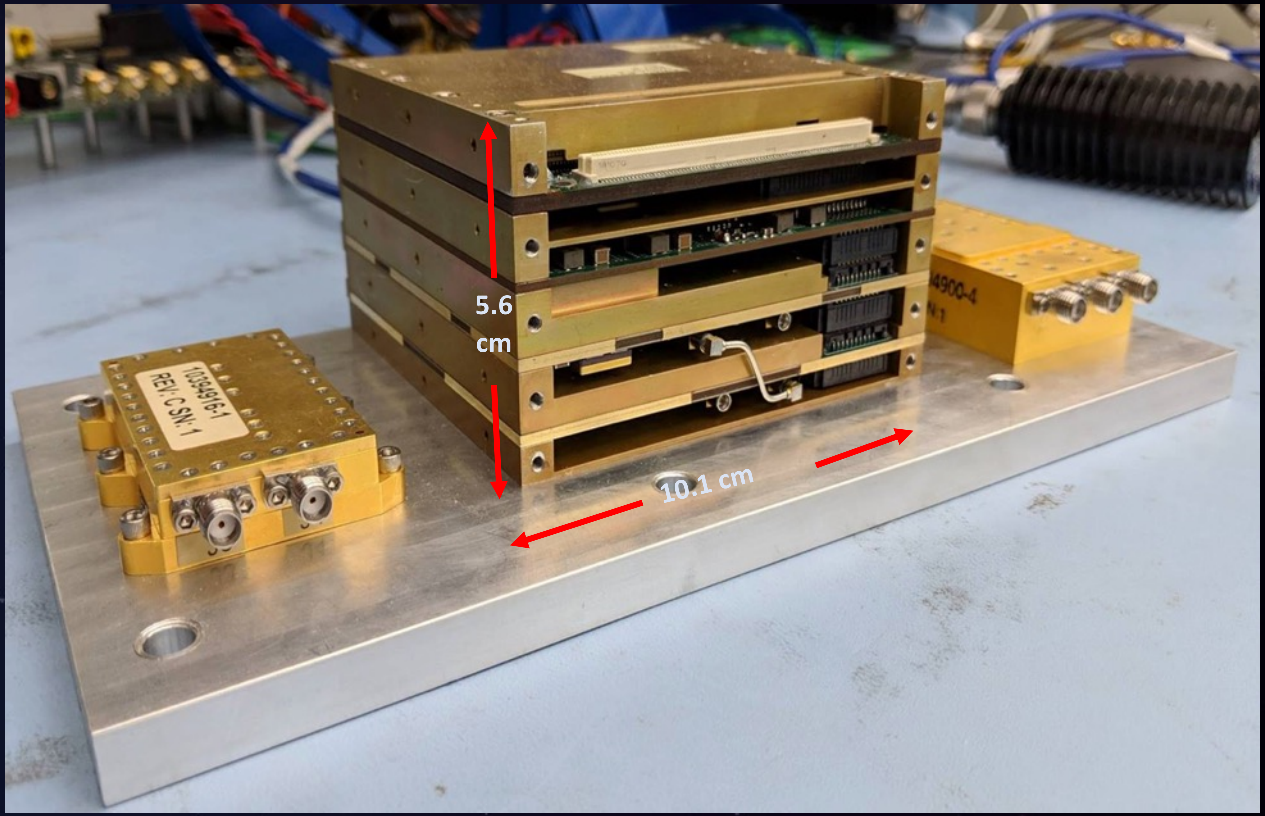
Chemical ‘green’ mono propellant (AF-M315E) to provide ≈300 - 1100 m/s propulsion and support deep space attitude & momentum management. Sponsored by NASA and AFRL. Developed by MSFC, Georgia Tech and JPL. Licensed to Plasma Process Inc

Telecom – The Iris Radio

- Low cost, flight proven, fully DSN compatible deep space transponder for small spacecraft
- 'Smart' software defined radio that frames downlink data and decodes uplink data for users
- Deep Space X-band uplink and downlink
- Multiple encoding schemes to reduce downlink bit error rates (Turbo ½, $^{1}/3$, $^{1}/6$, LDPC)

NEW Features *(in DSN validated Iris Software/Firmware)*

- *12 MSps downlink data rate (QPSK)*
  - *QPSK, OQPSK and GMSK modulation*
  - *Spacewire interface (optional) for higher data rates*
- *Precision navigation using PN DDOR*
- *Regenerative ranging for simultaneous downlink and ranging*
- *In-flight re-programmability (two additional memory slots)*
- *High data rate uplink (for re-program & relay applications)*
- *Carrier Sweep/acquisition and doppler compensation*
- *Spacecraft ID (SCID) filter (selectable)*
- *Four beacon tones for autonomous ops (signaling to ground)*
- *LDPC encoding for efficient downlink and decoding for uplink*
- *Command uplink decryption (per NASA STD-1006)*



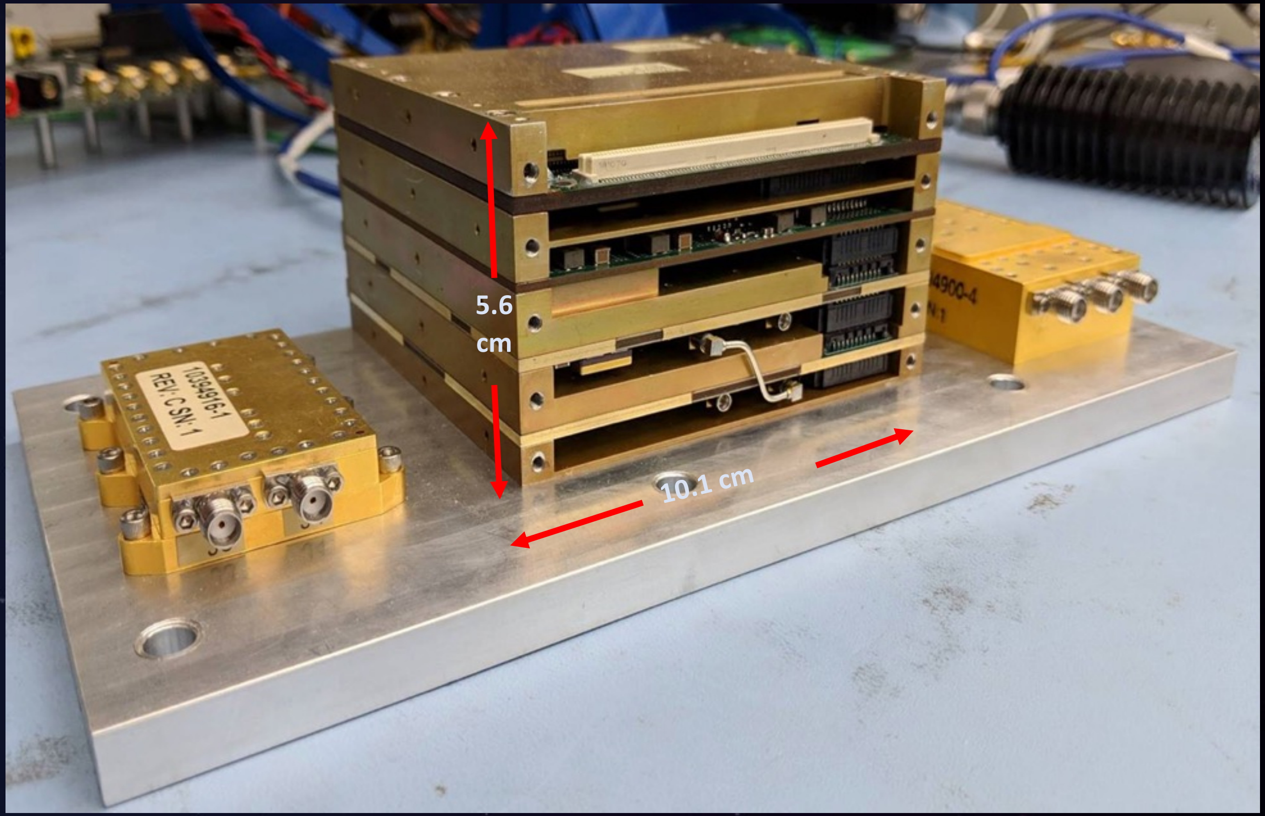
Volume : 10.1 x 10.1 x 5.6 cm = 0.57 U,
Mass: 0.86 kg (radio), 1kg with LNA and SSPA
Power (Total): 9.6W (Rx), 29W DC (Tx/Rx)
RF Output: 3.8W (EOL) – 5W (BOL)
2-ch LNA: 7 x 4.8 x 1.3 = 44 cc
3-ch SSPA: 8.7 x 4.3 x 1.8 = 68 cc
Receiver Noise Figure: 3.5 dB
Radiation tolerance: 23 krad

* *New features in yellow*

Licensed to Space Dynamics Laboratory (SDL)

Telecom – The Iris Radio

- The Future
  - Higher power SSPA
  - One-way ranging for Autonav
  - Ka-band for higher downlink data rates (25 Mbps)
  - Built-in diagnostics for autonomy
  - S-band for lunar proximity comm
  - Simultaneous communication channels (multiple frequencies)
  - More modular slice architecture
- All in basicly the same package



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Receiver Noise Figure: 3.5 dB

Planetary Propulsion for Small Satellites/CubeSats

Green monoprop for Lunar Flashlight

Electrical Controller
[MSFC & GT CAN & Grant]

- Cooperative Agreement Notice (CAN) Initiated in 2018 to cultivate alternative to elevating risk to VACCO LFPS.

Additive Manufactured Manifold
[MSFC & GT]

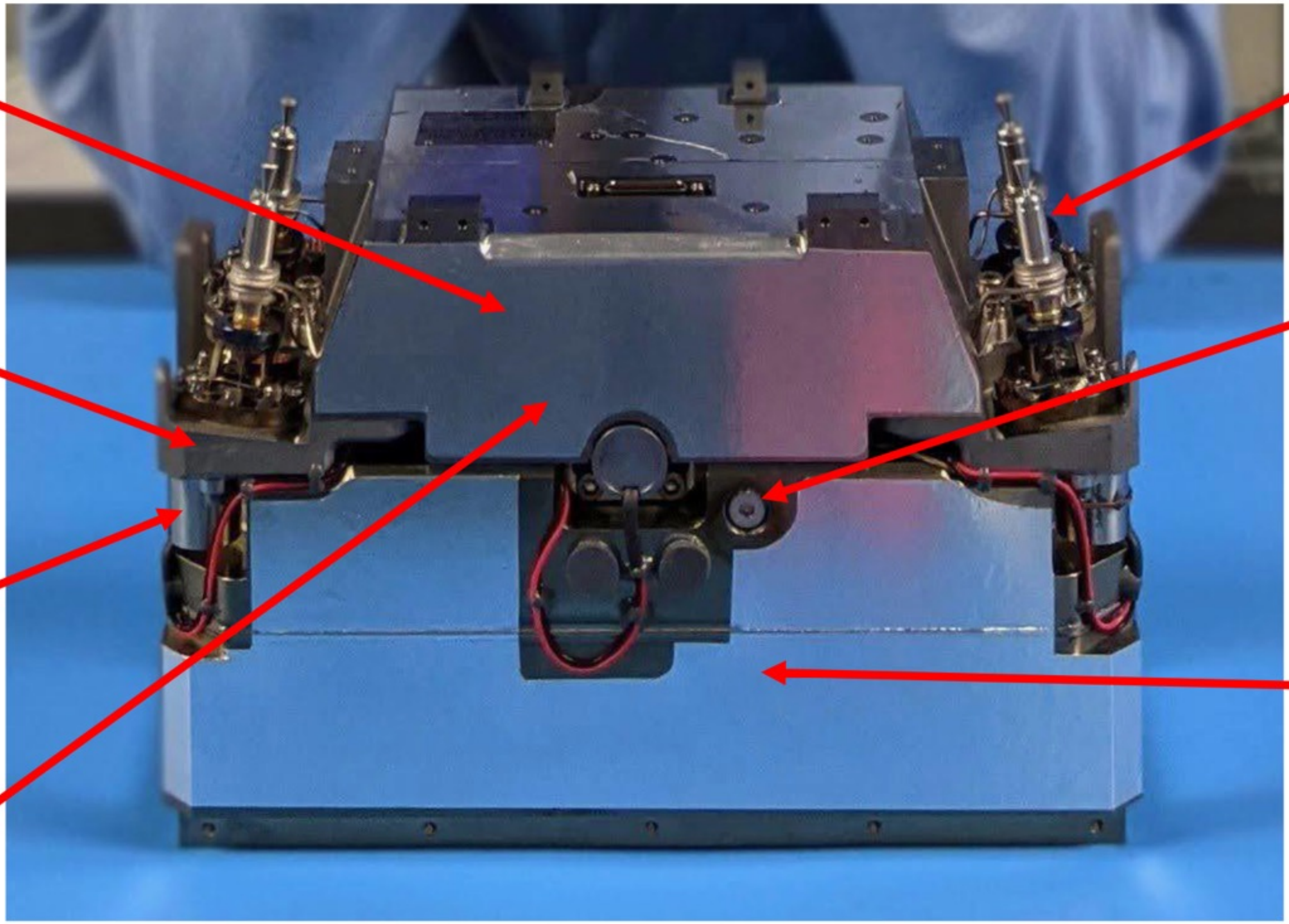
- LFPS manifold effort led to formal creation of 'Class C' AM Parts for Space Flight Application.
- Case Study for AIAA Series on AM.

Solenoid Valves (X5) - MSFC
[Center IRAD – Tech Transfer]

- *Commercial Tech Transfer Achieved*
- *Supported by Inter-Agency Agreement (IAA) with AFRL*

Pump - Flight Works Inc.
[AFRL SBIR PII & NASA CCRPP]

- Supported by Inter-Agency Agreement (IAA) with AFRL



100mN Thrusters (X4) – Plasma Processes LLC. [NASA SBIR PI/II/III]

- Supported by Inter-Agency Agreement (IAA) with AFRL

Fill & Drain Valve - MSFC
[Center IRAD – Tech Transfer]

- MSFC Best New Tech Award 2020
- Commercial Tech Transfer Achieved

Propellant Tank with PMD
[GT, GRC, & MSFC]

- Leveraged MSFC & GRC Co-Investment to develop propellant properties [Published].
- Traditional manufactured tank was path to satisfying SLS Payload Safety Review Panel (PSRP) Requirements expeditiously.

F Prime

A Flight-Proven, Multi-Platform, Open Source Software Product Line for Embedded Systems

https://nasa.github.io/fprime

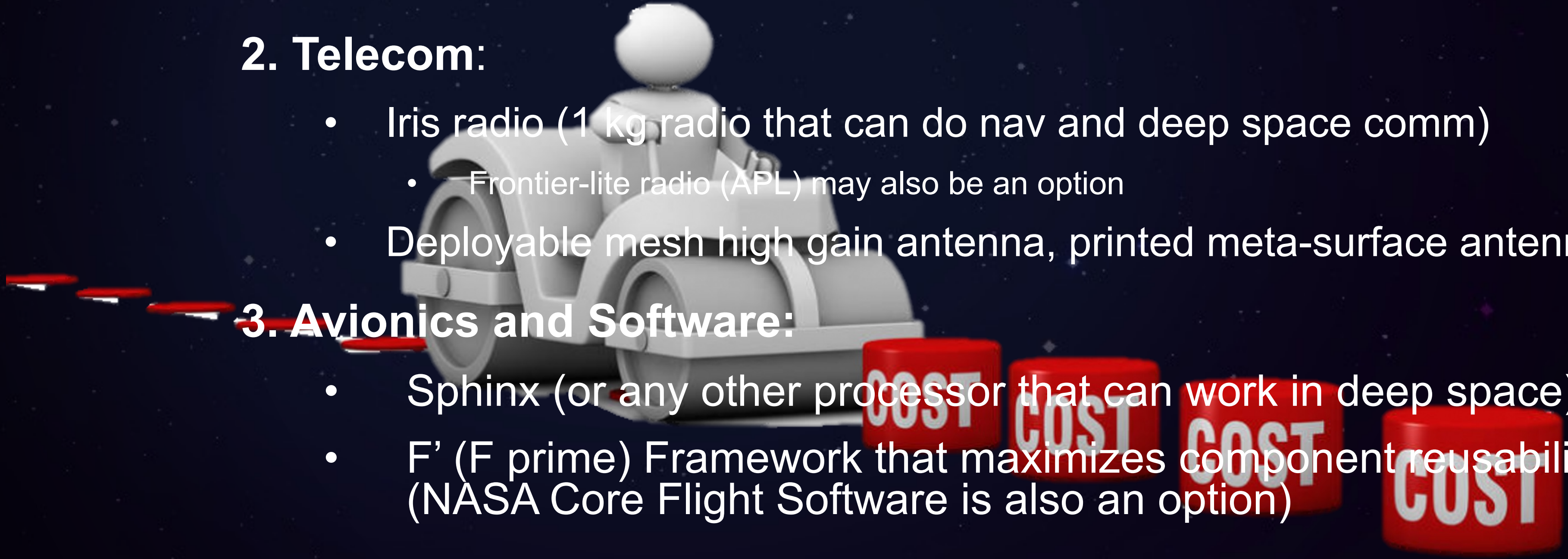
- F Prime is tailored to small-scale system deployments including CubeSats, SmallSats and instruments
- F Prime includes
  - An architecture that decomposes flight software into discrete components with well-defined interfaces
  - An C++ framework that provides core capabilities such as message queues and threads
  - Modeling tools for specifying components and connections and automatically generating code
  - A growing collection of ready-to-use components
  - Verification tools for testing flight software at the unit and integration levels
- Flight Deployments include the Ingenuity Mars Helicoper, the Lunar Flashlight, Near Earth Asteroid Scout and ASTERIA CubeSats, and the RapidScat Instrument; deployed on multiple platforms and operating systems

Key Technologies that Improve Performance at Reduced Cost

1. **Mechanical: Multiple machined parts, integration**
    - AM can now be used for pressurized primary structure
    - Multifunctional structures offer reduced integration cost without sacrificing performance (eg antennas, tanks, heat pipes)

2. **Telecom**:
    - Iris radio (1 kg radio that can do nav and deep space comm)
        - Frontier-lite radio (APL) may also be an option
    - Deployable mesh high gain antenna, printed meta-surface antennas

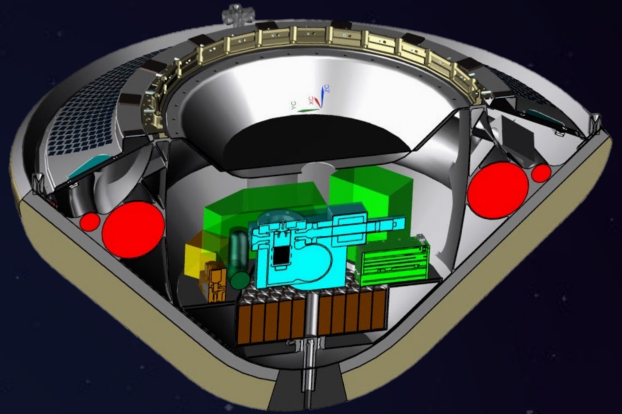
3. **Avionics and Software:**
    - Sphinx (or any other processor that can work in deep space)
    - F’ (F prime) Framework that maximizes component reusability (NASA Core Flight Software is also an option)

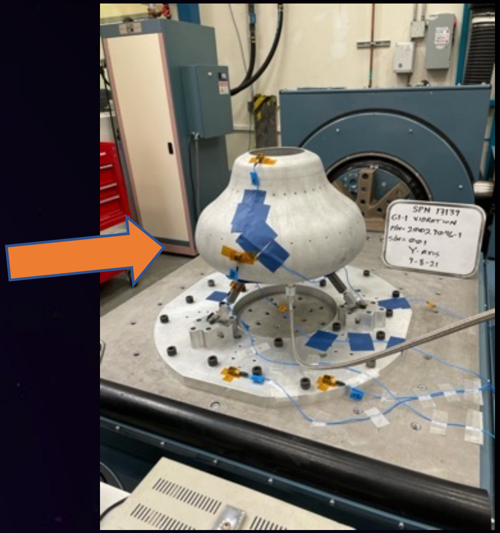


A High Performance Future
New SmallSat Technologies in Development

Quad-core flight computer, 100-300 krad TiD, redundant, low power (<10W)

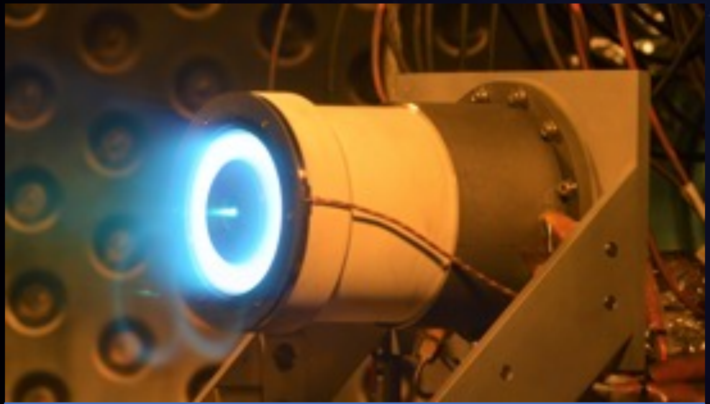
4X higher computing





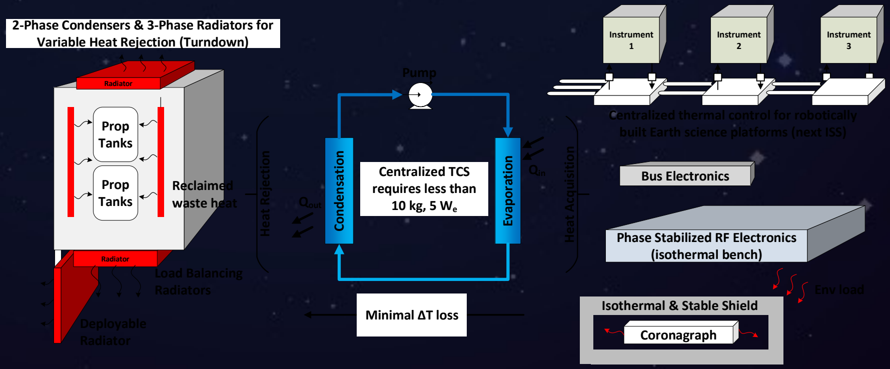
Additively manufactured primary structure with integrated pressurized (400 psi) tanks

25-30% lower mass



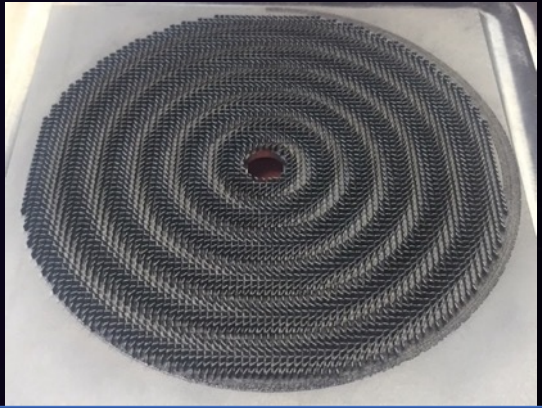
3 MN Hall thruster, 100-1kW power

3X higher performance



High efficiency 2-phase cooling system with additively manufactured evaporator panel

3X higher performance



26 dBi, 40% efficient Ka-band antenna

Dual purpose antenna and S/C structure

Summary

- Many new technologies have been or are about to be flight proven and can be purchased for a mission application. The limit does seem to be the inner solar system for these technologies, at least for now.

- Combining new technologies can allow for innovative new planetary missions that are lower in cost and can go further into the solar system.

- Autonomy (incl AI/ML) has yet to be fully applied and the benefits realized on spacecraft. SmallSats are a great platform for proving this technology

- The dream of having a spacecraft kit where all you do is print the structure and prop tank, add avionics and payload for a mission is no longer just a fantasy, but still has a ways to go.

Thank you!!

I'd like to thank the many people who believed that something smaller, more innovative and affordable is possible within NASA for planetary exploration.

- **HEOMD** – AES (now **ESDMD**)
  - Jason Crusan, Chris Moore, Jitendra Joshi, Andres Martinez
- **STMD**
  - Chris Baker, Justin Treptow, Roger Hunter, Elwood Agasid
- **SMD**
  - Thomas Zurbuchen, Lori Glaze, Jim Green, Joe Parrish
- **JPL**
  - Charles Elachi, Jacob Van Zyl, Firouz Naderi, Fred Hadeagh, Satish Khanna, Keyur Patel, Howard Eisen, Andy Klesh, Joel Krajewski and Tony Freeman

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www.jpl.nasa.gov